CEMENT AND CONCRETE

BY

LOUIS CARLTON SABIN, B. S., C. E.

ASSISTANT ENGINEER, ENGINEER DEPARTMENT, U. S. ARMY; MEMBER OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS

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PREFACE

THAT the use of cement has outstripped the literature on the subject is evidenced by the number and character of the inquiries addressed to technical journals concerning it. This volume is not designed to fill the proverbial "long felt want," for until within a few years the number of engineers using cement in large quantities was quite limited. These American pioneers in cement engineering, under one of whom the author received his first practical training in this line, needed no formal introduction to the use and properties of cement; their knowledge was born and nurtured through intimate association and careful observation.

To-day the young engineer frequently finds a good working knowledge of cement one of the essentials of success, and the gaining of this knowledge by experience alone is likely to be too slow and expensive, judged by twentieth century standards. In fact, the variety and extent of the uses to which cement is applied, and the knowledge concerning its properties, have of late increased so rapidly that even the older engineer, whose practice may have directed his special attention along other channels for a few years, finds it difficult to follow its progress.

One who wishes only a catechetical reply to any question that may arise concerning cement and its use will be somewhat disappointed in these pages; on the other hand, he who would devote special attention to the subject must, of course, go far beyond them. The author has attempted to take a middle course, avoiding on the one hand a dogmatic statement of facts, and on the other too detailed and extended series of tests, but giving, where practicable, sufficient tests to support the statements made, and endeavoring to show the connection between theory and practice, the laboratory and the field.

The original investigations forming the basis of the work were made in connection with the construction of the Poe Lock at St. Marys Falls Canal, Michigan, under the direction of the Corps of Engineers, U. S. Army. To the late General O. M. Poe, the Engineer officer in charge of the district at that time, and to Mr. E. S. Wheeler, his chief assistant engineer, may be credited a very large share of the value of the results obtained, since the accomplishment of a series of experiments of so comprehensive a character was made possible only through the broad views held by them as to the value of thorough tests of cement.

The author wishes to express his appreciation of the courtesy of General G. L. Gillespie, Chief of Engineers, U. S. A., in granting permission to use the data collected, and of the kindness of Major W. H. Bixby in presenting a request for this permission.

When not otherwise stated, the tables in the work are condensed from the results of the above mentioned investigations. In supplementing this original matter, much use has been made of the experiments of others as published in society transactions, technical journals, etc., to all of whom credit has been given in the body of the work.

If this attempt to place in one volume a connected story of the properties and use of cement serves to make the road to this knowledge a little less devious than that followed by the writer, the latter will be rewarded.

L. C. S.

SAULT STE. MARIE, MICH.
January 3, 1905.

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PART I

CEMENT

CLASSIFICATION AND MANUFACTURE

CHAPTER I

DEFINITIONS AND CONSTITUENTS

Art. 1. General Classification of Hydraulic Products

1. The use of a cementitious substance for binding together fragments of stone is older than history, and it is known that the ancient Romans prepared a mortar which would set under water. So far as our present knowledge of cement manufacture is concerned, however, the credit of demonstrating that a limestone containing clay possessed, when burned and ground, the property of hardening under water, is due to Mr. John Smeaton, who announced this as the result of his experiments made in 1756 in seeking a material with which to build the Eddystone Lighthouse. After this discovery by Smeaton nearly sixty years elapsed before M. Vicat gave the true explanation of this action, namely, that the lime during burning combined with the silica to form silicate of lime, the essential ingredient of hydraulic limes and cements.

In 1796, Parker, of London, obtained a patent for the manufacture of a cement from septaria nodules, and aptly named his product "Roman Cement." In 1824, Joseph Aspdin of Leeds, England, patented a process of manufacture of "Portland Cement."

2. The cements in general use in the United States to-day are of two kinds, Portland cements and natural cements, and in what follows our attention will be directed almost entirely to these two products.

Common limes were formerly used largely in engineering construction, but have of late been almost entirely superseded, for this purpose, by cements. Since the hardening of lime mortar depends on the absorption of carbonic acid from the atmosphere, these limes are sometimes called "air limes," while the hydraulic products which set under water are, for a similar reason, styled "water limes." Hydraulic limes, though playing an important rôle in foreign countries, are not manufactured or used to any extent in the United States. The European product known as "Roman" or "Vassy" cement, somewhat resembles our natural cement, but is usually inferior to the American article. Our chief interest in these products, which are used only abroad, is to know what relation they bear to the cements with which we are familiar. The following classifications are selected as being authoritative:

3. The conferences of Dresden (1886) and Munich (1884) on Uniform Methods of Testing for Materials of Construction, classified the hydraulic products as follows: —

(1) *Hydraulic limes:* made by roasting either argillaceous or siliceous limestones. They slake partially or wholly on the addition of water.

(2) *Roman cements:* made from argillaceous limestones having a large proportion of clay. They do not slake by the addition of water and hence must be mechanically ground to powder.

(3) *Portland cements:* obtained by burning to the point of insipient vitrification either hydraulic limestones or mixtures of argillaceous materials and limestones, and afterward grinding the product to fine powder.

(4) *Hydraulic gangues:* natural or artificial materials which do not harden alone, but which furnish hydraulic mortars when mixed with quicklime.

(5) *Pozzolana cements* produced by an intimate mixture of powdered hydrate of lime and finely pulverized hydraulic gangues.

(6) *Mixed cements:* the products of intimate mixtures of manufactured cement with certain materials proper for such a purpose. Mixed cements should always be designated as such and the materials entering into the composition should be stated, but it may be added parenthetically that these things are seldom done.

4. MM. Durand-Claye and Debray divide cements into six classes, namely, (1), Grappier cements — obtained by grinding the pieces of hydraulic lime which do not slake; (2), quick-setting (Vassy) cements — formed by burning very argillaceous limestones at a low temperature; (3), natural Portland cements, or those cements made from natural rock which correspond to artificial Portland in character; (4), mixed cements; (5), artificial Portlands; and (6), slag cements.

M. H. LeChatelier, an eminent French authority, divides hydraulic products into four classes, namely:[1] — Portland cements, hydraulic limes, natural cements, and mixed cements. He subdivides the third class, natural cements, into quick-setting, slow-setting and grappier cements, and includes natural Portlands among the slow-setting natural cements. Slag cements, which are put in a separate class by MM. Durand-Claye and Debray, are included in "mixed cements" by M. LeChatelier.

5. **Prof. I. O. Baker** gives a **classification** that is better adapted for use in this country than any of the above.[2] He divides the products obtained by burning limestone, either pure or impure, into lime, hydraulic lime and hydraulic cements. He then sub-divides cement into Portland, Rosendale (preferably called natural) and Pozzolana.

ART. 2. LIME: COMMON AND HYDRAULIC

6. **Common lime** is the product obtained by burning a pure, or nearly pure, carbonate of lime. On being treated with water it slakes rapidly, evolving much heat and increasing greatly in volume. It is now seldom used in engineering construction and will not be considered further.

7. Prof. M. Tetmajer has thus defined **hydraulic limes**: Hydraulic limes are the products obtained by the burning of argillaceous or siliceous limestones, which, when showered with water, slake completely or partially without sensibly increasing in volume. According to local circumstances, hydraulic limes may be placed on the market either in lumps, or hydrated and pulverized. The following table gives a classification of hydraulic limes according to M. E. Candlot[3] who states that the first

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[1] "Tests of Hydraulic Materials," by H. LeChatelier. Trans. Am. Inst. Mining Engrs., 1893.

[2] "Masonry Construction," p. 48.

[3] "Ciments et Chaux Hydrauliques," par E. Candlot.

class is seldom used for important work and that the fourth class is quite rare.

TABLE 1

Classification of Hydraulic Limes. E. Candlot

Class.	Per Cent. of Clay in Limestone.	Per Cent. of Silica and Alumina in Finished Product.	Hydraulic Index, or Ratio of Silica and Alumina to Lime.	Approx. Time to Set, Days.
Feebly Hydraulic Lime	5 to 8	9 to 14	.10 to .16	16 to 30
Ordinary " "	8 to 15	14 to 24	.16 to .31	10 to 15
Real " "	15 to 19	24 to 30	.31 to .42	5 to 9
Eminently " "	19 to 22	30 to 33	.42 to .50	2 to 4

Hydraulic limes should be burned slowly, and at such a temperature that sintering does not take place. The best hydraulic limes have a composition very similar to that of Portland cement. The comparatively low temperature at which they are burned permits them to slake on the addition of water. They gain strength much more slowly than cements.

Having considered the classification of hydraulic products as a whole, we may proceed to the discussion of Portland and natural cements, the hydraulic products which have by far the greatest importance here, and the only varieties which will be taken up in detail in the present work.

Art. 3. Portland Cement

8. As the classification of hydraulic products varies, so do opinions vary as to what shall be included under the name Portland cement. There seems to be agreement on at least one point, namely, that the burning shall be carried to a point just short of vitrification. Ideas concerning other points are crystallizing rapidly. The Association of German Portland Cement Manufacturers has given a definition of Portland cement in a practical manner by binding its members "to produce under the name of Portland cement only such an article as is made by calcining a thorough mixture, consisting essentially of calcareous and clayey substances, and then grinding the same to the fineness of flour;" and they further declare that "any article made in a manner differing from the above method, or to which during or after burning any foreign substances have been added," is not recognized by them as Portland cement, and the sale of such products under the designation "Portland Cement" is regarded by them as defrauding the purchaser. This declaration does not apply to such minor additions as are made to regulate the setting time of Portland cement, and which are permitted to an extent of 2 per cent."

9. M. LeChatelier has given the following **limits** for the amounts of the **materials** usually contained in good commercial Portland cements:[1] —

Silica	21 per cent. to		24 per cent.
Alumina	6	"	8	"
Oxide of Iron	2	"	4	"
Lime	60	"	65	"
Magnesia	.5	"	2	"
Sulphuric Acid	.5	"	1.5	"
Water and Carbonic Acid	1	"	3	"

The upper limit for lime (65 per cent.) is being exceeded in recent years.

These substances occur as "(1) SiO_2, 3CaO, the essentially cementitious ingredient; (2) Al_2O_3, 3CaO, the substance mainly active during setting and contributing somewhat to the subsequent hardening; and (3) a fusible calcium silico-aluminate whose chief function is that of a flux during burning to promote the necessary chemical reactions."[2] M. LeChatelier further holds that in good Portland cements the following formulas should be true:

$$\frac{CaO,\ Mg\,O}{SiO_2 + Al_2O_3} \leqq 3,$$

and

$$\frac{CaO,\ MgO}{SiO_2 - (Al_2O_3,\ Fe_2O_3)} \geqq 3.$$

in each case the quantities in the formulas being equivalents of the substances, not weights. The ratio of the acid constituents, silica and alumina, and the basic constituents, lime and magnesia, is called the **hydraulic index.** Although these formulas have been quite generally accepted as properly fixing the limits of the ingredients it may be noted that they are based on the assumption that SiO_2, and Al_2O_3, are equally capable of dispos-

[1] "Tests of Hydr. Materials," Tr. Am. Inst. Mining Engrs., 1893.
[2] Jour. Soc. Ch. Ind., Mar. 31, 1891, p. 256.

ing of a given quantity of lime and magnesia, and it is thought by some authorities that the assumption is not warranted.

In the Journal Society Chemical Industry, 1897, Messrs. S. B. and W. B. Newberry give the results of some investigations in this line from which they concluded that the essential ingredient of Portland cement is a tri-calcium silicate, but that the alumina occurs as a dicalcic aluminate. They therefore considered that the per cent. of lime should equal 2.8 times the per cent. of silica plus 1.1 times the per cent. of alumina.

10. The following **analyses** of brands in the market are selected from the various sources indicated in the table. They are given here merely to illustrate the proportions obtaining in commercial products.

TABLE 2

Analyses of Portland Cements

BRAND.	SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	MgO.	Na_2O K_2O.	SO_3.	H_2O & Loss.
1. Alpha	20.38			63.30	2.86		1.13	1.75
2. Atlas	21.30	7.65	2.85	60.95	2.95	1.15	1.81	1.41
3. Bronson	22.90	6.80	3.00	63.90	0.70	1.10	0.40	0.60
4. Buckeye	21.30	6.95	2.00	62.30	1.20		0.98	4.62
5. Empire	22.04	6.45	3.41	60.92	3.53		2.25	
6. Wyandotte	23.20	8.00	2.40	62.10	2.00			0.80
7. Omega	22.24	7.26	2.54	64.96	2.26		0.41	0.33
8. Yankton		7.70	4.30	60.00	0.80	1.20		
9. Giant	23.36	8.07	4.83	58.93	1.00	0.50	0.50	2.46
10. Medusa	23.20	7.03	2.41	64.19	0.97			2.20
11. Dyckerhoff	19.35	7.00	4.50	63.75				5.40
12. Germania	21.14	6.30	2.50	66.04	1.11			2.91
13. Alsen's	24.90	8.00	3.22	59.38	0.38	0.75	0.98	2.16
14. Alsen's	23.30	5.85	4.65	60.90	0.90	0.30	2.43	1.40

BRAND.	AUTHORITY.	RAW MATERIALS.	LOCATION.
1	"Directory Amer'n Cement Industries"	Cement Rock and Limestone	Alpha, N.J.
2	" "	" " " "	Northampton, Pa.
3	" "	Marl and Clay	Bronson, Mich.
4	" "	" " "	Bellefontaine, Ohio.
5	" "	" " "	Warners, N.Y.
6	" "	Soda Ash Waste and Clay	Wyandotte, Mich.
7	" "	Marl and Clay	Jonesville, Mich.
8	" "	Chalk and Clay	Yankton, S. Dakota.
9	U. Cummings "Amer'n Cements"	Cement Rock and Limestone	Egypt, Pa.
10	" "	Marl and Clay	Sandusky, Ohio.
11	" "	Limestone, Marl and Clay	Amoeneburg, Ger.
12	" "	Marl and Clay	Lehrte, Germany.
13	" "	Chalk and Clay	Itzehoe, Germany.
14	Richard K. Meade, "Exam. of P. Cem."	Chalk and Thames Mud	England.

Art. 4. Slag Cement

11. Slag cement is manufactured to a considerable extent in Europe and is beginning to assume some importance in the United States. It is a pozzolana cement in which the silica ingredient is supplied by blast furnace slag. Pozzolana cements have been defined as "products obtained by intimately and mechanically mixing, without subsequent calcination, powdered hydrates of lime with natural or artificial materials which generally do not harden under water when alone, but do so when mixed with hydrates of lime (such materials being pozzolana, Santorin earth, trass obtained from volcanic tufa, furnace slag, burnt clay, etc.), the mixed product being ground to extreme fineness."[1]

Slag cement somewhat resembles Portland in its properties, but is more like some of the natural cements in its constituents, while the manner of occurrence of these constituents and the method of manufacture are quite different than in either of these classes.

12. As this cement is a mixture of lime and pozzolanic materials, its value depends largely upon its extreme fineness and the intimate mixture of the ingredients. Its specific gravity is low, about 2.7 to 2.8, and it sets very slowly, although the setting may be hastened by the addition of certain substances such as caustic soda. On account of the sulphide present, most slag cements are not suited to use in air, as they crack and soften in this medium; neither are they suitable for use in sea water, nor in freezing weather, but when mixed with two or three parts sand and kept constantly wet with fresh water, they give quite satisfactory results.

Slag cement has an approximate **composition** of silica, 20 to 30 per cent., alumina, 10 to 20 per cent., and lime, 40 to 50 per cent. It usually contains calcium sulphide, the amount sometimes reaching three or four per cent. The characteristic greenish tint which slag cements exhibit when they harden in water is due to this ingredient, as is the odor of hydrogen sulphide sometimes given off by a briquet when broken, especially if it

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[1] "Report of Board of Engineers on Steel Portland Cement," Washington, 1900.

has hardened in sea water. Some slag cements have also quite a percentage of magnesia.[1]

Art. 5. Natural Cement

13. Natural cement, as its name implies, is made from rock as it occurs in nature. Argillaceous limestones, magnesian limestones, or argillo-magnesian limestones, having the proper proportion of clay, magnesia and lime, may be used for the production of natural cement. The burning is not carried so far as in the manufacture of Portland cement, and the resulting

TABLE 3

Analyses of Natural Cements

Reference.	Silica.	Alumina.	Iron Oxide.	Lime.	Magnesia.	Potash and Soda.	Carbonic Acid, Water and Loss.
	c	*d*	*e*	*f*	*g*	*h*	*i*
1	24.30	2.61	6.20	39.45	6.16	5.30	15.23
2	34.66	5.10	1.00	30.24	18.00	6.16	4 84
3	23.16	6.33	1.71	36.08	20.38	5.27	7.07
4	26.40	6.28	1.00	45.22	9.00	4.24	7.86
5	27.30	7.14	1.80	35.98	18.00	6.80	2.98
6	27.98	7.28	1.70	37.59	15.00	7.96	2.49
7	27.69	8.64	2.00	42.12	14.55	2.00	3.00
8	27.60	10.60	0.80	33.04	7.26	7.42	2.00
9	28.02	10.20	8.80	44.48	1.00	0.50	7.00

Reference.	Brand.	Place of Manufacture.
	a	*b*
1	Buffalo	Buffalo, N. Y.
2	Utica	Utica, Ill.
3	Milwaukee	Milwaukee, Wis.
4	Louisville	Louisville, Ky.
5	Hoffman	Rosendale, N. Y.
6	Norton High Falls	Rosendale, N. Y.
7	Akron	Akron, N. Y.
8	Utica	LaSalle, Ill.
9	Round Top	Hancock, Md.

Selected from table compiled by Mr. U. Cummings, "Brickbuilder," May, 1895.

[1] For an excellent resumé of the qualities and distinguishing characteristics of slag cements, the reader is referred to "Report of Board of Engineers on Steel Portland Cement as used in United States Lock at Plaquemine, La." Washington, 1900.

product is of lighter weight and usually quicker setting, though some natural cements are quite slow setting. The properties of these cements, coming from different localities, vary greatly. In fact, it is difficult to distinguish some natural cements from Portland, and they may be considered to grade into the natural Portlands. Light burning in manufacture, light weight per cubic foot, and slower rate of acquiring strength, may be considered the distinguishing characteristics from a physical point of view.

14. Analyses. — Table 3 gives the results of a number of analyses of natural cement, selected from a table compiled by Mr. U. Cummings.

Comparing these analyses with those given for Portland cement in Table 2, it is seen that natural cements have a higher percentage of silica, about the same amount of alumina, and a much smaller content of lime, than have Portlands. Many natural cements have a large percentage of magnesia, but the magnesia and lime together of natural cements usually do not equal the percentage of lime in Portlands. In other words the hydraulic index is usually higher than in Portland cements.

CHAPTER II

MANUFACTURE

Art. 6. The Manufacture of Portland Cement

15. Historical. — It is said that as early as 1810 a patent was obtained in England for the manufacture of an artificial product by calcining a mixture of carbonate of lime and clay. This, however, was not called cement, and it was not until 1824 that Joseph Aspdin, of Leeds, England, in obtaining a patent for the manufacture of a similar material, called his product "Portland Cement." This name was probably suggested by the fact that the color of the hardened product resembled that of a limestone quarried on the Island of Portland. The industry was introduced into Germany about thirty years later, and has since grown to very substantial proportions in both of these countries, as well as in France, Austria and Russia.

David O. Saylor was the first to manufacture Portland cement in the United States, at Coplay, Pa., about 1872, and works were established at that point in 1875. These were soon followed by other factories in Pennsylvania and Indiana, and at present cement is successfully manufactured in nearly half of the states of the Union, the production having steadily increased.

16. Materials Required. — The materials requisite for the manufacture of Portland cement are carbonate of lime and silica. The former may be in the form of limestone, chalk, or calcareous marl, the last two being preferable on account of greater ease of working. The silica may be in the form of shale or clay, the latter to be preferred. The clay need not be entirely free from impurities, but it should not contain any considerable amount of sand, for although silica is the most useful constituent of the clay, it must not be in this insoluble form. Although formerly authorities did not agree as to whether the alumina in the clay was an unwelcome constituent for Portland cement manufacture, it is now considered that the dicalcic or tricalcic aluminate formed plays a rôle in the setting of the cement, and possibly also in the subsequent hardening.

A few analyses of materials suitable for Portland cement manufacture are given in Table 4.

TABLE 4

Analyses of Cement Materials

MATERIALS.	SiO_2.	Al_2O_3 and Fe_2O_3.	$CaCO_3$.	$MgCO_3$.	SO_3.	Water and Loss.
White Marl, Empire [1]	.26	.10	94.39	.38	...	3.10
Clay, Empire [1]	40.48	20.95	25.80	.99	...	8.50
Gray Marl	7.26	1.49	84.10	.91	...	3.98
Clay	53.5	24.20	5.15	2.15	...	14.10
Limestone, Glens Falls [1]	3.30	1.30	93.13	1.58	0.30	...
Clay, Glens Falls [1]	55.27	28.15	10.43	2.25	0.12	...
Gray Chalk, Medway, Eng. [2]	5.45	3.87	88.72	...	...	...
River Mud, Medway, Eng. [2]	71.71	16.70	4.05	...	...	...

[1] "Manufacture Portland Cement in New York State," by Mr. Edwin C. Eckel, C. E.

[2] "Cement for Users," Mr. Henry Faija.

17. The materials for Portland cement manufacture, limestone, marl, clay, shale, etc., are widely disseminated, but the suitability of a certain locality for successful commercial manufacture depends upon the manner of occurrence of these requisites. In England the clay is dug from the old beds of the Thames and Medway Rivers, and chalk, which occurs in abundance, furnishes the carbonate of lime in most cases, though limestone is sometimes used. In Germany both chalk and marl are used; the chalk being a soft white marl similar to the deposits in this country, and the marl a "more or less hard limestone rock containing clay." In the United States both limestones and marls are used. The most important cement producing egion in the United States is in the Lehigh Valley, where an argillaceous limestone is employed. The factories using marl are situated in New York, Ohio, Indiana, Michigan, etc., where the marl is found overlying beds of clay suitable for cement making. In the Lehigh Valley region many advantages are combined. The cement rock of that locality has nearly the correct composition for Portland cement manufacture. The supply of this rock is almost inexhaustible, the managers of the works have had long experience in the production of cement from these materials, and a market for the product is near at hand.

Deposits of cement materials are of value only when the limestone or marl, and clay or shale, are found in large quantities and near together, when the physical character of the materials is such as to render them easy of comminution and mixture, when coal or other suitable fuel may be had at low prices, and when the market is not too far removed.

The following estimate of the relative quantities of cement made in the United States in 1902 from the several classes of materials has been made by Mr. E. C. Eckel:[1]

Argillaceous limestone and pure limestone	68 Per cent.
Marl and clay	14 "
Soft limestone and clay	4½ "
Hard limestone and clay	13½ "

18. General Description of Processes. The essentials of any method of Portland cement manufacture are that the materials shall be correctly proportioned, very finely comminuted and thoroughly mixed, that the mixture shall be carefully burned to just the proper degree of calcination and the resulting clinker ground to extreme fineness. How these essentials can be best accomplished depends upon the character of the raw materials and the cost of fuel and labor, so that the details of the method vary with the materials used and with the local conditions.

In order that the proportions may be accurately determined, it is usually necessary to dry one or both of the raw materials. The ingredients may be ground separately and afterward mixed, though with certain materials the grinding and mixing may be done at the same time. In this mixing, a large amount of water may be used, as in the "wet process," giving a very thin slurry; a moderate amount may be used, as in the semi-wet process, giving a slurry of creamy consistency; or the dry process may be employed, where the amount of water used is no more than sufficient to dampen the materials. The burning may be ac-

[1] *Engineering News*, April 16, 1903.

complished in any one of several styles of kiln, the selection depending upon the relative cost of labor and fuel, the relative necessity of economy and rapid production, and, perhaps we should add, the rigidity of the specifications which the finished product must fulfill. The grinding is a simple mechanical problem, to secure the required degree of fineness with least cost.

19. The Wet Process. Although an excess of water may be used to mix materials that require previous grinding, the wet process is particularly adapted to such raw materials as are easily acted upon by water. This method was developed in England, where it is still employed to some extent and it has been used in this country as well.

Proper amounts of the raw materials, previously ground if necessary, are placed in a wash mill with a large amount of water. The wash mill is a circular trough in which teeth or arms are made to revolve, agitating the mass.. When the materials are so finely divided as to be held in suspension, the thin slurry is run off into "backs," or shallow settling reservoirs, where the solid matter settles; the clear liquid is then run off, the slurry being allowed to dry further until it can be cut into bricks and placed on drying floors artificially heated. The bricks are then taken to the burning kilns and finally ground to form the finished product.

The disadvantages of this method are that much space is required for the settling floors, the amount of heat required to dry the brick is excessive, and the process is necessarily slow. These disadvantages are so great that the method above outlined is rapidly falling into disuse. Materials particularly adapted to wet mixing are still treated by this process, but the wet mixture is run directly into very long rotary kilns and is dried in passing through the first half of the length, which is heated by the gases from the lower portion where the burning is completed.

20. The Dry Process. This method of manufacture is best adapted to materials, such as limestone and shale, that must be dried and ground before they can be mixed. The rock as it comes from the quarry is first passed through a rock crusher, reducing it to the size of broken stone used for concrete; then to some other form of crusher, such as heavy rolls, until it is reduced to pieces about one-half inch or less in size. It is then dried by artificial heat.

The materials may now be combined in proper proportions and ground together to extreme fineness, thereby becoming thoroughly mixed. If the mixture is to be burned in the old style kiln, it must now be dampened so that it may be pressed into bricks to be charged in the kiln. If a rotary kiln is used, however, the dry mixture may be fed directly into it, or it may be moistened enough so that it will form into little lumps the size of wheat grains, and these fed to the rotary.

21. THE SEMI-DRY PROCESS. The two processes briefly described above are extremes admitting many modifications which will not be entered into in detail. What may be called the semi-dry process, however, has been so widely used in the United States that it deserves some special mention, and it may perhaps be best explained by giving the method formerly employed in a well-known American factory which, until a few years ago, was using the vertical kiln.

The carbonate of lime in the form of marl was found above the clay in beds varying in thickness up to 20 feet. The clay in general contained little sand, and the beds were of such thickness that whenever too much sand was present, the clay might be wasted. The materials were delivered to the factory, about three-quarters of a mile from the deposit, by small cars running on a narrow gage railroad.

When the clay reached the factory it was put in shallow wooden pans and run into dry kilns on light cars. After drying, which required 36 to 48 hours, the clay was ground and delivered in weighed quantities to the mixer. The main object of drying the clay was to be able to control the amount added to a given quantity of marl, and the grinding was to facilitate the mixing of the two ingredients. As the cars of marl entered the building, they were brought to a given weight by means of a scale, which was set and locked by the manager. The marl was then dumped directly into the wet pan or mixer.

The latter consisted of an iron pan, about 12 feet in diameter, in which revolved two cast iron rollers weighing three tons each. These rollers were on opposite ends of a horizontal axis which was attached to a vertical shaft in the center of the pan. This shaft being driven from below, the rollers traveled in a circular path; as the rollers were hung loose on the horizontal axis, they revolved about the latter only when sufficient friction was developed between their peripheries and the floor of the pan. In front of each roller traveled two blades, one of which pushed the material under the roller from the center, while the other did the same from the circumference.

A weighed amount of dry, powdered clay was admitted at the side of the mixer, from a hopper scale, at the same time as the marl was dumping into it, and sufficient water was added through a hose to bring the contents of the pan to a pasty mass. Five minutes were allowed for mixing each charge, when a slide was drawn, leaving two holes in the path of the wheels and on opposite sides of the pan. The material, or "mix," was delivered on a belt conveyor and carried to a pug mill, whence it issued in the form of rough bricks, partially cut by wires into six-inch cubes. These cubes, being loaded on cars, were run into the dry kiln, where they remained from two to four days, and were then taken to the kiln room to be filled, by hand, into the burning kilns, which were of the dome type.

In charging, layers of cement-brick and coke were alternated. For convenience, as well as to prevent the bricks being crumbled by a fall, the charging was done from three levels. From 36 to 72 hours were required for burning a charge. The kiln was then opened at the mouth, and the clinker, which had shrunk in volume about three-quarters, and in weight about one-half, was drawn off as fast as it cooled. The clinker was shoveled from the kilns to a pan conveyor and sorted as shoveled, only that which appeared properly burned being allowed to pass; the underburned portion was stored for further burning, and the overburned, wasted. Further sorting was done by two men stationed in the kiln room, who watched the clinker as it passed on the conveyor and picked out any pieces defective in burn that might have passed the hands of the shovelers.

The conveyor delivered the clinker to a Blake crusher, which broke it into pieces the size of pebbles; thence it passed to horizontal millstones, or, to what replaced these, ball and tube mills, for final reduction. The material was then delivered into cylindrical screens having about 2,500 meshes per square inch, that portion retained in the screen being returned to a stone supplied almost entirely with these screenings. The cement was then conveyed to the stock house, which was divided into bins of 1,500 barrels capacity, and finally packed in barrels by means of a screw blade fitting the interior of the barrel.

22. DETAILS OF THE MANUFACTURE: Preparation and Mixing of the Raw Materials. The main points in the preparation of the raw materials for burning are: first, the proper amount of each ingredient must enter the mixture; second, the materials must be reduced to an extremely fine state of division, with no lumps; and third, the mechanical mixing must be as perfect as possible. Unless the ingredients are dried, the first requirement is difficult to accomplish, especially with marl and clay, as the absorptive power of the materials renders it difficult to properly apportion them. More than three-fourths of the Portland cement manufactured in the United States is made from limestones. These must be ground before they can receive the required addition of clay or of purer limestone, as the case may be, and they are usually dried to facilitate the grinding as well as to permit of determining the correct proportions of the ingredients. These hard materials are first crushed in an ordinary stone crusher or between heavy rolls, then dried in rotary driers, or otherwise; next, mixed and ground together to an extreme fineness in ball or tube mills. When rotary kilns are employed, the mix may be burned dry, but with fixed kilns, it is moistened to form bricks which are charged in the kilns with alternate layers of coke.

Soft materials, such as marl and clay, are easy of reduction in water, and are naturally treated by the wet or semi-dry process, although they may be prepared by the dry process. In the former method the grinding and mixing are accomplished by edge runners, pug mills or wash mills. If the materials have not been dried before mixing, the mix or slurry should be sampled and analyzed before it is passed to the kilns. When fixed kilns are employed, it is desirable that the bricks should be as porous as possible, that the fire may more readily reach the interior of the brick. It is claimed by some manufacturers that by spreading the slurry on a floor to dry, and then cutting into rough cubes when dry enough to be taken to the dry kiln, more porous bricks are obtained.

23. BURNING: STYLES OF KILNS. The various styles of kilns in use may be divided into four classes, namely: (1) Common dome kilns, (2) Continuous kilns, (3) Chamber and ring kilns, and (4) Rotary kilns. The **dome kiln** is the simplest type. The chamber is usually egg shaped. Cement-brick and coke are piled in alternate layers, the use of the proper amount of the latter requiring much skill, as it is a matter of experience. As the draft in the kiln varies with the weather, this method of burning is more or less at the mercy of the winds. When the burning is complete, the kiln is allowed to cool before removing the clinker, and thus much heat is lost, and the lining of the kiln is destroyed by alternate heating and cooling. The amount of underburned and overburned clinker is likely to be large. The output is small, and fuel expense high.

The **Dietsch kiln** is one of the best examples of the second type, or continuous kiln. The slurry, in the form of bricks, is introduced at the base of the stack, into what may be called the heating chamber. Below this there is a right angle with a short horizontal section, over which the hot slurry is raked, to fall into the burning chamber. The clinker in the lower part of the latter is cooled by the air entering through the grates, while the slurry in the upper chamber is heated by the gases from the burning zone. At intervals a portion of the clinker, partially cooled, is removed at the bottom; this causes a general settlement in the kiln and leaves a space at the top of the burning chamber, into which the dried clinker from above is raked, and more fuel added. This kiln uses small coal for fuel and is more economical than the dome type.

The distinguishing feature of the **Schöfer kiln** is the contraction of the dome at the point where combustion takes place, concentrating the draft at this point. The air entering the shaft at the bottom cools the clinker already burned, while the gases from the clinker burning in the central section serve to dry the raw bricks above. Several kilns of this type are in successful operation in this country.

24. Chamber kilns are used largely in England with coke as fuel. The gases from the kiln are made to pass over the slurry spread on brick floors, the kiln proper being at one end of this chamber and the stack at the other. These kilns are intermittent, have a comparatively small output, and require considerable labor.

The **Hoffman ring kiln** consists of a series of compartments built around a large central stack. The chambers communicate by means of flues in such a way that the smoke and hot gases from one may be passed through other chambers before reaching the chimney. The kiln may be either "up draft" or "down draft," according to the direction in which the heat is drawn through the chamber. The compartments are charged from the sides, and when the moisture has been driven off from the material in the chamber first fired, the gases from this chamber are passed through the adjacent chambers, which have in the meantime been filled with raw materials. Although this kiln is economical of fuel if run continuously, much labor is required to charge and empty it. This type is not used in the United States, though it has been employed to some extent in Germany.

25. Rotary Kilns. — Although rotary kilns for other purposes had been in use for some time, the first patent for a process of manufacture of cement by their use was issued in 1877 to Mr. T. R. Crampton. The method, apparently, did not pass beyond the stage of laboratory experiment until 1885, when Frederick Ransome of England patented a rotary kiln, which, however, required many important modifications to make it a success.

About 1888 Mr. J. G. Sanderson and Dr. Geo. Duryee made some successful experiments with the rotary kiln for wet mixtures, and in the following year experiments were begun at the works of the Atlas Portland Cement Co. under Mr. P. Giron, which resulted in the construction of a practical kiln for burning dry mixtures. Prof. Spencer B. Newberry, at about the same time, perfected the rotary process for wet materials at Warners, N. Y., and Sandusky, Ohio.

A rotary kiln as used for the burning of cement consists of a steel cylinder five feet to six and a half feet in diameter and about sixty feet in length. This cylinder is lined with fire-brick, rests on rollers with its axis slightly inclined to the horizontal, and is revolved slowly by means of gearing. The mixture to be burned is introduced at the upper end of the cylinder, while a jet of gas, crude oil, or more frequently, powdered coal, is injected through a special burner at the lower end. As the cylinder revolves, the material works slowly toward the lower end, the clinkering temperature being maintained throughout about the lower third of the length. In some of the more elaborate styles, the clinker is passed through one or more cooling cylinders before it is conveyed to the grinding machinery. In the Hurry and Seaman rotary, the clinker, after it leaves the first cooling cylinder, is passed between rolls that serve to break any large lumps, and is moistened with water before its passage through the second cooling cylinder, which delivers the clinker warm, moist, and in small pieces.

The lining of rotary kilns has given much trouble, as the clinker acts upon fire brick lining to form a fusible compound at the high temperatures required in the burning. One method of overcoming this difficulty is to fuse upon the fire brick a coating of clinker which is beaten down while still plastic, so that it adheres to the brick and protects them more or less successfully from further injury. The kind of fuel and the burner giving the best result have also received much attention; while petroleum was first tried and is still used to some extent, powdered coal is now more commonly employed, and one of the most successful forms of burner is constructed like an injector, the pulverized coal being drawn in with the blast of air.

26. Output and Fuel Consumption of Different Kilns. — A comparison of the average output of the several styles of kilns described above, and the approximate fuel consumption, are given in the following table. Where it is necessary to dry the materials before introducing them into the burning kiln, the fuel required in drying is not included.

Style.	Barrels per Day.	Fuel as Per Cent. of Weight of Clinker.
Intermittent dome	30	20 to 30
Hoffman (per chamber)	25	15 to 20
Dietsch and Schöfer	50 to 75	15 to 20
Chamber	30	40 to 50
Rotary	120 to 150	30 to 40

27. Advantages of the Rotary Kiln. — Although the burning of cement in a rotary kiln requires a somewhat larger fuel consumption than with some other types, the ability to use a cheaper form of fuel, and the saving in the amount of labor required, much more than offset this disadvantage. Either wet or dry materials may be fed to the kiln, thereby eliminating the necessity of forming the slurry into bricks, drying and stacking them in the kilns. By the rotary process it is possible to so arrange a plant that the material is handled entirely by machinery from raw material to finished product. The control possible in burning with the rotary is much better than with any other style of kiln, as the intensity of the flame and the speed of revolution of the cylinder may both be regulated. On this account, as well as because the pieces of clinker are much smaller, the cement is more uniformly burned. The remarkable development of the Portland cement industry in the United States is due in no small measure to the adoption and perfection of the rotary kiln, for the labor expense in manufacture has been so reduced thereby that we are able to successfully compete with cements made abroad where lower wages prevail.

28. GRINDING. — In grinding it is not sufficient that the cement be so reduced that a certain percentage of it will pass a sieve having, say, 10,000 holes per square inch; but it is desired that as large a proportion as possible shall be of the finest floury nature. To accomplish this result it has been claimed that French buhr millstones are the best, but their great consumption of power has led to the introduction of other forms of grinding machinery, so that at present millstones find their chief use in natural cement manufacture.

It is usually considered that the greatest economy results from a gradual reduction of the clinker as it passes from one form of grinder to another, each machine being supplied with the size of pieces it is best adapted to handle. Large pieces of clinker are first passed through an ordinary rock crusher, such as the Gates or Blake. Where rotary kilns are in use, this step in the process may be omitted, as the clinker comes from the kiln in small, nut-like pieces.

29. Ball mills may also be used for the first reduction. The ball mill is a short cylinder of large diameter which is partially filled with flint or steel balls. When the cylinder revolves, the balls and the clinker fall upon hard metal surfaces, and as the material is ground to the size of sand grains, it falls through screens in the periphery into a hopper, where it is delivered to a conveyor, or to another form of pulverizer for further reduction.

30. Tube mills may be used in connection with millstones, but are usually employed for final reduction of the product of the ball mill. The tube mill is a steel cylinder, about 4 or 5 feet in diameter and 15 to 25 feet long, with axis horizontal or nearly so, and revolving on trunnions. The cylinder is lined with hard iron or porcelain, and is half filled with flint pebbles. The material is fed in at one end and is gradually pulverized as it works toward the other end. Some styles are not continuous in their action, but are charged and closed, the material being removed after a certain number of revolutions.

31. Griffin Mills. — The Griffin mill is an American invention that has found much favor, especially in grinding tailings from other mills. A heavy steel roller is attached to the bottom of a steel shaft, which is provided at its upper end with a ball-and-socket joint. When the shaft is given a gyratory motion, the roller presses by centrifugal force against the inside surface of a heavy steel ring where the grinding takes place. The material which drops below the roller is thrown up again by steel blades that are also attached to the shaft, and when finally of sufficient fineness, the powder escapes through screens above the ring into a hopper.

32. The method of grinding to be adopted at any mill depends upon the size and hardness of the particles of clinker, but usually the clinker is passed through at least two machines.

It has been stated[1] that the power consumed in grinding one ton of cement by the different principles is as follows:

For millstones	30 to 32 I.H.P.	per ton per hour.
For ball principle . . .	16 to 18 I.H.P.	" "
For edge runners . . .	12 to 14 I.H.P.	" "

The sifting of the product, which formerly required special revolving or shaking screens of wire cloth, is now usually done by the sieves attached to the grinding machinery.

33. SAND-CEMENT. — This product, which is also called silica cement, is composed of Portland cement and silicious sand mixed in any desired proportion and then ground to extreme fineness. This product is placed on the market by dealers, but rights to use the process may be purchased. In the construction of Lock and Dam No. 2, Mississippi River, between Minneapolis and St. Paul, Major F. V. Abbot[2] used the process, grinding with

[1] Mr. Henry Faija, in Trans. A. S. C. E., Vol. xxx, p. 49.

[2] Report of Mr. A. O. Powell, Asst. Engineer, Report Chief of Engineers, U. S. A., 1900, p. 2779.

a tube mill one part of Portland cement with one part fine sand. The cost, exclusive of plant, is estimated as follows:

½ barrel of Portland cement at $2.85	$1.42
½ " " sand at .05	.03
Cost of grinding	.50
Cost of royalty	.05
Cost of one barrel Silica cement	$2.00

This cement has given remarkably high tests considering the adulteration with sand, and is claimed to be specially useful in making impervious mortar and concrete.

Art. 7. Other Methods of Manufacture of Portland Cement

34. Portland Cement from Blast Furnace Slag. — The preparation of a true Portland cement from blast furnace slag has been followed in Germany and elsewhere in Europe for several years, and recently has been introduced in the United States. As this process utilizes a waste product, its popularity is likely to increase. Whereas, for the manufacture of slag cement only the slag from gray pig iron is available, it is found that in most cases the slag from white pig iron may be used for the production of Portland cement from slag.

The method of manufacture is briefly as follows: The slag as it comes from the blast furnace is subjected to the action of a stream of water, which granulates it and changes it chemically, the water combining with the calcium sulphide, which is injurious to cement, to form lime and sulphuretted hydrogen. The granulated slag is then dried, mixed with the correct proportion of dried limestone, and ground to extreme fineness. The mixture is next burned in rotary kilns, the remainder of the process being the same as that employed when ordinary raw materials are used. While a cement made from slag by this method may have some peculiarities due to the nature of the raw materials used, and should be very carefully tested before it is used in important work, it should not be confounded with slag cement, which is a mixture of granulated slag and hydrated lime subsequently ground, but not burned together.

35. Portland Cement from By-Products of Soda Manufacture. — The Michigan Alkali Company has installed at Wyandotte, Mich., a cement plant to utilize the large amount of limestone which they have as waste in the manufacture of soda products. The limestone which has served its purpose in the soda manufacture is in a finely divided and semi-fluid state; to this is added the proper percentage of clay, which has been dried and pulverized. The two are then very thoroughly mixed by pug mills and wash mills, the slurry corrected by small additions of one or the other of the ingredients, and finally burned in rotary kilns.

ART. 8. THE MANUFACTURE OF SLAG CEMENT

36. Slag cement is made by adding calcium hydrate to a granulated basic slag resulting from the manufacture of gray pig iron. The slag must be carefully selected as to its chemical composition, Prof. Tetmajer having found by extended experiments that slags containing silica, alumina, and lime in the ratio 30 to 16 to 40 are best adapted to the purpose. As the molten slag runs from the blast furnace it is suddenly chilled by being run into water, or is partially disintegrated by being treated with a strong current of water, air, or steam. It is thus reduced to coarse particles resembling sand, or to a spongy or fibrous mass which, after drying, is readily ground to a fine powder. The process of chilling results in a certain chemico-physical change that renders the powder capable of combining more readily with the slaked lime which is subsequently added. Slag which has been allowed to cool slowly will not form an hydraulic product when mixed with the lime, although the chemical composition of the slag may be identical in the two cases. The lime is dipped into water, or treated with steam, until slaked to a fine dry powder, and is then added to the powdered slag in proportions of about one part of the former to three parts of the latter, this proportion depending upon the composition of the slag used. The powdered slag and lime are sifted, then mixed and reground together to an extreme fineness, thus insuring an intimate incorporation of the ingredients. Since there is no burning in the process, it is evident that the finished product is merely a mixture, not a chemical compound as is the case with Portland cement.

37. One of the largest mills for the manufacture of slag cement in the United States is conducted by the Illinois Steel Company, and the following description of the process is condensed from a statement of Mr. Jasper Whiting,[1] manager of the cement department, and patentee of the process: Slag of the proper composition is chilled as it comes from the furnace by the action of a large stream of cold water under high pressure. The slag is thereby broken up, about one-third of its sulphur is eliminated, and it is otherwise changed chemically. A sample of the slag thus granulated is mixed with a proportion of prepared lime, and ground in a small mill whereby actual slag cement is produced. If the tests upon this trial cement are satisfactory, the slag is dried and then ground, first in a Griffin mill and then in a tube mill, where it is mixed with the proper amount of prepared lime and the two materials ground and intimately mixed together. The resulting product is said to be so fine that but 4 per cent. is retained on a sieve having 200 meshes per linear inch. The lime is burned from a very pure limestone and stored in bins, beneath which are two screens of different mesh, the coarser at the top. A quantity of lime being drawn on the upper screen is slaked by the addition of water containing a small percentage of caustic soda. The lime passes through the two screens as it slakes and is then heated in a dryer; the slaking being thus completed, the lime may be incorporated with the slag. The purpose of the caustic soda added in the above process is to render the cement quicker setting.

Art. 9. The Manufacture of Natural Cement

38. History. — The American product called natural cement was first manufactured at Fayetteville, Onondaga County, N. Y., in 1818, and used in the construction of the Erie Canal. Other early dates of manufacture are given as 1823, near Rosendale, N. Y., and 1824 at Williamsville, Erie County, N. Y., the products being used in the construction of the Erie and the Delaware & Hudson Canals. Factories were soon started in other states, and at present nearly every State in the Union has one or more natural cement factories, the total annual production being now about nine million barrels.

39. Materials Required. — The composition of rock from which natural cement may be made, varies within wide limits. As stated in §13, an argillaceous limestone, a magnesian lime-

[1] "Report of Board of Engineers on Steel Portland Cement," Appendix I.

stone or an argillo-magnesian limestone may be used. Argillaceous limestone makes what is sometimes called an aluminous natural cement, its essential ingredient being a bisilicate, or silicate of alumina and lime, while the product made from magnesian limestone is called magnesian cement and is composed of a triple silicate of lime, magnesia and alumina.

The Maryland cements are typical of the former or aluminous variety, containing only one to five per cent. of magnesia, while the Rosendale and the Milwaukee are magnesian cements containing 15 to 25 per cent. magnesia. (See Table 3.)

With a given raw material, the silica and alumina should bear a certain proportion to the lime and magnesia, but close limits cannot be stated for this proportion, as it varies with the chemical and physical character of the rock. The silica should be combined with the alumina, not in the form of sand.

The materials found at any locality may vary considerably as to chemical composition, especially among the several strata. In some cases the different strata are utilized to make two or more brands, which differ somewhat in their characteristics as to time of setting, etc. It is common also to mix two or more layers together in the manufacture, with the idea that the ingredients lacking in one stratum will be supplied by the others.

40. Description of Process. — As the proper ingredients to produce the cement have been incorporated by Nature, that part of the process of Portland cement manufacture preliminary to the burning is unnecessary. The rock occurs in strata and is either quarried in open cut where the stripping is light, or by means of tunnels. In open cut, a face of twenty feet or more is sometimes worked. As has already been stated, the strata vary in chemical composition, and while two or more brands are sometimes made at the same mill, it is a more general practice to mix the rock from several strata in the production of one brand. The idea is that if one layer contains too much silica, it may be corrected by another containing too much lime or magnesia. As the rock is not finely pulverized before it enters the kiln, each lump burns by itself and makes a certain cement; the piece of rock next it must make as distinct a product as though burned in a separate kiln. What is obtained, then, by this method is a mixture of several cements, and it is questionable whether the mere mechanical mixing of an over-limed cement with an over-clayed one will make a well balanced product. This practice may account, in a great degree, for the large variations that occur in the cement from a single factory, variations which are often, however, more noticeable in short-time tests than in the longer ones.

41. The rock, as quarried, is broken by an ordinary rock crusher or otherwise, into pieces varying in size up to six inches, and is then conveyed, usually by tramway, directly to the kilns. These are of the cylindrical continuous type, built of stone or steel, and lined with fire brick. The kilns are commonly about 45 feet high and 16 feet in diameter; the tramway leads to a loading platform on top of the kiln. According to the locality, the fuel may be either bituminous or anthracite coal of about pea size. The rock and fuel are spread in the top of the kiln in alternating layers, the proportion of fuel being usually regulated by the man in charge of the burning, but sometimes a machine is employed which automatically governs the amount of coal used. The temperature in the kilns is much below that required in Portland cement manufacture, but varies of course with the materials.

42. The calcined rock is conveyed first to some sort of a stone crusher; a common form is known as a "pot-cracker," and consists of a corrugated conical shell in which works a cast iron core, also corrugated. After passing the cracker, the material may be screened, giving a certain proportion of finished product, and another portion which may go directly to the finishing stones, while the coarsest pieces are conveyed to another form of cracker, such as iron edge runners, which prepares it for the millstones. In many factories ordinary under-run millstones are used, in others rock emery stones are employed, while in some factories stones found locally prove satisfactory. There have been recently installed in some of the natural cement factories, ball and tube mills for grinding as used for Portland cement clinker, and in several factories special forms of grinding machinery are in use that have been perfected by the managers of the works.

The product passes from the reducing mills to the "mixers," by means of which the material is thoroughly mixed to promote uniformity. It is now ready for packing, and may be conveyed directly to the chute from which the barrels or bags are filled.

In packing, the barrel rests upon a circular disc which is given a vertical jarring motion, and thus the cement is thoroughly settled in the barrel.

It is seen that the manufacture of natural cement is very similar to that portion of Portland cement manufacture succeeding the preparation of the raw material for burning. In general, less care is requisite with natural cement, the burning is carried on at a lower temperature, and the calcined rock is softer, so that less expense is incurred in grinding.

PART II

THE PROPERTIES OF CEMENT AND METHODS OF TESTING

CHAPTER III

INTRODUCTORY

43. In the tests of such structural materials as wood and steel it will not usually be difficult to determine the suitability of the material for the intended purpose, provided the test pieces truthfully represent the members to be used. It is known that so long as these members are protected from oxidation and over-loading they will retain their qualities, and there is always a reasonably clear understanding of what these qualities should be. On the other hand, in the testing of cement, one may be perfectly sure that from the moment the cement is manufactured until long after it has been in service in the structure its properties will be ever changing; and, further, the qualities which it is desirable the cement should possess are not always clearly in mind.

44. **Desirable Qualities in Cement.** — The desirable elements in a cement may be stated as follows: 1st, That when treated in the proposed manner it shall develop a certain strength at the end of a given period. 2d, That it shall contain no compounds within itself which may, at any future time, cause it to change its form or volume, or lose any of its previously acquired strength. 3d, That it shall be able to withstand the action of any exterior agency to which it may be subjected that would tend to decrease its strength or change its form or volume. When it is determined that a cement has these three qualities, it is certain that it is safe to use it, but it is further desirable to know that the

cement in question will accomplish the given object as cheaply as any other cement.

The cohesive and adhesive strengths of cement are not usually considered in the design of the structure into which cement enters. The design of a masonry arch does not comprehend any adhesive strength in the cement, except as it may be recognized as an additional factor of safety, and a masonry dam is so designed that there shall be no tension at the heel. These facts are due in a large measure to the very imperfect knowledge we have of the behavior of cements in various contingencies. With the increasing use of concrete, as in arches, locks, floors, roofs, etc., the tensile and transverse strengths of cement are coming to be relied on to a certain extent; and as its properties become better known, and as means of recognizing these properties become more certain and widespread in their application, cement will be more extensively employed in a scientific and economical manner.

Cement may be compared in one sense to timber and cast iron. A large factor of safety is employed when dealing with these materials because of hidden defects that may exist. The defects which lie hidden in cement may be even greater than these in proportion to its possible strength, and defects in cement are often more treacherous because their development may be deferred for some time. The importance of knowing whether the cement fulfills the second and third requirements noted above is therefore evident.

45. Having considered the qualities a cement should have, we may proceed to the detailed consideration of the various **tests employed** to disclose the presence or absence of these qualities. The strength a given cement will develop is investigated by chemical analysis, by obtaining the specific gravity and fineness, and by actual rupture tests, whether they be tensile, compressive, transverse, or shearing. By tests for change of volume and by chemical analysis, it is sought to determine whether a cement has within itself elements of destruction. For the power to withstand external agencies there are no adequate tests, though chemical analysis is considered an aid. The methods of use, the proportions of the materials, their incorporation and deposition are of great importance in insuring against external causes of injury.

46. Uniform Methods of Cement Testing. — In order that uniformity should prevail in the methods employed in testing cements, various societies have discussed the subject in detail, usually through committees, and much valuable work has been done along this line. The engineers of public works in many European countries have adopted specifications and laid down more or less detailed rules for testing. The Corps of Engineers, U. S. A., has recently adopted a similar code of rules.

The International Society for Testing Materials, with which the American Society for Testing Materials is affiliated, has considered the subject and still has committees at work upon it. The New York section of the Society of Chemical Industry has recently formulated a method for analysis of materials for the Portland cement industry. The American Society of Civil Engineers received a report in 1885 from a committee appointed to consider methods of cement testing, and in order to keep the subject abreast of the latest developments in the manufacture and use of cement, a second committee was appointed several years ago, which has been making a thorough discussion of the subject, and has submitted a preliminary or progress report.

47. Notwithstanding that so much has been done toward unification of methods, it may never be possible to determine accurately the value of one cement as compared with another tested in a different laboratory; though in tests of iron and steel no such difficulty is experienced. Certainly, as at present carried out, strength tests of cement are purely relative tests and do not show the absolute strength which may be developed in the structures; nor can the results be compared with the results obtained in other laboratories and any fine distinctions of quality drawn. To attempt to carry out acceptance tests in such a way as to show directly the strength which will be developed in actual construction, is only to introduce causes of irregularity in the tests.

CHAPTER IV

CHEMICAL TESTS

Art. 10. Composition and Chemical Analysis

48. Value of Chemical Tests. — The definite aid which chemical analysis may render in determining the quality of a cement is limited by the following considerations. It is not definitely known just what part is played by each of the compounds that go to make up commercial cement, and chemical analysis does not tell the manner of the occurrence of these compounds. A cement may have a chemical composition that is thought to be perfect, but if the burning has not been properly accomplished, it may be a dangerous product and analysis would show no defect. Some of the best authorities say that chemical analysis is useful principally in tracing the cause of defects which, by other tests, have been found to exist. However, there are some constituents which it is fairly well known a cement should not contain in any considerable quantities. An analysis may be of value in estimating quantitatively such constituents, while it may also be of service in detecting adulterations. It is not impossible, then, that chemical tests may yet play a more important rôle in cement testing, especially if the method of analysis can be made more simple and rapid, without too great a sacrifice of accuracy.

49. Lime. — The proportion of lime in Portland cement may vary from 59 to 67 per cent. A much greater range than this is allowable in natural cement, the percentage usually being from 30 to 45, according to the amount and character of the other active constituents. An analysis of Portland cement which shows a percentage of lime far outside of the limits mentioned above, should be regarded with suspicion and submitted to very thorough tests before acceptance. As already stated, the ratio of the silica and alumina to the lime in a cement is called the **hydraulic index.** The value of this ratio is usually between .42 and .48 for Portland cement.

Cement mixtures containing a large percentage of lime require a high temperature for calcination, are difficult to grind, and yield a slow-setting product. The danger in highly limed cements is that they will not be properly calcined and a portion of the lime will be left in a free state. The demand for high strength in short-time tests has led manufacturers to make a heavily limed product, and in some cases the limits of safety have probably been overstepped. The introduction of the rotary kiln, however, has so improved the facilities for burning cement that a higher percentage of lime is now possible.

There is no method known at present for determining quantitatively the amount of free lime in a cement, and it seems doubtful whether its presence can be detected with certainty by chemical analysis. The method usually employed for this purpose depends on the hydration of the lime and subsequent absorption of carbonic acid.

50. Magnesia. — The detection of magnesia in several concrete structures that had failed, led to the conclusion that magnesia, in quantities exceeding two or three per cent., was a dangerous element in Portland cement. In 1886–87 Mr. Harrison Hayter[1] mentioned several failures of masonry and concrete which he considered were due to magnesia, and concluded that cement should not contain more than one per cent. Later investigations, however, indicated that such failures could be explained in other ways, and that the magnesia found in the failing structure had come from the sea water and replaced the lime in the cement. Mr. A. E. Carey[2] has considered that "an excess of caustic lime or magnesia causes first, disintegration by expansion due to hydration, and second, being soluble, when conditions permit of their washing out, leave the concrete in a honeycombed state." Notice that this refers to caustic magnesia, and Prof. S. B. Newberry[3] has stated that "it is doubtful if magnesia is ever combined in Portland cement. Our own experiments tend to confirm the opinion of many German authorities that magnesia remains free in cement and does not combine with the constituents of clay after the manner of lime."

[1] Proc. Inst. C. E., Part 1, Session of 1886–87.
[2] *Ibid.*, 1891–92.
[3] *Municipal Engineering*, October, 1896.

On the other hand, M. H. LeChatelier[1] says that the "accidents occasioned by certain magnesian elements, and the similar results obtained in laboratory experiments, have been due to the employment of badly proportioned cements, containing free uncombined magnesia and too small a quantity of clay. Corresponding mixtures containing lime instead of magnesia would have caused still more serious accidents, yet it would not be concluded that there must be no lime in cement." Again, Dr. Erdmenger characterizes magnesia as an adulterant only, and considers that its effect is nil if a greater percentage of lime is added in the manufacture.

Some authoritative information on the amount of magnesia allowable in Portland cement is contained in the report of the magnesia commission of the Association of German Cement Makers, 1895: Three members of this committee, Messrs. Schott, Meyer and Arendt concluded that "the presence of magnesia up to ten per cent. causes no harmful expansion or cracking of the cement, even after several years." Mr. Dyckerhoff, however, presented a minority report, in which he pointed out that while a large amount of magnesia, not sintered, may not have an injurious effect, yet a content of more than four per cent. of sintered magnesia, whether added or substituted for part of the lime, has an injurious effect after long periods. The committee continued the ruling of 1893 that "a magnesia content of five per cent. in burnt cement is harmless," but held the question open for further investigation, indicating that this limit might be raised.

In view of the disagreement among such eminent authorities it is impossible to arrive at a satisfactory conclusion, but if the effect of magnesia depends upon the manner of its occurrence, whether free or combined, sintered or unsintered, then chemical analysis can be of but limited value as a test of quality in this regard. Natural cements frequently contain large proportions of magnesia replacing lime, and in this case an analysis is of the same value as an analysis for lime.

51. Alumina and Iron Oxide. — The amount of alumina which a cement should contain is not well established. Its presence tends to facilitate the burning, and it renders the prod-

[1] Trans. Amer. Inst. Mining Engrs., 1893.

uct quicker setting. Cements containing large percentages of alumina are inferior for use in air or sea water, and it is probable that the percentage of alumina should not exceed eight or ten to obtain the best results in all media. A slag cement may be detected by its large content of alumina. Oxide of iron acts as a flux in burning, but in the finished product is little more than an adulterant.

52. Sulphuric Acid. — French specifications say that Portland cements shall not contain more than one per cent. of sulphuric acid or sulphides in determinable proportions. This is doubtless intended for cement to be used in sea water. Adulterations with blast-furnace slag may sometimes be detected by the amount of sulphides present, but small quantities of sulphuric acid in the cement may be derived from the coke used in burning and have no injurious effect for use in fresh water. A content of 1.75 per cent. of sulphuric anhydride, SO_3, is now considered the maximum permissible. Sulphates mixed with the raw materials and burned with the cement may be harmless, while the same amount added after burning would not be permissible. [For tests on the effect of adding sulphate of lime to cement, see Art. 48.]

53. Water and Carbonic Acid. — The determination of these may give some idea of the deterioration of a product by storage, and they may also indicate defective burning. M. Candlot considers that in the case of Portland cement, a loss on ignition (water and carbon dioxide) exceeding three per cent. "indicates that the cement has undergone sufficient alteration to appreciably diminish its strength." Natural cements may, however, contain considerable proportions of these ingredients and still give good results.

54. Conclusions. — Finally, then, the determination of silica, alumina, magnesia and lime may be of value, first, in classifying a product, and second, as indicating whether the proportions contained in it are such that if properly manufactured it is capable of giving good results. What these proportions should be for Portland cement has already been stated, § 9. The determination of certain injurious ingredients is also of some value, but it must be remembered that the dangerous elements most commonly occurring, namely, free lime and magnesia, are not determinable by chemical analysis. It has been stated by

M. LeChatelier that "neither complete nor partial chemical analysis of the constituents of hydraulic materials can be ranked among normal tests. But chemical analysis may render real service in controlling the classification of a product concerning which there is reason to doubt the declaration of the manufacturer. Thus, a slag cement can be distinguished from a Portland by its tenor in alumina and water; certain natural cements, by their contents of sulphuric acid, etc."[1]

The methods of analysis for Portland cement are given in considerable detail in a little book, "The Chemical and Physical Examination of Portland Cement," by Richard K. Meade. The method of analysis suggested by the New York Section of the Society of Chemical Industry is published in the *Engineering Record* of July 11, 1903, and in *Engineering News* of July 16, 1903.

[1] "Tests of Hydraulic Materials," H. LeChatelier.

CHAPTER V

THE SIMPLER PHYSICAL TESTS

ART. 11. MICROSCOPICAL TESTS. COLOR

55. Microscopical examinations are of some interest and value to those who are thoroughly versed in the chemistry of the burning and hardening of cements, as an aid in determining the part played by each compound in the hardening.

Examinations may be made either of the dry powder, or of thin sections of hardened cement, or clinker. Dry powder of Portland cement appears to be made up of scaly particles, many of which are clearly defined and semi-transparent, while natural cement particles are more nearly opaque and less angular. Thin sections of Portland cement clinker have been found to exhibit colorless crystals somewhat cubical in structure, which are thought to form the essential hardening constituent; thin sections of hardened Portland cement show a clear crystalline structure. Prof. Hayter Lewis found that the particles in good Portland cement were angular in form, consisting of scales and splinters, while the particles of cement of poor quality were rounded or nodular.

Microscopic examinations have no place at present in ordinary tests of quality.

56. Significance of Color. — The color of cement is chiefly derived from its impurities, such as oxides of iron and manganese, rather than from its essential ingredients, and the color is therefore of minor importance. Other things being equal, a hard burned Portland cement will be darker in color than an underburned product. An excess of lime may be indicated by a bluish cast, and excess of clay or underburning may give a brownish shade. Gray or greenish gray is usually considered to be indicative of a good Portland.

57. The colors of natural cements have a wide range, varying from a light yellow to a very dark brown, without reference to quality. Owing to a popular idea that dark color indicated strength, some manufacturers have been said to add coloring matter to their product, but although this may have been true at one time, the correction of this false idea has doubtless rendered such a practice quite unnecessary now. Variations in shade in different samples of the same brand of natural cement may indicate differences in burning or in the composition of the rock; but the interpretation of color for any given brand must be the result of close study, for some cements become lighter on burning and others become darker, while in some cases no variation in shade can be detected for different degrees of burning.

ART. 12. WEIGHT PER CUBIC FOOT OR APPARENT DENSITY

58. Significance. — Since a hard burned Portland cement will usually be heavier than a light burned one, a test of the weight per cubic foot was once thought to be of great value in judging of the degree of burning. But it has been shown repeatedly that the weight per cubic foot depends quite as much on the fineness as on the burning. It also depends on the age of the cement, and its chemical composition. As a test for quality, the determination of the apparent density has therefore been discarded. However, it is an aid in classifying a product, since Portland cements weigh from 70 to 90 pounds per cubic foot when loosely filled in a measure, while natural cements weigh from 45 to 65 pounds. A knowledge of the weight per cubic foot is also useful in reducing proportions given by weight to equivalent volumetric proportions, and *vice versa*.

59. Method. — This test may be made with a very simple apparatus, and the results obtained, though not strictly accurate, are sufficient for all practical purposes. A metal tube, 2 feet 4 inches long, about 6 inches in diameter at the top, and 3 or 4 inches at the bottom, is supported by a frame resting on four legs. A metal cylinder, 6 inches in diameter and $6\frac{3}{32}$ inches deep, holding one-tenth cubic foot, is placed on the floor below the tube. A coarse sieve, through which all of the cement will pass, is placed on top of the tube and three feet above the bottom of the measure. The cement passes through the sieve, falling freely to the cylinder below, which is struck off level when full. The cement must not be heaped too much, and great care must be taken that the measure is not jarred while it is being filled or struck off. The cement is in such a light condition that a very slight jar is sufficient to cause it to settle.

The above apparatus is on the same plan as that used by Mr. E. C. Clarke on the Boston Main Drainage Works, and is described here for general use when it is desired to compare the results obtained by operators at different points. Should one wish simply to obtain a series of results on different cements which are to be compared among themselves, it is quite sufficient to sift each sample through a coarse sieve, and then with an ordinary scoop carefully fill a measure of any known capacity, without other apparatus.

Mr. Henry Faija has described an apparatus consisting of a funnel with a screw at the mouth which carries the cement horizontally to the point where it falls freely into the measure. Various other devices have been employed, but none seems to have met with universal favor.

60. To determine the relative accuracy obtainable with the simple form of apparatus first described, the author made a series of tests which may be summarized as follows: —

1st Method. — Cement passed a wire mesh sieve, holes .033 inch square and fell freely two feet through a 6-inch tube into a measure holding $\frac{1}{8}$ cu. ft. Five trials with a sample of Dyckerhoff Portland, highest weight per cubic foot, 81 lbs. 4 oz., lowest, 79 lbs. 2 oz., difference, 2 lbs. 2 oz. Three trials with Alsen's Portland, highest weight, 73 lbs., lowest, 72 lbs., difference, 1 lb.

2d Method. — Measure same size filled with scoop without other apparatus, and cement not shaken or jarred in measure. Five trials with Alsen's Portland, highest result, 73 lbs. 8 oz. per cu. ft., lowest result, 72 lbs. 12 oz., difference, 12 oz. Five trials with different sample of same cement, highest, 72 lbs. 4 oz., lowest, 72 lbs., difference, 4 oz.

3d Method. — Measure filled with scoop, and cement well shaken down as filling proceeded. Five trials with Alsen's Portland, highest result, 100 lbs. 8 oz., lowest, 97 lbs. 14 oz., difference, 2 lbs. 10 oz.

It appears from these tests that when the measure is filled with the scoop, the results are about as uniform as when the apparatus is used, provided the filling is always done by the same person. But the results obtained by different operators with the same sample of cement would probably vary less, one from the other, when the apparatus is employed. In other words, the personal factor is more nearly eliminated when the cement is passed through a sieve and allowed to fall freely from a given height.

61. As to the **effect of age** on the weight per cubic foot, it was found in one case that cement which weighed 93½ pounds per cubic foot when freshly ground, weighed but 88 pounds when a few days old, and 78 and 74 pounds after six months and one year, respectively.[1]

Many experiments have been made to show the **effect of fineness** on the weight per cubic foot, but as this subject will be taken up again under "fineness," it will suffice to quote one series of tests made by Mr. E. C. Clarke,[2] giving the "weight per cubic foot of the same sample of German Portland cement containing different percentages of coarse particles as determined by sifting through the No. 120 sieve."

Samples containing 0, 10, 20, 30, and 40 per cent. of coarse particles retained on No. 120 sieve gave the following weights per cubic foot: 75, 79, 82, 86 and 90 pounds, respectively.

It may be repeated that the weight per cubic foot is no longer considered an indication of quality, but should it be desired to specify a given weight, the method by which the test is to be made should also be stated.

ART. 13. SPECIFIC GRAVITY OR TRUE DENSITY

62. The apparent density or weight per cubic foot is influenced to such an extent by the degree of fineness of the cement that this test has been almost superseded by the test for specific gravity. Although the true density, or specific gravity, is not affected by the fineness, it is influenced by the composition, the degree of burning, and the age, or amount of aëration of the sample.

The **method** commonly employed in this test consists in determining the absolute volume of a given weight of the cement

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[1] "Cement for Users," by H. Faija, p. 54.

[2] "Record of Tests of Cements for Boston Main Drainage Works," Trans. A. S. C. E., Vol. xiv, p. 144.

powder by measuring the amount of liquid which it will displace. A simple form of apparatus may be constructed in any laboratory as follows: In a wide mouth bottle, having straight sides and holding 200 c.c. or more, fit a perforated cork. Through the cork slip a burette graduated in cubic centimeters from 0 to 50, placing the zero end down. Fill the bottle and the tube up to the zero mark, with some liquid such as turpentine, benzine or kerosene oil, but preferably benzine (62° Baumé naptha). By means of a funnel in the top of the burette, add slowly 100 grams of cement; then jar the bottle to remove air bubbles and read the burette. This reading, x, represents the volume of 100 grams of cement; and 100, the volume of 100 grams of water, divided by x gives the specific gravity of the sample.

63. Among other forms of apparatus which are also of simple construction and tend to facilitate the test, may be mentioned the following: —

M. Candlot[1] devised an apparatus consisting of a graduated tube terminating in a bulb at the upper end, the lower end of the tube being ground to fit the neck of a flask. The tube and flask being disconnected, sufficient liquid is placed in the bulb so that when connected with the flask and placed upright, the level of the liquid will be at or near the zero mark on the tube. The actual level of the liquid is read after standing a few minutes; the apparatus is again inverted and the flask disconnected to allow of the introduction of 100 grams of cement. The flask is then replaced and the contents of the apparatus well shaken to expel air-bubbles. When the latter have been completely expelled, the flask is placed upright, and after standing a short time the level of the liquid is again read, the difference between the two readings indicating the absolute volume of 100 grams of the cement powder.

The apparatus devised by **M. H. LeChatelier**[2] consists of a flask of a capacity of about 120 c.c., and having a neck some 20 c. in length, halfway up which is a bulb having a capacity

[1] "*Ciments et Chaux Hydrauliques*," par. *E. Candlot.*

[2] "Report of *Commission des Methode d'Essai des Materiaux de Construction*," The Engineer (London); Illustrated also in Meade's "Examination of Portland Cement," Spaulding's "Hydraulic Cement," and *Engineering News*, January 29, 1903.

of 20 c.c. Near the bottom of the tube, or flask, is the zero mark, and above the bulb the tube is graduated for a length corresponding to a capacity of 3 c.c., each graduation representing .1 c.c. The diameter of the tube is about 9 mm. The zero mark on the tube is below the bulb. The method of operation is similar to that described above.

64. The following style of apparatus (see Fig. 1) is suggested as a very convenient form, and one which may be used for another test soon to be described. In this form, the flask, of a capacity of about 200 c.c., has straight sides and a flat bottom. The lower part of the burette is of large diameter, about 15 mm., to allow the cement to pass readily, while the upper portion is made smaller, about 8 mm., to permit more accurate reading, and is graduated from 30 c.c. to 40 c.c., the divisions being 0.1 c.c. Half divisions may be estimated. The zero mark is in the larger part of the burette, but it is less difficult to make an accurate reading at the zero mark, since at the time of taking this reading the liquid is clear; this mark should entirely surround the burette. The mouth of the bottle and the lower end of the burette should be ground to fit, and a ground glass stopper should form a part of the apparatus. A long pipette will be found convenient for adjusting the level of the liquid to the zero mark.

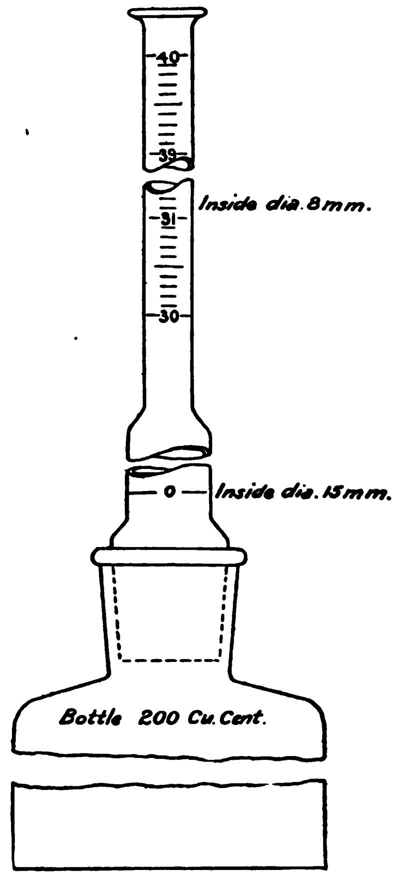

FIG. 1.—SPECIFIC GRAVITY APPARATUS

65. Turpentine is frequently employed for this test, but it is somewhat inconvenient to use, since its volume is so sensitive to changes in temperature. This sensitiveness renders it imperative that the temperature at the time of taking the final reading be the same as when the initial reading is taken, or that a correction be applied. To assure this condition the apparatus should be immersed in a water bath, and the temperature of the cement should be the same as that of the turpentine. The use of water in the apparatus does not offer this inconvenience, but it is possible that the hydration of the cement during the experiment might be sufficient to so affect the volume as to change the result, especially with quick-setting cements. Light oils, such as benzine and kerosene, are rather volatile, but the former (62° Baumé naptha) is recommended in the preliminary report of the Committee of the American Society of Civil Engineers. With the precautions mentioned above, turpentine may be used with good results; that which has been dried by standing over cement or quicklime is to be preferred.

66. This test may be extended to give interesting and valuable results, in the following manner: When the cement has settled in the bottle, leaving the liquid clear, pour off a portion of the latter and replace the burette by a glass stopper. Thoroughly agitate the remaining liquid and cement until the latter is in suspension; allow the cement to settle again without disturbance, and it will be found that it is graded in the bottle according to its fineness, the coarsest particles being at the bottom. With Portland cement, if a portion of the sample is underburned it will appear as the top layer, and be indicated by its yellow color. It will also be interesting to note what proportion of the cement is so fine that the separate grains are indistinguishable. That the bottle should have straight sides and a flat bottom is to accommodate this part of the test, which also dictates the use of some other liquid than water.

67. Effect of Composition, Aëration, Etc. — It has been said above that the composition of a cement affects its specific gravity, a highly limed cement having a higher density. On this account an analysis for lime is valuable in connection with this test, in order to determine whether a high specific gravity is due to a high percentage of lime or to hard burning.

The age, or aëration of a sample affects its specific gravity because of the absorption of water from the atmosphere. The absorption of two per cent. of water is sufficient to lower the specific gravity from 3.125 to 3.000. The following may be given as illustrating this point: a certain sample of natural cement when taken from the barrel had a specific gravity of 3.106; after it had been spread out in the air for two months its specific gravity was 3.000. A quantity of this aërated cement weighing 120 grams was placed in an iron vessel and heated over an oil stove for about one hour; at the end of this time the cement had lost two grams in weight. The specific gravity of the fresh cement being 3.106, 118 grams would have an absolute volume of 38 c.c.; two grams of water would occupy 2 c.c., hence 120 grams of the aërated cement would occupy 40 c.c., and $120 \div 40 = 3.00$, the specific gravity of the aërated cement as found above. It is not always possible to thus drive off all of the water absorbed, since a portion of it may enter into combination with the cement; but a sample should always be heated for at least thirty minutes at a temperature of 100° C. before making the test for specific gravity, and should any appreciable loss of weight occur, it is an indication of aëration.

68. A determination of the specific gravity is primarily a test for burning, but it may also be of much value in detecting adulterations, as with blast furnace slag or ground limestone. An admixture of 10 per cent. of either of these substances would suffice to lower the specific gravity from 3.15 to about 3.10. The specific gravity of Portland cement ranges from 2.90 to 3.25, but a first-class product should not show a lower specific gravity than 3.05. If fresh Portland gives a result below this it is probably either underburned or underlimed, or, perhaps, has been adulterated.

The specific gravity of natural cements has been found to vary from 2.82 to 3.25. The specific gravity of one sample of underburned natural cement was found to be lower than a sample of the same brand which was overburned, but it seems very doubtful whether this is true of other brands made from rock of a different character. It was also found that the specific gravity of the coarse particles of some natural cements is lower than that of the fine particles (see Table 10, Art. 15), while the opposite is true in the case of Portland cements.

No general rules can be given at present for the interpretation of this test that are applicable to all natural cements; it is thought that the test will be of value in comparing samples of the same brand, though it seems doubtful whether it will prove of value in comparing one brand of natural cement with another, since it is quite probable that the interpretation may vary with the variety of rock used in the manufacture. The value of the test for Portland cements is, however, well established.

CHAPTER VI

SIFTING AND FINE GRINDING

ART. 14. FINENESS

69. Importance of Fineness. — The fineness of cement is always conceded to be one of its most important qualities, and the determination of fineness is omitted in none but the very crudest tests. Unfortunately, however, sieves that are so coarse as to give delusive results are usually employed. It is very easy to show that grains of cement as large as one-fiftieth of an inch in diameter are practically valueless, but much more difficult to determine the point of fineness at which the particles begin to have cementitious value.

70. A moderately coarse sieve is easier to operate than a very fine one, less time being consumed in sifting. The impression seems to be quite general also that there is a fixed relation between the proportions of the different sized grains in different samples. Many specifications require that a certain percentage "shall pass a sieve having 2,500 holes per square inch." Now, there is little doubt that grains of cement larger than .005 inch in one dimension have very little cementitious value, and hence a cement, all of which would pass holes .015 inch square, while but 50 per cent. of it would pass holes .005 inch square, is little better than one which leaves a larger residue on the coarser sieve but the same residue on the finer.

In America and Germany it is the usual practice in the process of manufacture to pass the cement through a screen which will reject particles larger than about .015 inch in diameter; the futility in attempting to determine, with a sieve no finer than this, the proportion of the particles which are fine enough to be of value, is therefore apparent. Since the English cement makers have not been so progressive in the practice of screening, they have obtained the reputation of producing a coarse product. In many cases this reputation is probably a just one, but when tested with a very fine meshed sieve, some of the

English cements do not compare so unfavorably with those of German manufacture. It is a curious fact in this connection that the English are the most conservative in holding to the use of the coarse sieve in testing, which makes their cement appear so very much coarser than the American or German product.

71. SIEVES. — Sieves for cement testing may be made either of wire or silk gauze, set in metal or wood frames. Sieves of perforated metal plate are sometimes employed for sifting sand, but seldom for cement. It is with considerable difficulty that accurate gauze sieves are obtained. They are usually designated by numbers corresponding to the number of meshes per linear inch; this is in some respects an unsatisfactory method, for the size of the wire, which is quite as important as the number of meshes, is frequently not given at all, or stated in terms of some wire gage which is capable of various interpretations.

As usually supplied by different manufacturers, sieves purporting to have the same number of meshes per linear inch may vary in this regard as much as 10 or 15 per cent. Likewise the size of wire used by different makers, in sieves having the same number of meshes per inch, may vary quite as much. Again, on account of irregularities in the gauze, the holes in a given sieve vary one from another; in some cases an opening may be but 60 or 70 per cent. as large in one dimension as an adjacent one.

An ideal sieve should conform to the following requirements: (1) holes to be of uniform size and shape throughout, (2) sides of the holes to be very smooth, and (3) the spaces between the holes to be of such size and shape that particles will not easily rest there.

It is evident that the largest holes determine the character of the sieve. For example, a sieve having half its holes 0.01 inch square and the other half 0.02 inch square, would, if used long enough, separate the cement exactly as it would if all the holes had been 0.02 inch square. Hence, if a very small percentage of the holes are larger than the normal, it seriously impairs the accuracy of the sieve by introducing an indetermination; but holes smaller than the normal have no greater objection than that, as the sifting proceeds, they become spaces between the real or larger holes, and as such do not fulfill the third requirement mentioned above. The shape of the holes, whether round, square or hexagonal, seems of minor importance so long as uniformity is maintained. The second requirement is necessary, because, should particles adhere to the sides of the hole, the size of the latter would be decreased to that extent. The third requirement is for convenience, but would require consideration if the style of the sieve were changed to a punched metal plate.

72. The Committee of the American Society of Civil Engineers, in their report on "A Uniform System for Tests of Cement" in 1885, recommended three sizes of sieves for cement: No. 50 (2,500 meshes to the square inch) wire to be of No. 35 Stubbs' wire gage; No. 74 (5,476 meshes to the square inch) wire to be of No. 37 Stubbs' wire gage; No. 100 (10,000 meshes to the square inch) wire to be of No. 40 Stubbs' wire gage. For sand, two sieves were recommended, No. 20 and No. 30 (400 and 900 meshes per square inch) wire to be of No. 28 and No. 31 Stubbs'

TABLE 5

Sieves:—Number of Meshes per Linear Inch and Sizes of Openings, as Found by Measurement

Ref.	Number of Sieve.	No. of Meshes per Linear Inch.		Diameter of Wire in Decimals of an Inch.			Mean Size of Opening in Decimals of an Inch.				
		Across Web Wires.	Across Woof Wires.	Web. Diameter.	Woof. Diameter.	Difference.	Between Web Wires.	Between Woof Wires.	Difference.	Ratio Col. *g* to Col. *h*	Remarks.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	
1	20	20	19¾	.0185	.0169	.0016	.0315	.0337	.0022	.93	
2	20	20	19	.0165	.0168	.0003	.0335	.0358	.0023	.93	
3	30	30	28¾	.0119	.0119	.0000	.0214	.0229	.0015	.93	
4	30	30	30	.0118	.0118	.0000	.0215	.0215	.0000	1.00	
5	30	30	29½	.0116	.0122	.0006	.0217	.0217	.0000	1.00	
6	40	40	36	.0095	.0095	.0000	.0155	.0183	.0028	.85	
7	50	50	47	.0082	.0083	.0001	.0118	.0130	.0012	.90	
8	74	80	80	.0054	.0054	.0000	.0071	.0071	.0000	1.00	
9	100	101	88½	.0040	.0040	.0000	.0059	.0073	.0014	.80	
10	120	120	120	.0037	.0037	.0000	.0046	.0046	.0000	1.00	
11	200	210	170	.0022	.0022	.0000	.0026	.0037	.0013	.70	Approx.

wire gage, respectively. It seems to be impracticable to comply with these sizes of wires, because neither manufacturers nor engineers appear to agree as to what diameters of wire correspond to No. 37 and No. 40 Stubbs' wire gage.

73. The conferences of Dresden and Munich decided that fineness should be determined by sieves of 900 and 4,900 meshes per sq. cm., respectively, for Portland cement, and 900 and 2,500, respectively, for other hydraulic products, the size of the wires being as follows: for 4,900, .05 mm.; for 2,500, .07 mm.; and for 900, .10 mm. These sieves would have respectively 31,600 (178 × 178), 16,000 (127 × 127), and 5,800 (76 × 76) meshes per square inch, and the sizes of the holes would be approximately .0037 inch square, .005 inch square and .009 inch square, respectively. It was also decided that for sifting sand, punched metal plates were preferable to wire cloth sieves.

74. In Table 5 are given some of the results obtained by the writer which will serve to show what variations may exist in sieves which have been selected from a considerable number offered for use.

Table 6 gives the data available concerning certain sieves that have been used or recommended in this country and elsewhere.

TABLE 6

Sizes of Openings in Sieves Recommended or in Use

Ref.	No. Meshes per Linear Inch.	Size Wire Diameter.	Size Hole, Inch Square.	Remarks.
	a	b	c	
1	178	.00197	.00366	Established by Conferences, Dresden & Munich.
2	127	.00276	.00512	" " " " "
3	76	.00394	.00920	" " " " "
4	76	.00437	.00875	Present German Standard.
5	76	.00591	.00721	Recommended by H. LeChatelier.
6	176	.00162	.004	Silk mesh—Vyrnwy Reservoir.
7	103	.0022	.0075	" " " "
8	170	.00279	.00309	Cornell University, Marx & Mosscrop, 1887.
9	80	.00651	.00599	" " " " "
10	50	.00881	.01119	" " " " "
11	30	.01214	.02119	" " " " "
12	20	.01899	.03101	" " " " "
13	200	.0024	.0026	Progress Report, A. S. C. E. Committee, 1903.
14	100	.0045	.0055	" " " " " "

75. The **time sifting should be continued** will depend on the fineness of the meshes, the diameter of the sieve, the amount of cement taken, and the manner of sifting ; it will also depend upon the fineness of the cement, as well as its nature, and its condition as to dryness. But, although some care is necessary concerning these points, very large variations in results due to variations in the time the sifting is continued may easily be avoided. The diameter of the sieve is usually made greater for the finer meshes, but this is not always the case. It is a common practice in America to use one-tenth of a pound of cement in testing the fineness, using a scale weighing in ten-thousandths of a pound. Where the metric system is in use (and it may well be adopted in a cement laboratory), 100 grams of cement are usually taken.

76. M. H. LeChatelier recommends a sieve having 900 meshes per sq. cm., of wire 0.15 mm. diameter, giving holes 0.18 mm. (.0072 inch) square. He prefers machine screening, but says that for current tests it might be sufficient to screen by hand for ten minutes with a sieve three decimeters (about 12 inches) in diameter.

Table 7 is taken from experiments made by M. Durand-Claye and M. Candlot, and shows what differences may arise from varying the length of time that a sample is screened. The cements used were not the same in the two cases, but the sieves had each 5,000 meshes per sq. cm. (about 180 per linear inch), and 100 grams of cement were taken in each case. Had a coarse sieve been used, the differences would have been much less after the same lengths of time.

TABLE 7

Fineness: — Mechanical and Hand Sifting Compared

M. Durand-Claye. Mechanical Sieve Making 200 Revolutions per Minute.			M. Candlot. Hand Sieve, 12 Inches in Diameter.		
No. Revolutions.	Per Cent. Retained.	Diff.	After Minutes.	Per Cent. Retained.	Diff.
500	41.2	. . .	5	29.6	. . .
1,000	39.4	1.8	10	29.1	0.5
1,500	38.6	.8	20	28.4	0.7
2,000	38.0	.6	30	28.0	0.4
2,500	37.6	.4	40	27.7	0.3

77. Table 8 gives the results obtained by the author in sifting several samples. The No. 80 sieve was about 6½ inches in diameter, and Nos. 120 and 200 about 5½ inches. One hundred grams of cement were taken in each case, and the sieve was shaken vigorously by hand. It is seen that coarse samples require less time for sifting than fine samples, and that natural cements require a longer time than Portlands. With the No. 80 sieve, five minutes usually suffices to obtain the fineness,

TABLE 8

Effect of Time of Sifting on the Result Obtained in Testing Fineness

Reference.	Sieve.		Cement.			Per Cent. by Weight that had Passed Sieve after Sifting.							
	Approximate No. of Meshes per Inch.	Size Holes, Inch Square.	Kind.	Brand.	Sample.	1 Minute.	3 Minutes.	5 Minutes.	7 Minutes.	10 Minutes.	15 Minutes.	20 Minutes.	25 Minutes.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*
1	80	.0071 by .0071	Port.	X	685	91	92	93	93	...	...	...	...
2	"	"	"	Y	42 s	82	85	86	...	...	...	...	...
3	"	"	"	S	34 s	95	96	96	...	...	...	...	...
4	"	"	"	Z	43 s	100	...	...	...	...	...	...	...
5	"	"	Nat.	Bn	27 s	68	71	71	...	...	...	...	...
6	"	"	"	An	G	78	80	82	82	...	...	...	...
7	"	"	"	In	28 s	85	89	90	90	...	...	...	...
8	"	"	"	Gn	108 T	75	89	90	91	91	...	...	...
9	120	.0046 by .0016	Port.	X	685	45	78	82	...	84	84	...	...
10	"	"	"	Y	42 s	41	73	77	...	78	78	...	...
11	"	"	"	S	34 s	72	89	90	...	91	91	...	...
12	"	"	"	Z	43 s	54	94	96	...	97	98	...	...
13	"	"	Nat.	Bn	27 s	27	62	65	...	66	66	...	...
14	"	"	"	An	G	45	73	76	...	78	78	...	...
15	"	"	"	In	28 s	13	42	64	...	82	83	...	..
16	"	"	"	Gn	108 T	5	16	27	...	64	82	85	86
17	200	.0036 by .0037	Port.	X	685	...	58	65	..	68	70	71	..
18	"	"	"	Y	42 s	...	65	68	...	71	72	72	...
19	"	"	"	S	34 s	...	72	76	...	78	80	81	...
20	"	"	"	Z	43 s	...	74	78	...	81	82	83	...
21	"	"	Nat.	Bn	27 s	...	57	59	...	60	60	...	...
22	"	"	"	An	G	...	67	69	...	70	72	72	...
23	"	"	"	In	28 s	...	41	53	...	69	75	77	78
24	"	"	"	Gn	108 T	...	40	49	...	64	76	79	...

and with the No. 120 sieve, but little cement usually passed after the sifting had continued ten minutes, though with one brand of natural, Gn, it appears that the true fineness would not be indicated by sifting less than 20 minutes. With the No. 200 sieve 20 minutes is usually required, and in the case of two samples of natural cement, a still longer time appears to be necessary.

78. Conclusions. — Until there is a proper standard in the United States concerning sieves and methods of sifting, the best that can be done is to select, from the sieves that manufacturers have to offer, those which appear to be most nearly uniform in size of mesh, and then actually determine the size of the holes. This may be done by counting, under the magnifying glass, the number of meshes per inch each way, and determining the size of wire with a micrometer wire gage.

As to the time sifting should be continued, one can easily find by trial the time required in using a given sieve in order to confine the error within given limits. A fine natural cement should be selected to determine this, as such a cement requires the longest sifting. Care should be taken that the cement is well dried before making the test for fineness. It will be found that for sieves having holes between .003 inch and .004 inch square (sieves approximating 170 to 200 meshes per linear inch) 20 to 30 minutes are required, while for sieves having holes .007 to .009 inch square (approximately 70 to 100 meshes per linear inch) from five to ten minutes will usually suffice.

79. Specifications for Fineness. — The following table has been compiled to show what are considered reasonable requirements for fineness. In most specifications there is the usual indetermination concerning the sizes of holes in the sieves.

TABLE 9

Requirements as to Fineness

Specification.	Date.	Per Cent. Required to Pass Sieve Having 10,000 Holes per Square Inch.	
		Portland.	Natural.
U. S. Army Engineers	1901	92	80
U. S. Navy Department . . .	. . .	95	. . . .
City Pittsburg, Pa.	1900	90	77
New East River Bridge . . .	1897	90	. . . .
Topeka, Kan., Bridge . . .	1896	95	. . . .
Master Builders' Exchange, Phila.	1895	85	80

Art. 15. Coarse Particles in Cement

80. The Effect of Coarse Particles on the Weight of Cement. — To remove the coarse particles by sifting will reduce the specific gravity of a sample of Portland cement, as the unground particles are from the harder burned and denser portion of the clinker, and to remove these denser particles will, of course, decrease the average density of the sample. This is not always the case with natural cements, as is shown by the following tests: —

TABLE 10

The Relative Specific Gravity of Coarse and Fine Particles of Cement

Cement.			Specific Gravity.
Kind.	Brand.	Fineness.	
Portland	R	As received . . .	3.086
"	"	50-100	3 145
"	X	Pass 50	3.039
"	"	Ret. on 50 . . .	3.125
Natural	Gn	Pass 100	2.874
"	"	Ret on 50 . . .	2.817
"	An	Pass 50	2.945
"	"	Ret. on 50 . . .	2.817

The apparent density or weight per cubic foot of Portland will be reduced more than the specific gravity by the removal of the coarse particles; because not only will the true density be decreased, but the packing, which is facilitated by a wide range in the sizes of the particles, will be less perfect than when the coarse particles are present. In § 89 a table is given showing the changes in specific gravity and weight per bushel occasioned by removing the coarse particles by sifting.

81. Effect of Coarse Particles on the Time of Setting. — Table 11 gives the results of a number of tests on Portland and natural cements to determine the relative time of setting of samples from which the coarse particles had been removed by the No. 200 sieve, while Table 12 gives results obtained with a sample of natural cement of varying fineness.

In Table 11, 30 per cent. of water was used for all Portland cements, and 36 per cent. for all naturals, but the consistency varied as stated in the table. It is seen that in nearly every case the setting was hastened by removing the coarse particles, though this may have been due in part to the fact that with the same percentage of water the finer cement gave a stiffer paste.

For the tests in Table 12, the attempt was made to make all of the mortars of the same consistency by varying the percentage of water. As would be expected, the coarse particles are very slow setting. In fact, what hardness they attained was probably due largely to the fine dust that adhered to the grains. These coarse particles may be considered as practically inert, and their presence in a sample would naturally make it slow setting. To show this by actual test, however, is very difficult,

TABLE 11

Effect of Coarse Particles on the Time of Setting

Cement.		Cement Passing No. 20 Sieve.		Cement Passing No. 200 Sieve.	
Kind.	Brand.	Time to bear ¼ lb. wire. Minutes.	Consistency.	Time to bear ¼ lb. wire. Minutes.	Consistency.
Portland	Y	39	Trifle moist	13	Trifle dry
"	X	9	Moist	4	O. K.
"	Z	432	Trifle moist	354	Trifle dry
"	S	556	" "	341	" "
Natural	Gn	31	. . .	29	. . .
"	Bn	143	Trifle moist	151	Trifle dry
"	In	397	" "	256	. . .
"	Hn	256	. . .	233	. . .

Note: — 30 per cent. water used for all Portlands.
36 per cent. water used for all natural cements.

TABLE 12

Effect of Coarse Particles on Time of Setting

Natural Cement, Brand Gn — All pastes appeared same consistency.

Fineness.	Water Used as Per Cent. of Cement.	Time to Bear ¼ lb. Wire. Minutes.	Time to Bear 1 lb. Wire. Minutes.
Pass No. 20 sieve	33	14	159
" 50 "	36	29	219
" 100 "	38	24	214
Retained on 50, reground to pass 100	28	73	670
Pass No. 50, retained on No. 100	34	205	890

as the amount of water required to bring the mortars to the same consistency varies with the amount of coarse particles present, and as there is no very satisfactory method of testing the consistency, the tests for time of setting have in them this indetermination.

82. Effect of Coarse Particles on the Tensile Strength. — A cement having a certain quantity of coarse particles will frequently give a higher tensile strength when tested neat than a cement from which the coarse particles have been removed by screening. The reason for this may be found in the fact that a wide range in the sizes of grain of the powder facilitates packing, both when dry and when mixed with water to form a paste. Another reason is that the unground particles are stronger than the hardened mortar, and, considering the broken section of a briquet, the break does not take place through these particles, but they are pulled out of their bed; this virtually increases the area of section. Were the same sample of cement reground, so that a certain proportion of the coarse particles was rendered active, it might then give a higher strength, neat, than at first. If so, the reason would be found in the fact that the coarse particles, being the hardest burned, were really from the best part of the cement clinker, and rendering these particles active by fine grinding increased the cohesive properties of the cement so much as to overcome the physical effect of the coarse particles, which, when judged by neat tests, appear to be beneficial. The above serves to illustrate the difference between sifting and fine grinding which are so frequently confused in treating this subject.

83. Among the many tests that have been made to show the effect of sifting on the cohesive and adhesive strength of cements, a few may be given as follows: —

Mr. Maclay[1] gives a few experiments to show that the presence of coarse particles increases the cohesive strength, neat, seven days.

Lieut. W. Innes[2] gives two tables of results obtained by experimenting on very coarse cements. The tables show that removing the particles that would not pass through sieves of

[1] Trans. Am. Soc. C. E., Vol. vi.

[2] Minutes Proc. Inst. C. E., Vol. xxv.

1,296 meshes and 2,500 meshes per square inch, decreased the strength when tested neat at the ages of three months and six months; but increased the strength when sand mortars were used. The differences at six months were relatively somewhat less than at three months. By separating a sample of cement into two parts, that passing a sieve having 2,500 meshes per square inch and that retained on the same sieve, and then remixing the screenings with the fine portion, he found that the highest strength, neat, six months, was given by the mixture containing the largest amount tried (70 per cent.) of screenings.

84. In the tests of cement for the Cairo Bridge[1] a series of experiments was made to determine the effect of coarse particles on the value of both Portland and natural cements. The cement was separated into two parts, by a sieve having 10,000 meshes per square inch. Briquets were made both neat and with sand, the cement used being made of 100, 90, 80, 70 and 60 volumes of sifted cement to 0, 10, 20, 30, and 40 volumes, respectively, of cement screenings. The briquets were broken when six months old.

It was found that in the case of Portland cement, neat, the highest result was obtained with the largest (40) per cent. of screenings, but with one and two parts sand, the strength steadily fell as larger amounts of screenings were used. With Louisville natural cement the presence of screenings seemed to have little effect on neat tests; and with one part of sand to one of cement, the use of as much as 30 per cent. of screenings to 70 per cent. of sifted cement did not appear to decrease the strength. With two parts sand to one cement, the results were slowly diminished by successive additions of larger percentages of screenings.

85. M. R. Feret is said to have replaced with sand the grains of cement retained on sieves having 5,800 and 32,300 meshes per square inch, and found that, except in the case of neat cement mortars, the substitution of sand for coarse particles of cement did not decrease the strength. In experimenting on this subject Mr. Eliot C. Clarke[2] found that the coarse particles

[1] Jour. Assn. Engr. Soc., 1890, and *Engineering News*, Jan. 31, 1891.

[2] Trans. A. S. C. E., Vol. xiv, pp. 158–162.

TABLE 13

Effect of Removing Coarse Particles from Natural Cement

Cement.	No. Parts Sand to One Cement by Weight.	Water as Per Cent. of Weight Dry Ingredients.	Tensile Strength, Pounds per Square Inch.				
			7 da.	28 da.	3 mo.	6 mo.	2 years.
A	None	33.3	120	275	...	...	...
B	"	35.7	100	266	...	...	...
C	"	38.5	83	253	...	...	...
D	"	28.3	202	264	...	...	...
E	"	35.0	127	143	...	...	...
A	One	19.0	121	253	...	330	380
B	"	19.6	104	251	...	344	398
C	"	20.0	94	261	...	331	385
D	"	16.0	286	360	...	396	385
A	Two	16.1	...	168	215	223	210
B	"	16.1	...	203	245	267	302
C	"	16.1	...	218	297	317	358
D	"	13.9	...	227	230	245	262
E	"	15.8–16.1	...	71	40	57	50
A	Three	14.5	...	...	...	127	128
B	"	14.5	...	...	...	167	164
C	"	14 5	...	...	...	205	234
D	"	12.1	...	...	...	125	118

Fineness of Cement

	Per Cent. Passing Sieve No.		
	50	100	120
Cement *A*	82	70	64
Cement *B*	100	85	78
Cement *C*	...	100	91

Note: — All cement from same barrel, Brand Bn, Sample 27s.
Sand, crushed quartz 20–30.
All briquets made by one molder and stored in one tank.
All results, mean of 5 briquets, except two which are means of ten and two briquets, respectively.

A — Cement passing No. 20 sieve, holes .033 inch square.
B — " " " 50 " " .012 "
C — " " " 100 " " .0065 "
D — " retained on No. 50, reground to pass No. 100.
E — " passing No. 50, retained on No. 100.

of cement were somewhat better, for use in mortar, than fine sand, but very little better than coarse sand.

86. The tests given in Table 13 were made under the author's direction to determine the effect of sifting and the value of coarse particles. It is seen that in neat tests the strength is slightly diminished by sifting out the coarse particles; in the tests of mortars containing equal parts by weight of sand and cement, there is little difference in the strength of the three samples, though the coarser cement appears to gain its strength a little more rapidly. With two parts sand to one of cement, the greater value of the fine particles is very noticeable, and with one-to-three mortars the difference is still more marked, the sifted cement giving 80 per cent. greater strength than the unsifted.

87. In Table 14 these results are arranged in a different way. If we assume that the particles that will not pass the No. 120 sieve are not cement at all, but equivalent to sand,

TABLE 14

Effect on Tensile Strength of Removing Coarse Particles from Natural Cement

Cement.	Per Cent. Passing Sieve No. 120.	Parts Sand to One Cement.	Parts Sand and Coarse Particles to One Part Fine Particles.	Strength of Mortar after Two Years.
A	64	3	5.2	128
B	78	3	4.1	164
A	64	2	3.7	210
C	91	3	3.4	234
B	78	2	2.8	302
C	91	2	2.3	358
A	64	1	2.1	380
B	78	1	1.6	398
C	91	1	1.2	385

and that all particles passing this sieve are cement, we obtain a new set of proportions of sand to cement. Thus the sample of cement passing No. 20 sieve, sample A, would be composed of 64 parts cement and 36 parts sand, and the 1 to 3 mortar would have in reality the proportion 64 cement to 336 sand, or 1 to 5.2. It is seen that the tensile strength bears a closer relation to the richness of the mortar when considered in this way. There is, of course, no abrupt division in size such that

TABLE 15

Value of Coarse Particles of Cement, Natural and Portland

Reference Number.	Tensile Strength, Pounds per Square Inch.								
	Neat Cement.			1 Part Standard Sand to 1 Cement		3 Parts Standard Sand to 1 Cement.		3 Parts Limestone Screenings, ($\frac{20}{80}$) to 1 Cement.	
	3 mos.	4 mos.	1 yr.	3 mos.	1 yr.	3 mos.	1 yr.	3 mos.	1 yr.
	d	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*
1	330	. . .	390	. . .	. . .	108	139	160	234
2	259	. . .	336	. . .	. . .	193	217	269	332
3	295	. . .	334	. . .	. . .	203	224	251	319
4	306	. . .	370	. . .	. . .	102	106	137	170
5	309	. . .	343	. . .	. . .	92	96	139	155
6	. . .	630	706	786	812	378	395	472	589
7	. . .	550	553	755	838	423	463	538	677
8	. . .	621	665	745	891	455	469	561	676
9	. . .	615	651	746	841	357	399	425	568
10	. . .	591	764	765	837	362	354	405	506

Ref. No. 1. Natural cement passing No. 20 sieve.
" " 2. Natural cement passing No. 80 sieve.
" " 3. Natural cement reground before sifting, until all passed No. 80 sieve.
" " 4. Natural cement, 64¾ per cent. of cement passing No. 80 sieve mixed with 35¼ per cent. of limestone screenings retained between Nos. 20 and 80 sieves.
" " 5. Natural cement, 64¾ per cent. of cement passing No 80 sieve mixed with 35¼ per cent. of crushed quartz retained between Nos. 20 and 80 sieves.
" " 6. Portland cement passing No. 40 sieve.
" " 7. Portland cement passing No. 80 sieve.
" " 8. Portland cement reground (before sifting) until all passed No. 80 sieve.
" " 9. 81⅔ per cent. of cement passing No. 80 sieve mixed with 18⅓ per cent. limestone screenings retained between Nos. 40 and 80 sieves.
" " 10. 81⅔ per cent. of cement passing No. 80 sieve mixed with 18⅓ per cent. crushed quartz retained between Nos. 40 and 80 sieves.

Of the natural cement passing No. 20 sieve, 35¼ per cent. was retained on sieve No. 80, while 64¾ per cent. passed the No. 80 sieve. In lines 4 and 5 the coarse particles of cement (20–80) were removed and replaced by an equal weight of sand grains, retained between sieves 20 and 80.

Of the Portland cement passing No. 40 sieve, 18⅓ per cent. was retained on sieve No. 80, while 81⅔ per cent. passed sieve No. 80. In lines 9 and 10 the coarse particles of cement (40–80) were removed and replaced by an equal weight of sand grains retained between sieves 40 and 80.

All briquets made by same molder, each result mean of five specimens.

coarser particles act only as sand, while finer ones enter into combination as cement; part of the coarse particles will have some cementitious value, while some of the finer particles will have somewhat the effect of sand.

As to the sample composed of coarse particles reground, it must be considered that although this sample was passed through the No. 100 sieve, yet it was in reality much coarser than sample C, because the particles were harder, and the grinding in the mortar less thorough than the original grinding. Since this sample of reground cement gives so high a strength neat and with one part sand, it appears that the hard particles from which it was made are of excellent quality if ground fine enough, and the relatively lower results with larger proportions of sand must be attributed to imperfect grinding.

The coarse particles retained between sieves 50 and 100 gave a higher strength neat than was expected, but much of this strength may be due to the floury portion of the cement that doubtless adhered to the coarse particles instead of passing through the sieve.

88. The tests in Table 15 were made to determine whether the coarse particles of cement are of greater value in mortar than the same quantity of fine sand. The coarse particles of the cement were sifted out and replaced with sand grains of about the same size. The conclusion drawn from the preceding tests would indicate that some of the coarse particles of cement might be replaced by sand without diminishing the tensile strength; but the tests given in this table indicate that this is not the case when it is a question of substituting sand grains of the same size. Although such a substitution has little effect on the strength of rich mortars, it results in a decreased strength with mortars containing as much as three parts sand to one of cement by weight. (See § 85 in this connection.)

Art. 16. Fine Grinding

89. Effect of Fine Grinding on the Weight of Cement. — Fine grinding will decrease the weight per cubic foot, the fine cement not packing as closely as the coarser product. In "Cement for Users," by Mr. Henry Faija, the following results are given, showing the relation between fineness, weight, and spe-

TABLE 16

Relation of Fineness to Specific Gravity and Weight per Bushel

From "Cement for Users"

SAMPLE.	SPECIFIC GRAVITY.			WEIGHT PER BUSHEL.				
	a	b	c	a	b	c	d	e
1	3.00	2.97	3.07	116.5	107.5	121.0	112.0	115
2	3.03	2.94	3.04	116.0	104.0	130.5	109.0	115
3	3.02	2.91	3.035	114.0	100.0	128.0	104.5	109

cific gravity: (*a*), cement as delivered; (*b*), siftings that passed through sieve with 2,500 holes per sq. in.; (*c*), coarse, retained on above sieve; (*d*), cement all ground to pass above sieve; (*e*), coarse particles reground to pass above sieve.

90. Effect of Fine Grinding on Time of Setting. — Since the coarse particles of cement are practically inert, there is every reason to believe that finer grinding will increase the activity of a sample, since it will render some inert particles active. For the reason mentioned in § 81, however, it is difficult to show this difference in time of setting by actual tests.

Tests reported by Mr. David B. Butler[1] showed that several Portland cements which took an initial set in 20 to 30 minutes and hard set in 45 to 120 minutes would, when reground to pass a sieve having 180 meshes per linear inch, begin to set in from 1 to 7 minutes and set hard in 5 to 15 minutes. These may be considered extreme results; the rise in temperature of these cements during setting was so great as to indicate they were not normal cements, and variations in consistency of the pastes may have influenced the time of setting.

91. EFFECT OF FINE GRINDING ON STRENGTH. — Since the best burned clinker of Portland cement is the hardest, it follows that the unground particles would, if ground fine enough to become active, form the best portion of the cement. This is not, *a priori*, true of natural cements, because burning renders some varieties of cement rock softer at first, but when the burning is carried beyond a certain point they become harder again. The coarse particles in a natural cement may thus be either

[1] Proceedings Inst. C. E., 1898.

from underburned or overburned rock; hence it is possible that in some cases it might be better to leave the hardest particles in an unground state. Thus, while it has been generally accepted that fine grinding improves Portland in a twofold degree, — by bringing into action the best burned clinker, as well as by rendering a given weight of cement capable of coating a larger number of sand grains, — a similar conclusion concerning natural cement is not well established.

TABLE 17

Effect of Fine Grinding of Natural Cement on the Tensile Strength of Mortar

Reference.	Tensile Strength, Pounds per Square Inch.											
	Neat Cement.		1 Part Standard Sand to 1 Cement.		2 Parts Standard Sand to 1 Cement.				3 Parts Standard Sand to 1 Cement.		4 Parts Standard Sand to 1 Cement.	
	7 da.	6½ mo.	7 da.	28 da.	28 da.	3 mo.	6 mo.	2 yr.	6 mo.	2 yr.	6 mo.	2 yr.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*
1	268	538	224	381	207	354	291	70	202	48	156	49
2	283	473	230	350	245	433	426	102	302	65	212	78
3	278	538	307	433	292	469	406	92	305	61	240	65
4	392	592	368	538	271	344	369	160	274	110	205	90
5	. . .	. . .	. . .	. . .	21	. . .	73	45	. . .	. . .	. . .	. . .

Reference.	Fineness of Cement, Per Cent. Passing Sieve Number.	
	100	120
1. Cement as received passed through No. 20	76.5	72.4
2. Cement as received passed through No. 100	100.0	94.6
3. Reground in mortar, not sifted	95.8	91.5

Cement; Natural, Brand Jn.
No. 1. Passing No. 20 sieve.
" 2. Passing No. 100 sieve.
" 3. Reground before sifting.
" 4. Particles retained on No. 50 sieve, reground to pass No. 100 sieve,
" 5. Particles retained on No. 50 sieve, reground to pass No. 50 sieve, but retained on No. 100 sieve.

All briquets made by one molder and immersed in one tank. In general, each result is mean of five specimens.

92. Some tests bearing upon the value of fine grinding have already been given in Table 15. Samples 3 and 8 were reground with mortar and pestle before being sifted. If we compare the results given by sample 3 with those obtained with samples 1 and 2, not reground, it appears that the regrinding diminishes the strength in neat mortars but increases it in mortars containing three parts sand to one of cement. Regrinding appears to be no better, however, than sifting. Comparing sample 8 with samples 6 and 7, it is seen that regrinding Portland cement does not diminish the strength in neat mortars to the same extent as sifting does, and in sand mortars regrinding generally results in a greater increase in strength than sifting.

93. The results in Table 17 were obtained with another sample of natural cement and are of greater practical value as indicating the importance of fine grinding, since in these tests a sample is included obtained by regrinding the original cement without previous sifting. The conclusions concerning the cement retained on No. 50 sieve reground to pass No. 100, and the coarse particles alone retained between sieves 50 and 100, are practically the same as those drawn from Table 13.

As to the other three samples, the No. 20 sieve removed only a very few coarse particles, and that passing this sieve may be considered to represent the cement as received The No. 100 sieve removed about 24 per cent. by weight from the original cement, and the cement that was reground contained but about 4 per cent. of particles which would not have passed the No. 100 sieve. The third sample, reground cement, may be compared with the first to indicate the improvement obtained by finer grinding, and it may be compared with the second to determine the difference between removing the coarse particles by sifting and reducing them by finer grinding. In considering these results it will be best to neglect the two-year tests, since all of the samples failed at this age. A comparison of the results obtained with these three samples indicates that while the advantage of finer grinding is not apparent in neat tests, in sand mortars the value of finer grinding is more marked the larger proportion of sand used, so that with three or four parts sand, the strength with the fine samples is about 50 per cent. greater than with the cement as received. It also appears that the reground sample gains its strength more rapidly than the sifted sample, though at six months it seems to make little difference whether the coarse particles are removed by sifting or reduced by grinding.

94. Conclusions as to the Effect of Fine Grinding and Sifting on Tensile Strength. — The general conclusions to be drawn concerning fine grinding and sifting may be summarized as follows: According to the tests given, it appears that to remove the coarse particles from a sample of natural cement by sifting, or to reduce them by finer grinding, generally diminishes the strength obtained in tests of neat cement mortars. In one-to-one mortars, the strength of the finer samples is not much greater than when the coarse particles are present; but in mortars containing greater proportions of sand, the advantage obtained by eliminating the coarse particles is very marked in the case of natural cement, the strength given by the finer samples sometimes exceeding that of the original cement by more than 60 per cent. While the advantages of sifting and finer grinding are also important for Portland cements, there does not result such a large proportionate increase in strength.

Reground samples of natural cement gain strength more rapidly than resifted samples, but eventually the strength attained is about the same. In Portland cements regrinding seems to be of greater value than resifting. A sample of natural cement made from coarse particles reground gains strength rapidly, and for mortars with small proportions of sand, gives good results. The fact that such samples do not give a high strength with large proportions of sand is doubtless due to the fact that the grinding is not thorough, and the indications are that the material of which such coarse particles are composed would form a valuable part of the cement if ground fine enough.

The coarse particles of either natural or Portland cement may be replaced by grains of sand of the same size without materially affecting the strength attained by neat and one-to-one mortars, but for mortars containing larger proportions of sand, such a substitution results in a decreased strength.

95. Finally, it may be said that the process of manufacture and the character of the materials from which cement is made have such an influence on the relative proportions of fine and coarse particles that the percentage of finest particles cannot be determined by testing with a coarse sieve. While it is not known at what point of fineness grains of cement begin to have cementitious value, or what proportion of the cement should be the finest flocculent matter, it is certain that a cement should leave as small a percentage as possible on a sieve having holes .004 inch square, in order to have the greatest sand carrying capacity.

There is, however, a reason for using a comparatively coarse sieve in connection with the fine one. Overburned lime, which is likely to occur in Portland cements, is more dangerous in the form of coarse particles than an equal quantity in a fine condition, because coarse particles slake more slowly and it is better that expansion should occur early in the process of hardening if it is to occur at all. For the same reason a cement that would be unsound normally may be rendered less dangerous by regrinding.

As fine grinding is expensive, it is only a question as to when the increased strength obtained is offset by the extra expense incurred in grinding. There is now little trouble in obtaining either natural or Portland cement of which from 60 to 70 per cent. will pass holes .004 inch square. (See § 79.)

CHAPTER VII

TIME OF SETTING AND SOUNDNESS

ART. 17. SETTING OF CEMENT

96. Process of Setting. — When cement is gaged with sufficient water to bring it to a paste, and is then left undisturbed, it soon begins to lose its plasticity and finally reaches such a condition that its form can no longer be changed without producing rupture. This change of condition is known as the "setting" of cement and is considered to be, in a measure, distinct from "hardening." Setting usually takes place within a few hours, or perhaps minutes, while the hardening is continuous for months or years.

The precise chemical changes that take place in the setting and hardening of cements are not thoroughly understood. The chief cementitious ingredient in Portland cement is considered to be a tricalcium silicate, 3 CaO, SiO_2; in contact with water it forms hydrated monocalcic silicate and calcium hydrate. This process is believed to contribute more to the final hardening of the mortar than to the setting, though the hydration of the finer particles of this important compound also contributes to the first setting. It is considered that the calcium aluminates play an important rôle in the first setting of cement, as they set rapidly in contact with water, and it has been suggested that they form the chief active constituents of natural cement.[1]

These chemical changes cause the formation of crystals which by their interlocking and adhesion give strength to the new compounds. For a scientific and detailed treatment of this subject, the reader is referred to the articles of M. H. Le Chatelier in *Annales des Mines*, 11, pp. 413–465, Trans. Am. Inst. Mining Engineers, August, 1893; to the conclusions of S. B. and W. B. Newberry, *Cement and Engineering News*, 1898; and to "The Constitution of Portland Cement from a

[1] S. B. Newberry, "Mineral Resources of the United States," 1892.

Physico-Chemical Standpoint," a paper by Mr. Clifford Richardson read before the Association of Portland Cement Manufacturers at Atlantic City, June 15, 1904, *Engineering Record*, August 13 and 20, 1904, *Engineering News*, August 11, 1904.

97. THE RATE OF SETTING AND ITS DETERMINATION. — The setting of cement being a gradual and continuous process without well-defined points of change, it is necessary, in order to compare the rates of change in condition of different samples, to adopt an arbitrary standard. The method usually adopted is to determine the resistance of the mortar to the penetration of a wire or needle. The wires used by General Totten and recommended by General Gilmore for this purpose are now in general use in this country. One of the wires is $\frac{1}{12}$ inch in diameter and is loaded to weigh $\frac{1}{4}$ pound; the other is $\frac{1}{24}$ of an inch in diameter and loaded to weigh one pound. The paste is said to have reached "initial set" and "end of set" when these two wires, respectively, fail to make an impression on the surface.

98. M. Vicat also suggested a needle test as follows: The cement paste is placed in a conical ring, 4 cm. in height and 7 cm. in diameter at the base. The consistency should be such that a rod 1 cm. in diameter and weighing 300 grams does not entirely pierce the mass. This consistency having been obtained by trial, a needle of circular cross-section having an area of 1 sq. mm. and loaded to weigh 300 grams, is gently lowered on the paste. The moment when this needle no longer penetrates the mass is called the beginning of the set, and the time in which it fails to make an impression upon it is called the end of setting. It may be mentioned in passing, that, according to a few comparative tests made by the author, when a cement paste has "set" by Gilmore's "heavy" wire, $\frac{1}{24}$ inch weighing one pound, it requires about 1,100 grams weight on the Vicat 1 sq. mm. needle to make an impression on the paste. Vicat's method was indorsed by the Munich Conference and was suggested in the recent progress report of the Committee of the American Society of Civil Engineers.

99. M. LeChatelier has suggested a modification of this method by substituting for the rod 1 cm. in diameter a disc of the same diameter carried by a slender rod, the disc being loaded to weigh 50 grams, the normal consistency being such that the disc will stop midway in the ring, or "vase." The beginning and end of setting he would define by the penetration of the needle (1 sq. mm. in section) to mid-depth in the ring, the weights being 50 grams and 3,000 grams, respectively.

100. An **approximate method** of determining time of setting is also in use as follows: After mixing the cement paste to the proper consistency, place enough of it on a glass plate to form a thin cake, or "pat," about three inches in diameter and one-half inch thick at the center, thinning toward the edges. When the pat is sufficiently hard to bear a gentle pressure of the finger nail, the cement is considered to have begun to set, and when it is not indented by a considerable pressure of the thumb nail, it may be said to have set.

101. Mr. Henry Faija objected to all methods which are based upon the rates of acquiring hardness, on the ground that there are periods in the early stages of hardening that may be more rationally defined. He considers that the time at which the water leaves the surface of the pat, depriving it of its glossy appearance, is really the beginning of setting, and that this time may or may not correspond to the result obtained by the use of the needle.

102. Variations in the Rate of Setting. — Some of the qualities which determine the actual rate of setting of a cement are, its composition, degree of burning, age and fineness. Aside from these qualities of the cement itself, the addition of certain salts subsequent to the manufacture also influences the rate. The observed rate of setting will be influenced by the details of the test, such as the quantity, temperature and composition of the water used in gaging, the amount of gaging, the temperature of the cement, and the temperature and character of the medium in which the pat is placed after molding.

103. An over-limed or highly limed cement is usually slower setting than an over-clayed one. Among natural cements, those of the aluminous variety are usually quick setting. Other things being equal, a well-burned Portland cement will be slower setting than an underburned sample. It is not certain that such is the case for all natural cements, though it probably is true of most of them. It has been said that underburned cements owe their quick setting to their porosity, but the formation of different compounds in the higher temperature may also account for the difference.

104. The **effect of the age** of cement on its time of setting is very marked, but varies widely with different samples. The idea that cements invariably become slower setting by storage is a false one. The origin of this error may be found in the fact that by the time cement has reached its destination, it has usually passed through the earlier and more rapid changes in characteristics. Dr. Erdmenger[1] has stated that some Portland cements become slower setting, while some set more rapidly as a result of storage. Dr. Tomei made experiments on several Portland cements[2] which show that they generally become quicker setting at first (from one to four months after grinding), and then become gradually slower setting, until at the end of a year they set in about the same length of time as when fresh. The writer has seen this trait exhibited very

TABLE 18

Time of Setting of Five Samples of Natural Cement as Affected by Aëration

Reference.	Sample.	Water.		Temp. Air Where Made.	Time Setting Cement from Package.			Time Setting Cement Aërated 19 Days.			Remarks.
		Per Cent. Dry Ingrds.	Tempera-ture.		¼ Lb. Wire. Min.	1 Lb. Wire. Min.	Diff. f–e. Min.	¼ Lb. Wire. Min.	1 Lb. Wire. Min.	Diff. i–h. Min.	
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	
1	84 R	32.0	65°	67-73°	52	110	58	54	173	119	Five samples, same brand. U_2 and O_2 required more and less water respectively than the others to make same consistency.
2	83 R	"	"	"	50	100	50	51	164	113	
3	82 R	"	"	"	44	100	56	48	166	118	
4	U_2	34.7	"	"	60	280	220	100	326	226	
5	O_2	29.3	"	"	101	349	248	147	306	159	
6	84 R	40.0	"	"	87	1200	1110	130	1241	1111	
7	83 R	"	"	"	80	1178	1098	122	1233	1111	
8	82 R	"	"	"	72	1202	1130	125	1227	1102	
9	U_2	42.7	"	"	109	1256	1147	202	1221	1019	
10	O_2	37.3	"	"	192	1247	1045	234	1216	982	

plainly by samples of Portland cement of American manufacture, but has not noticed it in natural cements. Table 18 gives the results of some tests on the effect of aëration on the time of

[1] "Notes on Concrete," by John Newman, p. 11.
[2] Trans. A. S. C. E., Vol. xxx, p. 12.

setting of five samples of natural cement from the same factory.

105. The **coarse particles** in a cement retard the setting because they are inert. Either fine grinding or sifting will doubtless hasten the rate of setting, but, as has been stated above, the detection of changes in the rate is difficult. Table 11, § 81, gives the results of a few tests on this subject.

106. Addition of Salts. — The time of setting of a cement is sometimes regulated at the factory by addition of sulphate of lime to the finished product. Such additions are admitted to the extent of two per cent. by the regulations of the Association of German Portland Cement Makers, and are now quite generally made by American Portland cement manufacturers. Table 19 gives the results of a few experiments on the effect of plaster of Paris on the time of setting of several cements.

TABLE 19

Effect of Plaster Paris on Time of Setting

Cement.		Water as Per Cent. of Cement and Plaster Paris.	Time to Bear ¼ lb. Wire, Minutes, with Plaster Paris as Certain Percentage of Cement and Plaster Paris.					Time to Bear 1 lb. Wire, Minutes, with Plaster Paris as Certain Percentage of Cement and Plaster Paris.				
Kind.	Brand.		0%	1%	2%	3%	6%	0%	1%	2%	3%	6%
Portland	S	24	232	477	460	425	40	498	917	910	860	832
"	R	24	95	375	381	358	75	345	745	776	778	750
"	X	26	4	258	287	268	84	305	625	725	668	694
Natural	Gn	34	38	106	107	86	42	543	414	527	671	632
"	An	34	93	179	302	295	93	193	439	592	725	698

It is seen that small percentages retard the initial setting in a marked degree, the maximum effect usually being given by 2 per cent. of the plaster. Larger percentages tend to make the cement quicker setting again, so that with 6 to 10 per cent. added, the cement may begin to set quicker than without the addition of plaster. The final set (time to bear one pound wire) does not appear to be thus hastened by large percentages. This might be considered to indicate that the hastening of the initial set is caused by plaster of Paris taking up the water from the cement and obtaining sufficient hardness to bear the light wire.

The probable explanation of the action of a small amount of sulphate of lime in retarding the setting is that suggested by M. Candlot,[1] namely, that the aluminate of lime, to which is due the initial setting, dissolves less readily in a solution of sulphate of lime than in pure water. If the aluminate does not commence to hydrate until the silicate of lime has set, the subsequent combination of the sulphate and aluminate may cause the mortar to disintegrate.

107. Solutions of **common salt** have been found to retard the setting, but when a large percentage of salt is used, it sometimes forms a crust on the top which may resist a light wire and thus make the paste appear to be quicker setting. **Sea water** generally retards the setting somewhat more than solutions of common salt, probably on account of the magnesian salts present, but M. Candlot says that cements to which sulphate of lime has been added set more rapidly when gaged with sea water than when gaged with fresh water.

The effect of **calcium chloride** on the setting of cements is entered into in detail in M. Candlot's treatise on "Cements and Hydraulic Limes," and may be summarized as follows: A weak solution of calcium chloride renders Portland cement slower setting because the aluminate of lime dissolves more slowly in such a solution than in pure water. On the other hand, the aluminate dissolves rapidly in a concentrated solution of calcium chloride, and therefore such a solution hastens the setting of Portland cement. Aluminous cements, *i.e.*, cements containing a very high percentage of alumina, are not appreciably affected by gaging with a comparatively weak solution of calcium chloride on account of the large excess of aluminate of lime present; and on the other hand, cements containing no alumina are not affected, as in such cements the hardening is due to the silicate of lime. A weak solution of the chloride hastens the hydration of the free lime, and therefore a cement which contains a dangerous percentage of the latter may be made sound by gaging with such a solution, as the lime may thus be hydrated before the cement sets. The chloride of calcium test for soundness is based on the supposition that the free lime may be hydrated by the action of the chloride soon after the setting of the cement, and thus the expansive action be hastened.

[1] *"Ciments et Chaux Hydrauliques," par E. Candlot.*

The effect of **sugar** on the time of setting does not seem to be well known, but it is said [1] that the presence of saccharine matter may either accelerate or retard the setting of the cement, depending on the amount of sugar present, the character of the cement and the amount of water used.

108. The **quantity of water** used in gaging has a most important influence on the test for time of setting, an increased quantity of water retarding the setting. This may be seen from Table 20.

TABLE 20

Effect of Consistency of Mortar on the Time of Setting

Cement								
Natural Cement.	Water as per cent. of cement by weight	26.7	28.6	30.8	33.3	36.4	40.0	
	Minutes to bear $\frac{1}{12}$ inch wire weighing $\frac{1}{4}$ pound.	20	23	30	42	46	55	...
	Minutes to bear $\frac{1}{24}$ inch wire weighing 1 pound	28	41	57	76	78	85	...
Portland Cement.	Water as per cent. of cement by weight	24	26	28	30	32	34	36
	Minutes to bear $\frac{1}{12}$ inch $\frac{1}{4}$ pound wire	2	2	3	7	21	28	38
	Minutes to bear $\frac{1}{24}$ inch 1 pound wire	160	188	279	289	371	403	583

As might be supposed, this influence varies with different samples, and M. H. LeChatelier [2] has given the following table which illustrates this point.

TABLE 21

Effect of Consistency of Mortar on Time of Setting

Cement.	Per Cent. Water.	Time Setting, Minutes.
Portland A	24	20
	34	85
Portland B	25	7
	35	45
Quick setting Vassy	50	5
	58	10

[1] "Masonry Construction," I. O. Baker, p. 98.

[2] "Tests of Hydr. Materials," p. 33.

109. It is necessary, then, in writing specifications and in making tests, where the time of setting is at all carefully considered, to note the consistency of the paste used in the test. Practically, it is preferable to use a paste rather thinner than that usually employed for briquets.

The consistency is sometimes defined by M. Vicat's apparatus of a rod 1 cm. in diameter, or by M. LeChatelier's modification of the same mentioned above, or by the requirement that it shall be at the point of ceasing to adhere to the trowel. Another definition is that it shall, when placed on a glass plate, flow toward the edges only on repeated jarring of the plate. This last is a very fair approximate method, though giving a rather thin paste.

That mortars set more slowly than neat cement paste is largely due to the increased amount of water present in the former, this excess of water being required to moisten the grains of sand. The relation between the time of setting of mortars and neat cement paste is not definite. M. Candlot found the time of setting of one-to-three mortars to be from two to twenty times as great as that of the paste of neat cement of normal composition.

110. The **temperature** of the cement and water also has an important bearing on the observed time of setting. As the temperature of the materials is increased, the time of setting diminishes in about the same proportion. The following table gives a few of the results obtained by M. Candlot[1] with Portland cements.

TABLE 22

Effect of Temperature of Materials on Time of Setting

	Temperature, Degrees C.	Time of Setting, Minutes.
Cement No. 1	6	60
	15	25
	25	4
Cement No. 2	7	350
	20	295
	30	190

Table 23 gives the results of similar tests made under the author's direction. The temperatures of cement and water

[1] *"Ciments et Chaux Hydrauliques,"* par *E. Candlot.*

were varied while the temperature of the room in which the tests were made remained nearly constant, or from 63° to 67° Fahr.

TABLE 23

Effect of Temperatures of Cement and Water on the Time of Setting of Paste

Temp. cement and water, Degrees, Fahr. . . .		40	50	60	70	80	90	100	110
Minutes to bear $\frac{1}{12}$ inch wire weighing ¼ pound.	Portland	270	247	225	196	175	158	135	. . .
	Natural	102	90	84	72	60	54	55	43

111. Amount of Gaging. — If a cement paste containing a moderate amount of water be insufficiently gaged, it will appear dry, when a more thorough working might make it plastic. Thus an insufficient gaging may make a cement appear quicker setting. It is also the case that when a cement is regaged after having begun to set, the second setting will take place more slowly; this, however, is a somewhat different matter.

112. The **temperature and character of the medium** in which the pat is kept during the setting process will have a decided influence on the rate of setting.

This is clearly shown by the following table, given by M.

TABLE 24

Time of Setting as Affected by Temperature of the Water and of the Medium in which Cement Sets

Sample.	Temperature		Time Required to			
	Of water at time of gaging.	Of air during setting.	Begin to set.		Set.	
	Degrees C.	Degrees C.	Hr.	Min.	Hr.	Min.
1	0	1	6	47	11	0
	16	16	0	20	2	23
2	0	1	5	30	8	8
	16	16	0	52	5	13
3	0	3	12	0	20	0
	15	15	0	43	3	3
4	0	3.5	0	24	1	3
	15	17	0	20	0	45

Paul Alexandre,[1] from which it appears that different samples are affected in very different degrees. It is seen that the higher the temperature, the more rapid the setting.

113. At temperatures below 32° F. (0° C.), setting seems to be entirely suspended. If a cement paste, which has been submitted to such low temperatures since gaging, is brought into a warm room, the setting process begins as though the mortar had just been gaged. It must not be concluded, however, that freezing has no evil effect on mortars. (See Art. 50.)

114. Setting in Air and Water. — A cement paste sets much quicker in air than in water. This is due to the percolation of water to the interior of the pat, when it is immersed as soon as made, being analogous to using an excess of water in gaging. When a pat sets in dry air, the evaporation of water from the surface hastens the hardening of that portion. If immersed directly after it has set in air, it re-softens, and this is also true of some briquets immersed when twenty-four hours old. The time of setting of cements that are to be deposited under water may well be tested in that medium, when they should be protected by a mold of some form to retain their shape. Ordinarily the time of setting should be tested in moist air.

Cements are said to set more quickly in compressed air than in free air; this may be partially due to the higher temperature usually existing in the former.

115. Requirements as to Time of Setting. — What is desirable as to time of setting will, of course, depend on the work in hand; certain purposes requiring that the cement shall be able to retain its shape soon after deposition, while in other cases ability to mix large quantities at a time, without fear of the cement setting before it is in place, may be very convenient. An extremely quick setting cement should be regarded with suspicion until it has proved itself of good quality. It is sometimes stated that where a quick setting mortar is desired, natural cement must be used, but this is not true; either Portland or natural may be found with almost any rate of setting desired. As a general rule, however, among cements that have been stored several months, the Portlands are slower setting.

[1] *"Recherches Experimentales sur les Mortiers Hydrauliques," par Paul Alexandre.*

Portland cement will ordinarily begin to set in from twenty minutes to six hours, and natural cement in from ten minutes to two hours, though there are many cements the time of setting of which is outside of these limits.

116. Conclusions. — The purpose aimed at in the test for time of setting will, to a certain extent, regulate the method to be employed. The pressure of the finger nail will be sufficient to determine (after a little experience) whether a cement will answer a certain purpose in this regard. But, if one is working to rigid specifications, or pursuing investigations as to the effect of different treatment on time of setting, it becomes very desirable to have a method of determining and defining the consistency of the mortar, and an accurate method of determining the rate of setting.

In the author's experience, the Vicat consistency apparatus as modified by M. LeChatelier (see § 99) has proved unsatisfactory except for thin pastes of neat cement or mortars containing less than two parts of sand. If the paste is not of such a consistency as to run freely into the ring, or "vase," an error may be introduced in the method of filling the latter. In operating with a natural cement it was found that a neat paste, in which the water used was 32 per cent. of the dry cement, required a gross weight of 640 grams to make the disc (1cm. diameter) penetrate midway in the vase; with 33 per cent. water, a weight of 410 grams was required; 34 per cent., about 250 grams; 35 per cent., 175 grams; 37 per cent., 155 grams. It would seem that some modification of this apparatus might be made which would not only indicate when a thin, neat cement paste has the assumed "normal" consistency, but which would also define the consistency of a given mortar, whether of neat cement or of sand mixture.

General Gilmore's wires are very simple, and will perhaps answer the purpose of obtaining the time of setting as well as any method in use. They can be used somewhat more accurately if the wires are made to slide vertically in a frame, than when held in the hand.

The necessity of care in all of the details of this test, temperature and amount of water, amount of gaging, character of medium, etc., has been sufficiently emphasized in the preceding paragraphs.

ART. 18. CONSTANCY OF VOLUME

117. That a cement should not contain within itself elements which may lead to its destruction, is evidently a most important quality. It is probable that nearly all cements undergo a slight change in volume during induration, contracting in air and expanding in water. But it is the detection of those larger changes, which result from bad proportions or defective manufacture, and which cause deterioration or even complete disintegration, that is the object of the tests for soundness.

118. Causes of Unsoundness. — The most frequent cause of unsoundness is considered to be the presence of free lime or magnesia. (See §§ 49 and 50.) Any one of the following causes may account for the presence of free lime in cement: (1) An excessive percentage of lime may have been used in proportioning the raw materials; (2) the raw materials may not have been sufficiently mixed to render the mass homogeneous; (3) hard particles of lime, such as shells, may not have been ground fine enough in making the mix to permit them to enter into combination with the other ingredients during burning; or (4) the cement may have been underburned, so that part of the lime did not enter into combination.

The particles of free lime which occur in cements are naturally rather difficult to slake on account of their impurity and the high temperature at which they have been calcined, and the same thing is probably true of magnesia. It may thus require weeks or months of exposure to the atmosphere to correct tendencies to expand due to the presence of free lime or magnesia. Likewise when such defective cements are immersed in water of ordinary temperature, the expansion may not occur for a considerable period. This fact has led to the use of hot tests of various kinds to detect such faults, but before touching on these so-called "accelerated tests," the ordinary cold-water test will be described.

119. TESTS FOR SOUNDNESS.— The Committee of the American Society of Civil Engineers on a "Uniform System for Tests of Cement" recommended, in 1885, the following test for soundness: "Make two cakes of neat cement two or three inches in diameter, about one-half inch thick, with thin edges. One of these cakes, when hard enough, should be put in water and examined from day to day to see if it becomes contorted, or if cracks show themselves at the edges, such contortions or cracks indicating that the cement is unfit for use at that time. In some cases the tendency to crack, if caused by the presence of too much unslaked lime, will disappear with age. The remaining cake should be kept in air and its color observed, which for a good cement should be uniform throughout, yellowish blotches indicating a poor quality; the Portland cements being of a bluish-gray, and the natural cements being light or dark, according to the character of the rock of which they are made." For the ordinary cold test this method will probably give as valuable results as any of the forms that are suggested.

120. The German regulations require a very similar test, except that in the case of slow setting cements the pat is not immersed until twenty-four hours old. While a cement that is decidedly bad may show its defects in from one day to one week by this cold water test, it may be the case that cracks will appear only after several months' immersion. It has therefore been proposed to hasten the destructive action of the free lime or magnesia by submitting the cakes of cement to steam, hot water, or dry heat.

121. The Kiln Test, recommended by Prof. Tetmajer in 1890, consists in placing in an air bath, pats which have been kept in moist air for twenty-four hours; and then gradually raising the temperature of the air bath to 120° C. This temperature is maintained for at least one-half hour after the disengagement of steam has ceased. The pats should show no tendency to expand under this treatment, but if cements fail to pass the test, the results of the ordinary cold water treatment are to be awaited. This test is intended for cements that are to be used in air.

122. The Boiling Test, which was also recommended by Prof. Tetmajer, consists in placing the pats, twenty-four hours after made, in water of ordinary temperature, and gradually heating the water to bring it to the boiling point in about an hour; five or six hours in the boiling water should develop no defects. This is a severe test, and has been objected to on the ground that cements which have been well proportioned, but which are a trifle underburned, will fail to pass this test while giving good results in mortars to be used in the air. This test, however, is steadily gaining in favor, and is used in many cement works as a test of quality.

123. The Warm Water Test. — Mr. H. Faija was an early experimenter in accelerated tests for soundness, and about 1882 he began the use of a "steamer," using a temperature of about 110° Fahr. After eleven years' use he still believed this temperature to be high enough to detect tendencies to expand in faulty cements. The apparatus[1] "consists of two vessels, one within the other, a water space being thus maintained between them, which assists in equalizing the temperature of the inner or working vessel." The latter is partially filled with water and is provided with a rack or shelf near the top. A thermometer is inserted through the cover of the inner vessel, and the water within is kept constantly at 110° Fahr. As soon as the pat is gaged, it is placed on the rack in the vapor, which will be at about 100° Fahr. After six or seven hours in this moist heat, the pat is immersed in the warm water. "In the course of twenty-four hours it is taken out and examined, and if then found to be quite hard and firmly attached to the glass, the cement may at once be pronounced sound and perfectly safe to use; if, however, the pat has come off the glass and shows cracks or friability on the edges, or is much curved on the under side, it may at once be decided that the cement in its present condition is not fit for use." Mr. Faija also recommended, in case of failure in the first test, that the cement be spread out in a thin layer for a few days and a second test made. If the cement passes this second test, it is pronounced sound and fit for use after being stored a sufficient length of time.

124. The Hot Water Test. — The temperature to be used in accelerated tests for soundness is a point which has received much attention and is still under discussion. In 1890 M. Deval described a series of experiments he had made, in which he employed a temperature of 80° C. While this is much more severe than the temperature used by Mr. Faija, it is still mild in comparison to some temperatures that have been advocated.

125. Mr. W. W. Maclay, who was probably the first engineer in this country to introduce a hot test requirement in

[1] "Portland Cement Testing," by H. Faija, Trans. A. S. C. E., Vol. xvii, p. 222.

specifications, gave the results of his experiments in a paper presented to the American Society of Civil Engineers in 1892. The method used "consists in molding six pats of pure cement and water, about one-half inch thick and about three inches in diameter, on thin glass plates, and of the same consistency as for the briquets for tensile strength." The treatment to which these pats are submitted is as follows: —

No. 1, in steam (vapor) bath, temperature 195° to 200° F., as soon as made.

No. 2, in same vapor bath when set hard (bear $\frac{1}{24}$ inch wire weighing one pound).

No. 3, ditto, after twice the length of time in air allowed the second pat.

No. 4, ditto, after 24 hours.

No. 5, in water of temperature about 60° F. when set hard.

No. 6, kept in moist air at temperature of about 60° F.

"The first four pats are each kept in the steam bath three hours, then immersed in water of a temperature of about 200° Fahr. for twenty-one hours each, when they are taken out and examined. To pass this test perfectly, all four pats, after being twenty-one hours in hot water, should, upon examination, show no swelling, cracks, nor distortions, and should adhere to the glass plates. The latter requirement, while it obtains with some cements nearly free from uncombined lime, is not insisted upon; the cracking, swelling and distortion of the pats being much the more important features of this test. The cracking or swelling of No. 1 pat alone can generally be disregarded."

126. Deval's Method. — Making tests of mortar briquets, which have been kept in hot water, seems to be the most rational accelerated test for soundness. This method was used in Germany several years ago, when it was claimed that a definite relation existed between the results thus obtained and the longer time cold water tests. This theory being disproved, threw discredit on the hot test, but M. Deval[1] has since made many experiments showing that it is of much value in detecting bad products.

The method consists in making briquets with three parts sand to one of cement, and after twenty-four to seventy-two

[1] "Hot Tests for Hydraulic Cements," M. Deval, *Bull. Soc. d'Encouragement*, etc., 1890, pp. 560–583.

hours in moist air, according to the rate of setting, immersing them in water maintained at 80° C., the briquets being broken after an immersion of from two to seven days. These hot water briquets are to be compared with briquets stored in water of the ordinary temperature and broken at seven and twenty-eight days after immersion.

127. Among other tests M. Deval compared the results obtained with six samples of Portland cement as follows: —

No. 1. Good finely ground cement of modern make.

No. 2. Coarsely ground cement of good quality, but partially aërated.

No. 3. Quick setting cement with low per cent. lime and lighter burn.

No. 4. Made from clinker having property of disintegrating spontaneously while cooling; large proportion of inert material.

No. 5. Under-burnt cement; contains free lime.

No. 6. Over-limed cement.

The results of the tests are given in the following table: —

TABLE 25

Cold and Hot Tests on Six Samples of Portland Cement (M. Deval)

Cement.	Tensile Strength in Kilos per Sq. Cm.			
	Cold.		Hot.	
	7 days.	28 days.	2 days.	7 days.
1	15.0	23.3	17.2	24.3
2	6.7	13.7	7.6	11.0
3	6.2	16.5	7.3	16.2
4	2.9	3.9	Disintegrated.	
5	6.1	12.2	Disintegrated.	
6	7.6	20.2	Disintegrated.	

No. 4, when allowed forty-eight hours to set, gave 3.2 kilos at two days, and 4.3 kilos at seven days, when tested hot. Among the cements which disintegrated in the hot water, the only one that gave a high result cold was No. 6, and this sample, it is stated, would crack and swell badly even in cold water if mixed neat. It is quite possible, however, that a sample might be found which, not having quite as flagrant defects as No. 6, would pass all the cold tests but be condemned by the hot test.

128. The conclusions drawn from these experiments have been stated as follows: —

"(1) Tests made cold do not indicate the quality of the cement, inasmuch as cement containing excess of lime, and, in consequence, deplorably bad, may give excellent results."

"(2) Portland cement of good quality, mixed with normal sand in the proportion of one to three, resists water at 80° C. Its strength at two and seven days after setting is about equal to that which it would have at seven and twenty-eight days in the cold."

"(3) Poor cement containing much inert material does not resist the action of water at 80° C. unless the setting be allowed to proceed for some days before immersion."

"(4) Cements containing free lime do not withstand the action of water at 80° C. if immersed twenty-four hours after setting." Comparison of the strength hot and cold will suffice for the detection of even small quantities of free lime.

129. Before passing to the comparison of the tests for soundness already outlined, a few other tests which have been suggested for use may be briefly mentioned.

The **Chloride of Calcium Test** depends on the fact that slaking of free lime is hastened by feeble solution of chloride of calcium. (See § 107.) Concerning this test, Prof. F. P. Spalding[1] says he "has found it to give true indications in a number of cases, including some unsound magnesian cements. It consists in mixing the mortar for the cakes with a solution of 40 grammes chloride of calcium to one liter of water, allowing them to set, immersing them in the same solution for twenty-four hours, and then examining them for checking and softening as in other tests."

130. M. H. LeChatelier's Method. — The method recommended by M. H. LeChatelier for testing soundness requires the use of a cylindrical mold, about 1¼ inches in diameter and of about the same height, which is made of thin metal and

[1] "Notes on the Testing and Use of Hydraulic Cement," by Fred. P. Spalding.

slit along a generatrix. The mortar is to be placed in the mold as soon as made, and immersed at once in cold water; the mold is held firmly by a clamp, and a flat plate at either end of the mold retains the mortar in shape until set. When setting has taken place, the mold is unclamped and the widening of the slit indicates the expansion of the mortar. If desired, the swelling may be increased and hastened by transferring the mold and its contents to hot water as soon as the cement is set. The same writer has suggested a modification of the hot test by placing briquets in cold water and gradually heating to near the boiling point, this temperature being maintained for six hours.

Various other tests have been suggested, such as the effect of regaging; withstanding immersion as soon as gaged; allowing large thin cakes to harden in air and striking them to obtain a musical sound. Most of these tests, however, are worthy of passing notice only.

131. Discussion. — There are but few experiments to show that a cement which will actually fail and disintegrate when properly used, may still pass the cold water neat pat test; yet there is no doubt that inferior cements may pass this test perfectly, "inferior cements" being those which will not give the best results in practice, though they do not disintegrate.

Cement is at present used in a very crude way, and it is only in exceptional cases that a poor quality of material may be detected in the completed structure. This is sufficient reason why so few failures can be found in cement work which may be attributed to a poor quality of cement. But in the more economical manner in which this material is, even now, beginning to be used, it is absolutely essential to know what its future behavior will be. That the cement will never be exposed to hot water in actual use, is a weak argument against hot water tests. It must be remembered that the chief object of testing cement is to arrange the various products in their true order of merit, and any system which will effect this result is perfectly legitimate. On the other hand, it is due to the manufacturers that a test which will occasionally reject perfect cements should not be adopted when it is possible in any other way to detect poor products with certainty.

132. It is possible that the temperature used and recommended by Mr. Faija is sufficiently high to detect unsoundness or a tendency to "blow." It has never been clearly proved that it is not, but the higher temperature of 70° to 100° C. has appeared to meet with greater favor. The writer made a few experiments to compare results obtained with mixtures of Portland cement and lime when using the temperature of 110° Fahr. (43° C.) with those obtained in water at 190° Fahr. (88° C.), and in water at the ordinary temperature of 60° to 65° Fahr. (16° to 18° C.). Quicklime, in proportions varying from one to ten per cent., was added to the cement, and seven pats were made from each mixture of cement and lime.

These pats were subjected to the following treatment:—

Pat No.	1,	placed in	vapor of	water at	110° F. when made.
"	2,	"	"	"	110° F. when set.
"	3,	"	"	"	110° F. after 24 hours.
"	4,	"	"	"	190° F. when made.
"	5,	"	"	"	190° F. when set.
"	6,	"	"	"	190° F. after 24 hours.

Above six pats immersed in the hot water after three hours in vapor.

Pat No. 7, placed in cool water when set.

When no lime was added, pats 1, 2 and 3 revealed no defects; pats 4 and 5 showed small cracks in two days, but pat No. 6 still adhered to the glass after eight days. Pat No. 7 was perfect after two months. With 2 per cent. lime added to the cement, pat No. 1 was slightly warped and cracked, and Nos. 2 and 3 were off glass; Nos. 4 and 5 were cracked and warped; No. 6 was off glass, and No. 7 became detached from glass after two months, but was otherwise perfect. With 4 per cent. lime, all the pats failed, the one in cool water being off glass, cracked and warped after one day.

It must be remembered that the free lime occurring in cement is of a different character from the quicklime added in these tests, because the former contains impurities and has been calcined at a very high temperature, and would therefore slake more slowly. It has been said that as small an amount as 1 per cent of free lime in cement is dangerous. If this is true, and it probably is, the temperature of 110° Fahr. would seem to be inadequate to quickly indicate a tendency to "blow."

133. Some of the results obtained by M. Deval have already been given (§ 127). Mr. Maclay made similar tests on several samples of Portland cement, using a temperature of 200° Fahr., but these tests only permit of comparing the strength acquired in cold water in seven and twenty-eight days with the strength in hot water at ages of from two to seven days. Long time tests, showing that the cements which give low results in hot water and normal results in cold water on short time tests, give in reality a low strength at the end of six months or more, have been almost entirely lacking until very recently.

Table 40, § 226, gives some of the results obtained by the author in hot tests and long time cold tests on Portland cement. It is seen that the hot test at 80° C. indicated, in seven days,

TABLE 26

Cold and Hot Tests on Samples of One Brand of Portland Cement

Cement.	Parts. Sand	Date Made. 1894.		Age.	Tensile Strength.	Briquets Stored.		
		Mo.	Da.			Moist air.	Water.	
B′	2	4	16	5 da.	8	1 da.	80° C.	4 da.
A	2	7	2	5 da.	235	1 "	"	4 "
B′	2	4	16	7 da.	13	1 "	"	6 "
A	2	7	2	7 da.	229	1 "	"	6 "
B	3	7	2	7 da.	197	1 "	15 to 18° C.	6 da.
A	3	7	2	7 da.	108	1 "	"	6 "
B	3	7	2	28 da.	298	1 "	"	27 "
A	3	7	2	28 da.	198	1 "	"	27 "
B′	2	4	16	7 mo.	411	1 "	"	7 mo.
A	2	7	2	6 mo.	465	1 "	"	6 "

Behavior of Pats Made July 2, 1894

No. 1 in vapor, when held ¼# wire. } Immersed in water 80° C. after three
No. 2 in vapor, when held 1# wire. } hours in vapor.
No. 3 in tank, when held 1# wire.
No. 4 in tank ; two hours after held 1# wire.

Cement: A, No. 1 off glass in two days; No. 2 warped some in two days.
" A, No. 3 O.K. after twenty-one days; off glass and warped in fifty-two days.
" A, No. 4 loose on glass in twenty-one days; off glass and warped in fifty-two days.
" B, No. 1 off glass and warped some in two days; No. 2 entirely disintegrated in two days; No. 3 loose on glass in twenty-one days; off glass and warped in fifty-two days; No. 4 loose on glass in twenty-one days; off glass and warped in fifty-two days.

the inferior quality of sample W, although it gave normal results in cold water up to twenty-eight days; the two year tests with mortars containing two parts or more sand, show it to be inferior. If we attempt to carry the analogy too far, however, we fall into the error which placed the hot test in disrepute for several years, that is, we must not expect that the strength in cold water after a long time will be exactly proportional to the strength developed in hot water in a few days.

134. In Table 26 are given the results of tests by the author, on samples of a single brand of Portland cement. The portion marked "A" had been spread out in open air for seventy-seven days in a thin layer. The portion marked "B" was taken directly from the barrel July 2d, and B′ was taken from the same barrel April 16th. Samples B and B′ are not identical, because the cement had undergone some change, though stored in the barrel. Each result is the mean of five briquets.

In the short time cold tests there was nothing to indicate that the cement directly from the barrel was not good, except the very small evidence in the fact that pat No. 3 was loose on glass plate after twenty-one days. In fact, the cold water briquet tests at seven and twenty-eight days unmistakably declare in favor of the sample B. On the other hand, how sharply did the hot tests bring out the defects, two days in hot water being sufficient to entirely disintegrate one of the pats. Although sample B′ showed a considerable tensile strength at seven months with two parts sand, yet the pats of neat cement failed, even in cold water, after two months, altogether too late a date to be of any value in preventing the use of the cement.

135. In a paper read before the American Society for Testing Materials, July, 1903,[1] Mr. W. P. Taylor of the City Testing Laboratory, Philadelphia, gives some very interesting data concerning the behavior of cements that failed to pass the boiling test. The method employed was to make cakes of cement in the form of a small egg, keep them in moist air for twenty-four hours, then place them in cold water which is gradually raised to the boiling point and maintained at that temperature for three hours. The results cited show that some unsound ce-

[1] Proceedings Amer. Soc. for Testing Materials, 1903.

ments may be much improved by sifting out the coarse particles, and that a cement failing in the boiling test when fresh may pass it satisfactorily after four or five weeks.

Examination of the results showed that 96 per cent. of a large number of specimens which did not pass the hot water test failed within three hours, and 99 per cent. in four hours. This fixes a practical limit to the time necessary to continue the test. Some very valuable tests are cited to show the ultimate failure in cold water of samples that failed in the hot tests. Ten cements which passed the cold water pat test of twenty-eight days' duration, but which failed in the boiling test above described, gave normal results in one-to-three mortars at twenty-eight days, showing a tensile strength of 217 to 252 pounds per square inch, but gave only 47 to 147 lbs. per square inch at four months.

Another valuable comparison is given by Mr. Taylor: A compilation of data, covering over a thousand tests on many varieties of cements, showed that "of those samples that failed in the boiling test but remained sound at twenty-eight days (in cold water), 3 per cent. of the normal pats showed checking or abnormal curvature in two months; 7 per cent. in three months; 10 per cent. in four months; 26 per cent. in six months and 48 per cent. in one year; and of these same samples, 37 per cent. showed a falling off in tensile strength in two months; 39 per cent. in three months; 52 per cent. in four months; 63 per cent. in six months and 71 per cent. in one year."

136. It may be of interest to introduce here some of the opinions that have been expressed concerning hot tests. M. Candlot[1] says that cements of normal composition, the burning of which has not been carried to the point of vitrification, would be condemned by the hot test of neat cement, although mortars made with them show no signs of alteration in sea water, and, when preserved in air, give entirely satisfactory results. Referring to the tests of one-to-three mortar briquets in water at 80° C., he considers that "cements containing free lime give in hot water, lower resistances than in cold water; cements of good quality give resistances at least equal and nearly always greater in hot water than in cold. Cements well proportioned

[1] *"Ciments et Chaux Hydrauliques," par M. Candlot,* pp. 144–145.

and homogeneous, but not having obtained the maximum burning, give satisfactory results with this test."

In using the slit cylinders mentioned in § 130, M. H. Le Chatelier found[1] that the addition of 5 per cent. of lime could be detected by cold tests in a few hours, while 5 per cent. of magnesia could not be detected in twenty-eight days. The cement containing 5 per cent. lime disintegrated almost at once in hot water, while the sample to which 5 per cent. of magnesia had been added, swelled considerably in one day.

Mr. A. Marichal[2] found that "the percentage of water entered in combination, after ten days in hot water, was the same as for six months in cold water, and that the strength of the cement was increasing with the amount of water entered in combination. It was discovered incidentally, that cement containing over 5 per cent. of magnesia, or 3 per cent. of uncombined lime, would not stand the boiling test."

137. Hot Tests for Natural Cements. — All that has preceded concerning hot tests refers to their use for testing Portland cements. Very little is known concerning the value of hot tests for natural cements. There are comparatively few natural cements that are absolutely bad, but to distinguish between the first and second quality of this variety of products is much more difficult than to make a similar distinction with Portlands. One point is certain, natural cements must not be expected to withstand boiling water. Mr. de Smedt experimented with fifteen brands of natural cement, and found that thirteen of them went to pieces in boiling water in two hours, although none of them was thought to contain caustic lime. Prof. Tetmajer has stated that for Roman cements, boiling water, or even 75° C., is not at all conclusive, and recommends 50° C. for trial, but our natural cements are not strictly comparable with Roman cements.

138. The author has experimented with three temperatures, namely, 50°, 60°, and 80° C., and is inclined to consider that 80° C. is likely to give the most useful information for sand mortar briquets but not for neat cement pastes. Table 41, § 227, gives the results of hot briquet tests on six brands of

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[1] "Tests Hydr. Materials," by H. LeChatelier.

[2] Trans. Amer. Soc. C. E., Vol. xxvii, p. 438.

natural cement. It is seen that, with two parts sand, brands Jn, Hn, and Bn, give very low results at 80° C., and these brands are really inferior cements as shown by the two-year cold tests. Brand Jn is the only one that gave a lower result at seven days than at five days when tested at 80° C., and this brand failed entirely at two years, though it gives normal results in cold water up to six months. Neat cement pats of this brand, after being stored in cold water for nearly one year, were found to be cracked, although they had been perfect after one month in cold water. It was also found that neat cement pats of this brand warped and cracked in two days when placed in water of 60° C. when set.

139. CONCLUSIONS. — It may be said that although the limits within which the hot tests are reliable have not been well established, and although a strict adherence to them may at times reject a usable product, yet it is believed that sufficient experiments have been made to indicate that they are of much value, and should be made in all cases where the quality of the cement is of high importance.

The present indications seem to be that Portland cements may well be tested in the form of neat cement pats and sand mortar briquets at a temperature of about 80° C. Natural cements in the form of neat paste should not be called upon to resist a temperature above 60° C., but 80° C. will probably give the most useful information with sand mortars. In either case, the mortar should be allowed to set in moist air of ordinary temperature, then transferred to the vapor, to remain two or three hours before immersion in the hot water. It is not recommended that these hot tests should replace the ordinary cold tests, but simply that in cases where the extra work involved is not prohibitive, the hot tests should be made in connection with the cold tests.

CHAPTER VIII

TESTS OF THE STRENGTH OF CEMENT IN COMPRESSION, ADHESION, ETC.

140. In testing the strength of cement the object is threefold: 1st, to obtain an idea of the strength that may be expected from the cement as used in the structure; 2d, to obtain a basis for comparing the value of different cements in this regard; and 3d, to determine the ability of the cement to withstand destructive agencies, whether these agencies be due to exterior causes or emanate from the character of the cement itself. To illustrate the last point it is only necessary to mention such destroying agents as free lime (interior) and frost (exterior). It is evident that the stronger the cement the more effectually will these agencies be resisted.

The strength of cement may be tested by compression, shearing, bending, adhesion, abrasion and tension. The tensile test is the one most frequently used, but the tests will be considered in the order named.

ART. 19. TESTS IN COMPRESSION AND SHEARING

141. Value of Test. — In practically all forms of masonry construction, cement is called upon to resist compression. In consequence of this fact, the opinion is somewhat general that the greatest amount of informatiôn would be obtained by compressive tests. But the compressive strength of cement is so much greater than its tensile strength, that when failures occur, they are likely to be due to other forms of stress. In short, the ratio of the compressive strength to the crushing force it is likely to be called upon to resist, is usually much greater than the corresponding ratio in tensile strength.

142. There is no doubt that compressive tests are of much interest and value, especially so since the use of concrete and steel in combination has become general, but as yet the facilities for making the test are not available without considerable expense. This is on account of the larger force required (the compressive strength being six to ten times the tensile) and because the uniform distribution of the stress over the surface of the specimen, and the accurate recording of the force exerted, are even more difficult than the corresponding operations in tensile tests. Prof. Sondericker,[1] in a paper read before the Boston Society of Civil Engineers, describes an apparatus in which he seems to have overcome a part of these difficulties.

A convenient specimen for compressive tests is a cube measuring two inches on a side. The specimens are prepared and treated in the same way as briquets for tensile tests. Before testing, two opposite faces of the cubes are usually ground so as to be true planes, parallel to each other, or the opposite sides may be faced with plaster of Paris, though this is not recommended. Grinding two surfaces to true planes increases very much the work involved in testing, so that several tensile tests may be made in the time required to make one compressive test.

143. Conclusions. — Although tests of compressive strength are of interest from a scientific point of view, it is not considered that they would give much greater information concerning the relative qualities of cements than is given by tensile tests, and therefore they need not be included in an ordinary series of acceptance tests.

144. Tests of Shearing Strength. — Although cement is frequently called upon to withstand a shearing stress, tests of this kind are very seldom made. Some of the difficulties encountered in compressive tests are also present in tests of shearing. Prof. Cecil B. Smith made quite an extended series of shearing tests by cementing together three bricks, the middle one projecting above the other two, and the pressure being so applied as to avoid any transverse stress. It is evident that by this method the adhesive strength is also brought into play. Shearing tests need not be included in normal tests of quality.

ART. 20. TESTS OF TRANSVERSE STRENGTH

145. It is probable that the earliest rupture tests of cement were made by submitting rectangular prisms to a bending stress; but such tests have long held a place subordinate to trials of tensile strength. A mass of masonry, taken as a whole, is very apt to be subjected to a bending stress, but it is a ques-

[1] Jour. Assoc. Engr. Soc., Vol. vii, p. 212.

tion whether a transverse test on a small specimen gives any better idea of the ability of a large beam to carry its load, than do simple tensile and compressive tests.

In *Engineering News* of December 14, 1893, appeared an article giving the comparative results obtained in tensile and transverse tests. The tensile specimens had an area of one square inch at the smallest place, and the transverse specimens also had an area of cross-section of one square inch. It was found that the modulus of rupture computed by the common formula $f = \frac{3\,W\,l}{2\,b\,d^2}$ was from 1.1 to 3.8 times the tensile strength developed by the briquets. Some comparative tests made at St. Mary's Falls Canal are discussed in Art. 56.

146. The objections to transverse tests are: 1st, if the specimens are made but one inch in cross-section, it is difficult to handle them without injuring them, and if the section is made much larger than one inch square, a much greater amount of cement is required to make the specimens and more room required to store them; 2d, it would seem that the results obtained might be less trustworthy than those in tensile tests because of the greater influence of the outside layers, which are subjected to the greatest accidental variations, on the apparent strength of the specimen. On the other hand, it may be said that, when no testing machine is at hand, the apparatus requisite to make a crude test may easily be improvised. All that is required is a rectangular wooden mold, three knife edges, and a pail with a quantity of sand or water.

147. When it is a question of making tests of transverse strength accurately and rapidly, the apparatus required is no more simple than the apparatus for tensile tests. In the construction of metal molds in large quantities it makes little difference whether the form requires curved or straight lines. As far as breaking is concerned, there is a certain force to be applied, and a machine that will answer for one test may also be used for the other. In the matter of clips, there may be a slight advantage as to simplicity in a clip designed for transverse breaking.

In making transverse tests the author has used a form two inches square and eight inches long. By placing the end supports five and one-third inches apart, the modulus of rupture by the formula $f = \frac{3Wl}{2bd^2}$ becomes equal to W, the center load applied.

148. Finally, it may be said that there is little objection to substituting transverse tests for tensile tests, although no evident advantage would be gained. It would also seem that there is no object in making tests for quality by both transverse and tensile tests, though from a scientific standpoint comparative tests of transverse and tensile strength are of great interest.

ART. 21. TESTS OF ADHESION AND ABRASION

149. ADHESION.—The test for adhesion is also one of long standing, being used during that time when engineers were content with an approximate idea of what might be expected of an hydraulic product. It has been stated above that when failure occurs in a mass of masonry, it is more frequently a failure in tension than in compression; it may be added, that it is also more likely to fail in adhesion than in cohesion. Hence, an adhesive test is a very proper one to make, and will give most valuable results. In fact, it is perhaps the most rational rupture test, and were it not for the difficulties involved in its application, it would doubtless come into general use.

150. One of the greatest difficulties experienced in making adhesive tests is the preparation of the specimens of stone or other material to which the mortar is to adhere. In early experiments common brick were used, or pieces of stone were cut to the same shape as brick, and two or more pieces cemented together. In later methods the flat surfaces of two specimens are sometimes joined with their axes at right angles, thus making the cemented surface square. The upper brick being held on two supports, a load is applied to the lower brick.

151. Mr. I. J. Mann, in a paper presented to the Institution of Civil Engineers,[1] described a method of testing adhesion in which are used test pieces $1\frac{1}{2}$ inches long by 1 inch wide by $\frac{1}{4}$ to $\frac{3}{8}$ inch thick. These are cemented together in a cruciform shape, and a simple spring balance machine with properly arranged levers pulls them apart. The upper block is supported at its ends and an inverted U-shaped piece bears upon the ends of

[1] Proc. Inst. C. E., Vol. lxxi, p. 251.

the lower block. The stress is applied through a conical shaped pivot bearing on the U-shaped saddle. Mr. Mann states that test pieces may be made either of plate glass or close grained limestone, the latter being sawn into pieces of the right size.

152. Another method is to make test pieces to fit one end of the mold used for tensile tests, and after placing the piece of stone in the mold, to fill the other end with the mortar to be tested. The objection to this method is the expense of preparing pieces of this form. It has been suggested to substitute artificial stone for the cut stone samples. Thus, suppose it is required to test the adhesion of a certain mortar to granite: mold half briquets of a mixture of ground granite with cement, and after these have well hardened, replace them in the mold and fill the other end of the mold with the mortar to be used. It is quite certain that the same result would not be obtained in this way as though the specimens were cut from a piece of solid granite.

153. One of the **simplest methods** of applying this test is one which the author has used for some time. The test pieces are in the form of flat plates one inch square and one-fourth inch or less in thickness. These plates being placed in the center of a briquet mold, the ends of the mold are filled with mortar. The plates may be improved by cutting shallow grooves in two opposite sides to make a more perfect fit with the sides of the mold. This may easily be done with a round file. Besides the simple form of the test pieces and consequent ease of making them, this method has the further advantage that a test may be made almost as readily and accurately as a tensile test of cohesion. Also, since the adhesive area is one square inch, the results may be compared with cohesive tests on specimens having the same area of cross-section.

154. The experiments on adhesive strength made by Mr. Mann were probably more extensive than any others published. His results are useful mainly as showing the lack of cementitious properties in the coarser grains of cement, and this point he proves very clearly by quite a large number of experiments. It was also developed that cement that had been rendered slow setting by aëration or "cooling" gave a lower adhesive strength than samples directly from the makers, which set more rapidly. But the method followed by Mr. Mann, of immersing the specimens as soon as cemented together, may have had something to do with this result; the quicker setting samples would earlier resist the injurious action which is likely to follow the immersion of such small quantities of mortar before they have set.

155. All of the things which influence the results in testing the cohesive strength must also be considered as affecting the adhesive test. The consistency of the mortar, the method of gaging, the pressure applied in cementing the specimens, and the conditions of storage until the time of breaking, will all have an influence on the result obtained. In addition to these, the character of the samples as to the kind of stone used, its structure, the physical condition of the surfaces, etc., must all be considered. It is therefore clear that many difficulties must be met before the test for adhesion can ever be included in standard tests.

156. Special tests directed toward ascertaining the comparative adhesion of cement to different varieties of stone, the effect of the various differences in manipulation, the comparative adhesion of mortars containing various proportions of sand, etc., are of undoubted value. But, before the adhesive test can be considered a normal one for cement, much of this experimental work will be required.

The results of a number of adhesive tests made under the author's direction are given in Art. 51.

157. TESTS OF ABRASION. — Abrasion tests of cement are not at all common, and for the ordinary uses to which cement is put, its resistance to such action is of little interest except as it may imply other kinds of strength. Occasionally, however, it may be desired to have a mortar which will withstand wear, as, for instance, in making concrete walk. In such cases, tests for resistance to abrasion have some interest and value.

The test is usually made on a sample prepared as for tensile or compressive tests, by submitting it to the wearing action of an emery or grindstone, or a cast iron disc covered with sand. The number of revolutions of the stone or disc is recorded, automatically if possible, and the loss of weight is determined after a given number of revolutions.

A few tests of this kind made at St. Mary's Falls Canal are given in Art. 58.

CHAPTER IX

TENSILE TESTS OF COHESION

158. THE testing of cement by applying tensile stress to a previously prepared briquet, containing definite proportions of cement and water, or of cement, sand and water, is the strength test which is now in most general use. The value of this method in comparison with that of other forms of rupture tests has already been briefly discussed.

That cement fails oftener in tension than in compression is one reason for preferring the tensile test. Its ready applicability is a still more important point in its favor.

ART. 22. SAND FOR TESTS

159. Whether the tensile test should be applied to neat cement briquets or to those prepared from sand mortars has been a disputed point, but there are now but few authorities who recommend the use of the neat test exclusively. When tests for soundness are not carefully made, the behavior of the cement in neat briquets gives, perhaps, a better idea as to the reliability of the cement than do sand tests, but otherwise the sand test is a better index of the value of the cement. The principal objection to the sand test is that the use of sand introduces another cause of variation in the results obtained by different experimenters. This objection has considerable weight, because it is impracticable to find sand in widely separated localities which is absolutely the same in composition and physical properties; but two cements which appear to be of equal value when tested neat may exhibit quite different characteristics when used with sand, and it is believed that this fact far outweighs the objection noted. As soon as regularity in sieves is established, the size of the sand grains may be regulated. The chemical and physical properties of the sand and the shape of the grains is a more difficult matter. The **crushed quartz** that is used in the manufacture of sandpaper was recommended by the Committee of the American Society of Civil Engineers of 1885, and if some care is taken to select that which is clean and made from pure quartz, there is little difficulty in obtaining a uniform product of this kind.

160. The **German Normal Sand** is obtained by washing and drying a natural quartz sand. In various parts of Germany sand answering the purpose may be found. Some tests made in this country to compare the "normal" German sand with American crushed quartz have shown the sand to give a somewhat higher strength, while other tests have shown an opposite result.[1] A few of these tests are given in Table 27.

TABLE 27

Results Obtained with German "Normal" and American "Standard" Sand in Three Laboratories

Sand.	Age. Days.	Strength of Mortar, 1 Cement, 3 Sand, Obtained at Laboratory Number 3	4	5
Normal	7	218	173	201
Standard	7	253	219	211
Normal	28	317	341	281
Standard	28	334	300	283
		Per Cent. of Water Used.		
Normal	. . .	8	9	. . .
Standard	. . .	9	10	. . .

Mr. Max Gary has stated that "the Russian standard sand gives markedly lower, and the Swiss sand considerably higher, strength than the German."

161. Tests with Natural Sand. — It is not to be concluded from what has preceded that one must make mortar tests with a "standard" sand only. On the contrary, one may obtain valuable results by using in tests the sand which it is proposed to use on the work. The only point to be insisted upon is that a cement shall not be rejected on account of the poor quality of the sand used in testing. It is thus very desirable that a certain proportion of the tests be made with a pure quartz sand, and by making parallel tests with the natural sands, the

[1] Article by Clifford Richardson, *Engineering Record*, Aug. 4, 1894.

coefficient of the latter may be obtained. In any case it is necessary, in order to obtain comparable results, to sift the sand used for tests.

162. Fineness of Sand for Tests. — The American practice in using crushed quartz is to reject the coarser particles by a sieve having 20 meshes per linear inch (holes about .03 inch square) and to reject the finer particles by a sieve of 30 meshes per linear inch (holes about .02 inch square). The size of grain of German normal sand is practically the same. In using a natural sand it is not necessary to use this size of grain, but it is better to do so, or at least to use some definite size or definite combination of sizes; as, for instance, one-half of 20 to 30 (passing holes .03 inch square and not passing holes .02 inch square) and one-half 30 to 50 (passing holes .02 inch square and failing to pass holes .012 inch square). Such a method will permit of duplicating a given size of grain at any time, while if the sand is used as it occurs in nature, considerable variations will be found. The effect of the quality of sand on the strength obtained is discussed in Chapter XI.

Art. 23. Making Briquets

163. Proportions. — The proportions of the ingredients should always be determined by weight rather than by measure. It will be found more convenient to use metric weights for the dry ingredients. The water should then be measured in cubic centimeters, which is equivalent to weighing it in grams. The proportion of sand to be used for mortar briquets will depend upon circumstances, but for short time (seven day) tests good results are not usually obtained with natural cement if more than two parts of sand by weight are added to one part of cement. Portland cement may be tested at seven days with three parts of sand to one of cement. If too large a proportion of sand is used, the briquets are liable to be injured in handling, and very low strengths are not as accurately recorded by the testing machine.

164. CONSISTENCY: DETERMINATION. — The consistency of the mortar has such a marked influence on the strength obtained that its importance can hardly be overestimated. The difficulties attendant upon specifying the consistency of a given mortar have already been touched upon in § 116. The Committee of the American Society of Civil Engineers of 1885 recommended the use of a "stiff plastic" mortar, but this phrase has had various interpretations.

The present Committee in its progress report[1] recommended the use of the Vicat apparatus: "In making the determination, 500 gr. (17.64 oz.) of cement are kneaded into a paste, and quickly formed into a ball with the hands, completing the operation by tossing it six times from one hand to the other, maintained six inches apart; the ball is then pressed into the rubber ring (§ 98) through the larger opening, smoothed off, and placed (on its large end) on a glass plate, and the smaller end smoothed off with a trowel; the paste, confined in the ring resting on the plate, is placed under the rod bearing the cylinder, which is brought in contact with the surface and quickly released. The paste is of normal consistency when the cylinder (1 cm. in diameter and loaded to weigh 300 grams) penetrates to a point in the mass 10 mm. (0.39 in.) below the top of the ring. Great care must be taken to fill the ring exactly to the top."

The following **simple test** taken from French specifications will determine a good consistency of mortar to use for briquets. It should be capable of being easily molded into a ball in the hands, and when dropped from a height of one and a half feet on a hard slab, this ball should retain its rounded form without cracking. The mortar should also leave the trowel clean when allowed to drop from it. Were a smaller quantity of water used, the mortar would be crumbly and the ball would crack when dropped on the slab, while a larger amount of water would cause the mortar to adhere to the trowel and the ball would be flattened by striking the slab.

165. Another method of determining the proper consistency, which the author believes will prove very satisfactory, is to make several batches of mortar containing the same weights of cement and sand, but having different percentages of water. As each batch is mixed, the volume of the resulting mortar is measured by pressing it lightly into a metal cylinder (a small tin pail will answer the purpose), taking pains to fill the cylinder in the same manner each time. That batch of mortar which

[1] Proc. Amer. Soc. C. E., Jan. 1903; also *Engineering News*, Jan. 29, 1903, and *Engineering Record*, Jan. 31, 1903.

occupies the least volume, when thus lightly packed, is the one in which the amount of water used is most nearly correct. Should either the mortar which contained the least water or that which contained the most water chance to have the least measured volume, then more trials must be made until such a consistency is obtained that either more or less water will increase the bulk of the mortar. This method will give a consistency somewhat more moist than that which gives the highest results on short time cohesive tests, but it is believed that where briquets are made by hand, more uniform results will be obtained when the mortar is a trifle moist. This method is not suited to daily use, as it requires too much time, but is valuable as a check on one's ideas of proper consistency.

166. EFFECT OF CONSISTENCY ON TENSILE STRENGTH.—Tables 28 and 29 give a few of the results obtained by the author

TABLE 28

Variations in Consistency of Mortar.—Effect on Tensile Strength, Neat Natural Cement

CEMENT.		AGE OF BRIQUETS.	TENSILE STRENGTH, POUNDS PER SQUARE INCH. WATER USED EXPRESSED AS PER CENT. OF DRY INGREDIENTS BY WEIGHT.				
Brand.	Sample.		25%	30%	35%	40%	45%
Gn	83 R	7 days	113*b*	205*d*	122*f*	72*g*	51*h*
Gn	84 R	"	92*b*	72*d*	58*f*	54*g*	39*h*
An	G	"	162*c*	165*e*	108*f*	75*g*	54*h*
An	N	"	152*b*	194*c*	204*e*	134*f*	79*g*
Hn	26 S	"	226*d*	176*f*	99*g*	56*h*	35*i*
Gn	83 R	28 days	189*b*	244*d*	211*f*	182*g*	135*h*
Gn	84 R	"	149*b*	168*d*	114*f*	107*g*	108*h*
An	G	"	210*c*	228*e*	165*f*	102*g*	80*h*
An	N	"	173*b*	286*c*	254*e*	208*f*	150*g*
Hn	26 S	"	333*d*	309*f*	217*g*	121*h*	89*i*
Ln	31 S	1 day	162*c*	148*e*	97*f*	63*g*	36*h*
Ln	"	7 days	178*c*	177*e*	124*f*	71*g*	45*h*
Ln	"	28 days	207*c*	257*e*	202*f*	140*g*	88*h*
Ln	"	3 mos.	300*c*	389*e*	333*f*	264*g*	197*h*

SIGNIFICANCE OF LETTERS

a — barely damp.
b — very dry; no moisture shown on surface briquets.
c — dry; slight moisture shown on surface briquets.
d — trifle dry.
e — about right consistency.
f — trifle moist.
g — moist.
h — very moist; would just hold shape.
i — extremely moist; would not hold shape.

in tests to determine the effect of consistency on the tensile strength of natural cement mortars. All of the briquets were made in the usual manner and stored in fresh water until time of breaking. Each result given is the mean of from two to ten briquets. The letters affixed to each result indicate the degree of moisture which the mortar appeared to have when mixed, varying from "a," barely damp, to "i," so wet that the mortar could not hold its shape when laid on a glass slab.

The results in Table 28 were obtained with neat cement mortars of several brands of natural cement. The first point to be noted is the variation in the amount of water required by different samples to give the same consistency; thus, Brand An, sample N, when mixed with 35 per cent. water, appeared to have about the same consistency as did sample G of the same brand mixed with 30 per cent. It is also apparent that the strength of all samples is not affected alike by given variations in the amount of water used in mixing; comparing the results obtained when 45 per cent. water is used with that given when 25 per cent. water is used, it is seen that at seven days the wet mortar gives 42 per cent. of the strength obtained with dry mortar for sample 84 R, Brand Gn, while with the sample of Brand Hn the strength of the wet mortar briquet is but 16 per cent. of that given by the dry mortar. Of the six samples tested at seven days and twenty-eight days, three gave the highest strength at seven days when mixed with 25 per cent. water, and five gave the highest strength at twenty-eight days when 30 per cent. water was used. The results on Brand Ln show the greater proportionate gain with age of the wet briquets.

Table 29 shows similar results for mortars made with one, two and three parts sand. With one part sand the wet mortar made from Gn, 21 R, which gave but 22 pounds per square inch at seven days, gave 429 pounds, or nearly the highest strength, at six months. A similar result is shown for sample 15 R of the same brand when mixed with two parts sand, the highest strength at one year and two years being given by the mortar containing the greatest per cent. of water. That mortars containing three parts sand to one cement may be more easily damaged by an excess of water, is indicated by the results on Brand Ln in this table.

167. The effect on the strength of Portland cement mortars,

TABLE 29. — Variations in Consistency of Mortar. Effect on Tensile Strength, Natural Cement Mortar; Sand, Crushed Quartz 20—30

Cement.		Parts Sand to One Cement by Weight.	Age of Briquets.	Tensile Strength, Pounds per Square Inch. Water Used Expressed as Per Cent. of Dry Ingredients by Weight.												
Brand.	Sample.			8.5	10 to 11.1	12.5	13 to 14	15 to 15.3	16.6	18	20 to 20.6	22	24.5	25	26	30
Gn	21 R	1	7 days.				58*b*			71*e*		38*h*			22*i*	
"	"	1	28 "				102*b*			170*e*		129*h*			76*i*	
"	"	1	3 mos.				210*b*			379*e*		354*h*			278*i*	
"	"	1	6 "				234*b*			416*e*		438*h*			429*i*	
Ln	31 S	1	7 days.		76*b*			151*c*			120*f*			58*h*		29*i*
"	"	1	28 "		109*b*			225*c*			232*f*			125*h*		79*i*
"	"	1	3 mos.		138*b*			322*c*			389*f*			322*h*		221*i*
"	"	1	6 "		190*b*			367*c*			458*f*			378*h*		245*i*
Gn	16 R	2	28 days.		100*b*		154*d*	120*e*		89*g*	63*h*					
"	"	2	6 mos.		230*b*		316*d*	363*e*		351*g*	283*h*					
"	"	2	1 year.		234*b*		347*d*	366*e*		354*g*	308*h*					
"	"	2	2 years.		249*b*		332*d*	399*e*		360*g*	317*h*					
Gn	15 R	2	28 days.			184*c*	186*d*	166*e*	139*g*	109*h*						
"	"	2	6 mos.			226*c*	260*d*	287*e*	313*g*	303*h*						
"	"	2	1 year.			190*c*	232*d*	288*e*	291*g*	323*h*						
"	"	2	2 years.			186*c*	220*d*	237*e*	265*g*	281*h*						
Ln	31 S	3	7 days.	62*b*		42*e*			22*f*		13*g*		3*h*			
"	"	3	28 "	108*b*		104*e*			84*f*		54*g*		36*h*			
"	"	3	3 mos.	148*b*		224*e*			176*f*		102*g*		78*h*			
"	"	3	6 "	160*b*		240*e*			218*f*		142*g*		75*h*			

NOTE: — For significance of letters following each result, see Table 28.

of variations in consistency, has been investigated by Mr. Eliot C. Clarke,[1] M. Am. Soc. C. E., and by M. Paul Alexandre,[2] Chief Engineer, Ponts et Chaussées. The results of one series of experiments made by M. Alexandre are given in Table 30. The mortars were mixed with fresh water and the samples immersed in sea water.

TABLE 30

Variations in Consistency of Mortar

EFFECT ON TENSILE STRENGTH, PORTLAND CEMENT MORTAR.

25 pounds cement to 1 cu. ft. sand (about 1 to 4 by weight).

Consistency.	Water Per Cent. of Sand.	Resistance, Lbs. per Sq. In. at Age of							
		3 Days.	7 Days.	28 Days.	3 Mos.	1 Year.	2 Years.	3 Years.	4 Years.
Dry	14	31	56	73	77	69	67	88	Disintegrated
Ordinary	22	25	46	74	116	153	170	162	190
Wet	30	16	35	55	89	126	136	180	189

From "*Recherches Experimentales sur Les Mortiers Hydrauliques,*" *par M. Paul Alexandre, Annales des Ponts et Chaussées*, Sept., 1890

It is seen that the highest strength at three days and seven days is given by the dryest mortar, at twenty-eight days to two years by that of the ordinary consistency, and at three years by that containing the highest per cent. of water. All of the samples exhibited white spots in the broken section at three years, and at four years the dry mortar briquets had lost their coherence on account of their porosity permitting the sea-water to permeate them.

168. Conclusions. — It may be concluded, then, that the consistency of the mortar has a very marked effect on the tensile strength obtained; that different samples of cement are not affected in the same degree by given variations in consistency; that the effect of consistency is usually shown most plainly in short time tests; and that while the dryer or stiffer mortars give the highest results on short time tests, the moist mortars attain a greater strength after a certain time.

[1] "Records of Tests of Cement made for Boston Main Drainage Works." Trans. A. S. C. E., Vol. xiv.

[2] *Annales des Ponts et Chaussées*, Sept., 1890.

169. Temperature of the Ingredients and of the Air where the Briquets are Made. — The temperature of the mortar and of the air in which the briquets are prepared is a matter of some moment. In 1877, Mr. Maclay [1] reported a series of experiments on Portland cements from which conclusions may be drawn concerning the effects of the temperature of the mortar. These experiments indicate that mortar having a temperature of 40° Fahr. when gaged, will attain greater strength in from seven days to three weeks than a mortar having an initial temperature of 70° Fahr. One is most likely to work somewhere between these two temperatures, but it may be mentioned that according to Mr. Maclay's experiments, it appears that mortars gaged at a temperature of 90° or 100° Fahr. also attain a higher strength than those gaged at 70° Fahr.

Similar experiments made by M. Candlot [2] indicate that mortars gaged with cold water give but feeble resistance at first, but in from two weeks to one month, such mortars surpass in strength those gaged with warm water. M. P. Alexandre [3] immersed some briquets at a temperature of about 90° C. (194° Fahr.) for forty-eight hours and then at 15° to 18° C. (60° to 65° Fahr.) until broken, while other briquets were maintained at the latter temperature from the time of molding. The briquets that were broken at the age of four days showed that the highest strength had been obtained by the briquets which had been kept hot for forty-eight hours, but at twenty-eight days and three months those briquets which had not been subjected to this high temperature gave the highest strength.

170. Table 31 gives a few of the many experiments on this point made under the author's direction. It appears that the briquets made in a low temperature (34° to 37° Fahr.) are usually stronger than those made in the ordinary temperature of 65° to 68° Fahr. In some cases the difference was not very great, and in some of the tests the briquets made in the ordinary temperature gave higher results at one day and seven days than those made in the cold; but at twenty-eight days the cold-made briquets were nearly always in the lead, and in many

[1] "Notes and Experiments on the Use and Testing of Portland Cement," Trans. A. S. C. E., Vol. vi, p. 311.

[2] "*Ciments et Chaux Hydrauliques.*"

[3] "*Les Mortiers Hydrauliques.*"

TABLE 31

Temperature of Materials and of Air where Made. Effect on Tensile Strength, Natural and Portland Cements

Cement.	Parts of Crushed Quartz 20-30 to One Cement by Weight.	Water Used, Per Cent. Dry Ingredients.	No. Hours in Air Where Made.	No. Hours in Damp Closet Warm Room.	Tensile Strength, Pounds per Square Inch. Age of Briquets When Broken. 1 Day. Warm.	1 Day. Cold.	3 Days. Warm.	3 Days. Cold.	7 Days. Warm.	7 Days. Cold.	28 Days. Warm.	28 Days. Cold.	3 Months. Warm.	3 Months. Cold.	6 Months. Warm.	6 Months. Cold.	1 Year. Warm	1 Year. Cold.
Natural, An 13 S	0	31.4	12	36*a*	162	152	...	...	167	220	210	254	240	363	...	...	...	...
" " "	0	31.4	24	24*b*	173	136	...	...	158	191	203	208	186	246	...	...	...	...
" Gn 21 R	1	18.7	3–5	19–21*c*	51	37	...	...	67	77	185	214	347	349	446	438	...	...
" " "	3	13.2	12	12	...	...	...	...	...	...	65	110	250	240	312	312	267	234
Portland, H 21 S	0	20.0	24	2	...	...	655	577	675	673	719	740	707	741	...	...	...	...
" " "	3	12.0	28	4	...	...	...	...	241	251	342	381	460	512	476	529	...	...

NOTES: — All briquets made by same molder; each result is mean of five to ten specimens.

Results in columns headed "warm," temperature of materials used and air where made = 65° to 67° Fahr.

Results in columns headed "cold," temperature of materials used and air where made = 34° to 37° Fahr.

a. In damp closet 36 hours, except 1 day specimens which were 12 hours in air where made and 12 hours in damp closet.

b. In damp closet 24 hours, except 1 day specimens which were 24 hours in air where made.

c. In damp closet 19 to 21 hours, except 1 day specimens which were 3 to 5 hours in air where made, 0 to 2½ hours in damp closet and 16½ to 21 hours in tank.

cases this difference held good at three months and six months. Some of the results indicated that if the briquets were allowed to remain twenty-four hours or more in the cold air, it tended to counteract the beneficial effects of cold molding, but this point was not satisfactorily established.

171. From the foregoing the following **conclusions** may be drawn: To make briquets of cold materials and allow them to remain some hours in cold air, retards the hardening of the briquets; but when briquets so treated are, after a few hours, placed in a medium of ordinary temperature, they gain strength more rapidly than briquets made of warm materials and kept continuously at the ordinary temperature of 60° to 70° Fahr. After being placed in a warmer medium, the briquets made with cold materials in cold air frequently gain strength at such a rate as to surpass in strength the warm-made briquets at seven days; the former almost invariably surpass the latter at twenty-eight days. In some cases it appears that this superiority of cold-made briquets is maintained up to six months, but in other cases the difference seems to disappear after three months.

Although these variations in temperature have not as marked an effect on tensile strength as have many other variations in manipulation, yet in carefully conducted experiments one should always operate in a constant temperature. As a matter of convenience, 65° to 70° Fahr. will commend itself, and this temperature may well be taken.

172. GAGING BY HAND. — The objects to be attained in gaging are to thoroughly incorporate the cement and sand, to evenly distribute the water throughout the mass, and, if possible, to give the mortar a certain tenacity resembling that of putty. This last object is not always possible of attainment with mortars containing a large dose of sand.

The ordinary method of preparing mortars in the laboratory is to gage with a trowel on a glass, slate, or marble slab. In gaging mortars, the cement and sand are first mixed dry; the materials are then drawn away from the center, leaving a crater to receive the water, which is all added at one time. The dry material is then gradually turned from the edges toward the center until all of the water is absorbed, after which the mass is thoroughly worked with the trowel in such a way as to rub the material between the trowel and plate until the consistency is uniform throughout. A batch of mortar sufficient for five briquets cannot usually be properly gaged by this method in less than five minutes.

The Committee of the American Society of Civil Engineers, in their preliminary report on methods of manipulation, suggested that "as soon as the water has been absorbed, which should not require more than one minute," the mortar should be kneaded with the hands for one and one-half minutes, the process being similar to that used in kneading dough.

173. **HOE AND BOX METHOD.** — Mr. Alfred Noble used for many years a form of gaging apparatus, consisting of a box with sloping bottom, in which the mortar is worked by means of a hoe. The author has used an iron box made on this principle (Fig. 2), which has given excellent results. The box is 2 feet 7½ inches long, 6 inches wide at the bottom, and at the

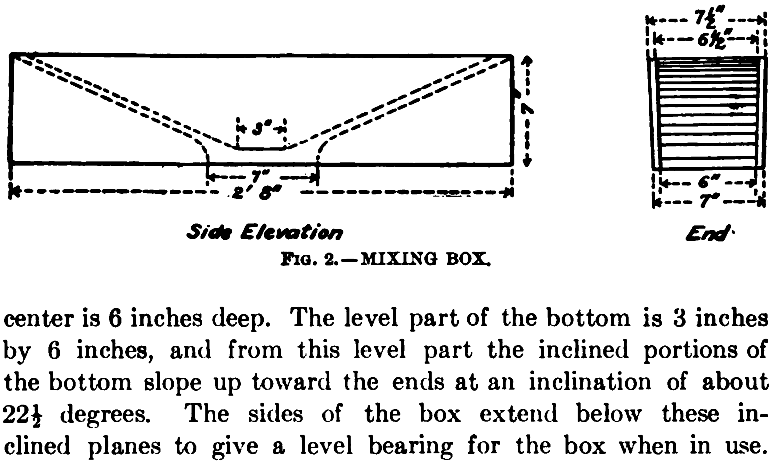

FIG. 2.—MIXING BOX.

center is 6 inches deep. The level part of the bottom is 3 inches by 6 inches, and from this level part the inclined portions of the bottom slope up toward the ends at an inclination of about 22½ degrees. The sides of the box extend below these inclined planes to give a level bearing for the box when in use. It is also well to have the sides flare enough to give a width of 6½ inches at the top to prevent the hoe from becoming wedged. A "German clod hoe," which is strong and heavy, yet a trifle flexible in the blade, is used in connection with the box.

The weighed quantities of the dry ingredients being put in the box and well mixed, the measured volume of water is added. Two minutes of hard work, in which the operator may put all his strength, is sufficient to bring the mass to plasticity if the amount of water added is correct. A return to the trowel and slab method of mixing is not likely after a trial of this simple device.

174. Machine for Mortar Mixing. — As the mixing by hand is a rather slow and tedious method, and the hoe and box method are not very generally known, several machines have been devised to do the work. None of them, however, has given such satisfactory results as to bring it into general use.

One of the machines is called a "jig," or "milk shake" machine,[1] and consists of a cup which moves rapidly up and down, this motion being imparted by means of a hand wheel, crank and connecting rod. The dry cement and water being placed in the cup and tightly covered, a few rapid turns of the wheel are sufficient to reduce the cement to a paste. This form is only applicable to neat cement mortars, and has been said to give unsatisfactory results even for these, though in some laboratories this machine has been used for all neat mortars.

Other forms have been made in which the mortar is thoroughly stirred by means of forks or blades projecting into the mortar from a horizontal arm above. The gager devised by Mr. Faija is constructed on this principle, and similar machines may be obtained from manufacturers of testing apparatus.

175. Steinbrüch's Mortar Mixer is a German machine operating on a different principle. It consists of a circular shell having on its upper side and near its outer edge a circular groove, or trough, to receive the mortar to be mixed. In this trough rests a wheel on a fixed horizontal axis, which is above the pan and normal to the axis of the pan. A cross-section of the rim of the wheel is a semicircle fitting the groove in the pan. The gearing is such that the pan is made to revolve about its vertical axis, and the wheel about its horizontal axis, the inner surface of the trough and the under side of the periphery of the wheel where the two are in contact moving in the same direction at a given instant. The mortar is thus rubbed between the two. Small blades, or plows, scrape the sides of the trough as the latter revolves, thus keeping the mortar in the bottom of the trough. The wheel and the plows are mounted on hinged axes, or supports, so that they may be raised from the pan when the mortar

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[1] S. Bent Russell, *Engineering News*, Jan. 3, 1891.

is to be cleaned out. The mixing requires about two and one-half minutes. The price of the machine is about $130.

176. The amount of gaging which a mortar receives has an important effect on its consistency and the strength it will attain. This was found to be the case in several experiments where mortar gaged eight minutes in the box described above, gave from 15 to 35 per cent. greater strength at one year than that which was gaged but two minutes, the amount of water used being the same in the two cases. Experiments on this point are given in Table 78, § 364. It is therefore important to eliminate, if possible, the variations which must follow hand mixing, but as yet no apparatus has seemed to meet with general approval, though among machine mixers those similar to that used by Mr. Faija seem to have given the best results. The hoe and box method described in § 173 partially eliminates the personal equation, and for facility of operation and thoroughness of mixing leaves little to be desired.

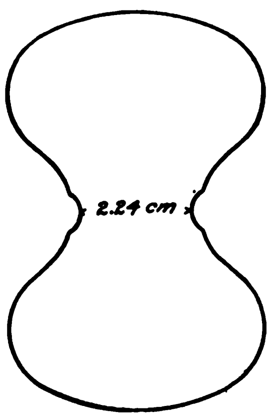

FIG. 3. — FORM OF BRIQUET USED ON THE CONTINENT OF EUROPE.

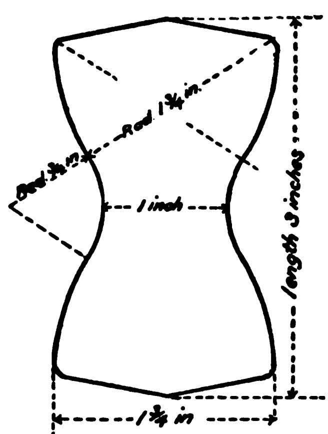

FIG. 4. — FORM OF BRIQUET USED IN THE UNITED STATES.

177. FORM OF BRIQUET. — The shape and size of the briquet have been the subject of much discussion and experiment. Mr. John Grant, a pioneer in tensile tests, tried many forms before finally adopting one quite similar to the form afterward recommended by the Committee of the Amer. Soc. C. E. in 1885. Mr. Alfred Noble also made a series of experiments on different styles of molds and clips, and presented the results in a paper read before the American Society of Civil Engineers.[1]

There are two forms of mold that are now in quite general use. On the continent of Europe the form most generally used is that shown in Fig. 3. It has a cross-sectional area of five square centimeters (.775 sq. in.) at the smallest place, and the heads of the briquet are elliptical in form, the major axes being transverse to the briquet axis. The curve forming the side of the briquet in the central portion is of very short radius, giving the effect of a semicircular notch on either side of the briquet at the smallest section. These notches have the effect of confining the break to this place.

The other form of mold is the one mentioned above as recommended by the Amer. Soc. C. E. Committee, and used in America and England. A briquet of this form is shown in Fig. 4. The cross-sectional area at the center is one square inch, and the increase of section toward the ends is gradual, the radius of the curve at the side of the briquet being $\frac{3}{4}$ inch.

178. Area of the Breaking Section. — Formerly a section of $2\frac{1}{4}$ square inches was more commonly used here and in England, while an area of 16 square centimeters (2.48 sq. in.) was common in France and other continental countries. The larger the area of the breaking section, the smaller will be the computed strength per square inch; this point seems fairly well established, although the experiments recorded in a very excellent paper by Mr. Eliot C. Clarke[2] indicate no apparent difference in strength between briquets 1 square inch and $2\frac{1}{4}$ square inches in section.

M. Durand-Claye found that the tensile strength of a briquet varied more nearly as the perimeter than as the area of the section. The experiments of M. Candlot do not point to this conclusion, though they clearly show that the indicated strength per square centimeter is very much greater for a briquet having an area of five square centimeters at the small section than for a briquet of 16 square centimeters area.

Mr. D. J. Whittemore[3] experimented with briquets that were

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[1] Trans. Amer. Soc. C. E., Vol. ix, p. 186.

[2] Trans. Amer. Soc. C. E., Vol. xiv, p. 141.

[3] "Tensile Tests of Cements," etc. Trans. A. S. C. E., Vol. ix, p. 329.

circular in cross-section. He found that while the ultimate strength of a briquet was about proportional to the periphery of the breaking section for the ordinary solid briquet, yet if a core were inserted in the mold, giving the cross-section an annular form, this proportion was not maintained. It was concluded from this that the apparent peripheric strength could not be explained by saying that the surface of the briquet had gained a greater strength than the interior, but that the explanation must rather be sought in the method of applying the stress in breaking the briquet. The force being communicated to the surface of the briquet, the stress is not uniformly distributed throughout the breaking section, because of the low elasticity of the mortar.

M. Paul Alexandre showed that the difference in strength per unit area decreased with age, although it did not entirely disappear at one year. It would therefore seem that the explanation of this phenomenon may be found in a combination of these two causes; more rapid hardening of the smaller specimens, and greater inequality of stress in breaking the briquets of larger section.

179. Form of Briquet Suggested. — As a result of experiments which will be described under the head of "Clips,"[1] (Art. 25) the following conclusions were drawn as to the desirable features for a briquet:

1st. The smallest section should not have an area much less than one square inch. Probably an area of five square centimeters would represent a minimum.

2d. The area of the section of the briquet between opposite gripping points should be about one and three-fourths times the area of the smallest section.

3d. The distribution of stress over the smallest section should be as nearly uniform as possible.

4th. The curve of the sides at the breaking section should not be very sharp; one-half inch might be taken as a minimum radius.

5th. The area of the vertical section from the gripping point to the plane of the end of the briquet — the section subjected

[1] These experiments were described by the writer in detail in "*Municipal Engineering*," Dec., 1896, Jan. and Feb. 1897.

to shear when the stress is applied — should be nearly as great as the area of the neck of the briquet.

6th. The face and back of the briquet should be parallel planes, to permit of easy storage.

7th. The total volume should be kept as small as is consistent with the other conditions.

Fig. 5 represents a form of briquet which will, it is thought, satisfactorily fulfill the above requirements, and in which it is believed the full strength of the smallest section may be more nearly developed than with present forms. The curve at the central section has a radius of one inch, and the line of the side of the briquet is continued in a tangent one-half inch in length, having an inclination of nearly 45 degrees with the axis of the briquet. The total length of the briquet is four inches, the ends being formed by straight lines tangent to the curves forming the corners. If the clip is so formed that the gripping points bear at the centers of the one-half inch tangents forming the sides of the briquet, the distance between opposite gripping points will be 1¾ inches.

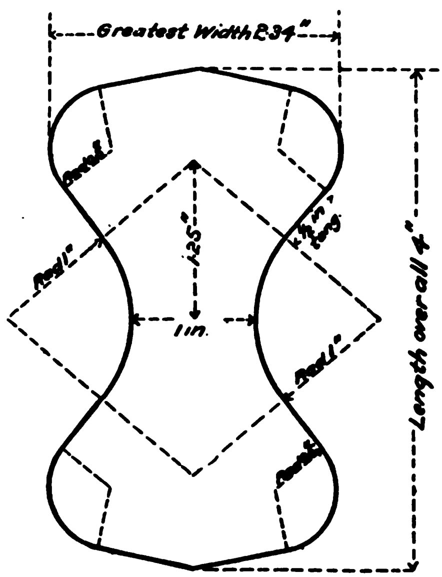

FIG. 5.—FORM OF BRIQUET SUGGESTED FOR USE

180. Comparison with other Forms. — Comparing this briquet with the forms in common use, the German and the form shown in Fig. 5 both have an area between opposite gripping points about 1¾ times the area of the smallest section, but in the form shown in Fig. 4 this ratio is too small to fulfill the second specification.

The unequal distribution of stress over the breaking section of the briquet has already been mentioned as a probable partial cause why briquets of small cross-section show a greater strength per unit area than those having a larger area of cross-section. In Johnson's "Materials of Engineering" is given the theory of the distribution of stress over the breaking section of a briquet, as developed by M. Durand-Claye, and published in *Annales des Ponts et Chaussées* of June, 1895. Applying the formulas there given to three styles of briquet, the A. S. C. E. form of 1885, the German standard, and the form shown in Fig. 5, it is found that the ratios of the maximum stress to the mean stress are, for the three forms respectively, 1.54, 1.52 and 1.22. From a theoretical point of view, this means that with a total pull of 100 pounds on each briquet, the outer fiber of the briquet shown in Fig. 4 would be subjected to a stress of 154 pounds per square inch, while with the form suggested above, the stress on the outer fiber would be but 122 pounds per square inch ; briquets of the latter form should, therefore, theoretically, show a breaking strength 1.27 times the strength given by briquets of the same mortar made in the A. S. C. E. form of 1885.

The German form has too sharp a curve at the sides to fulfill the fourth requirement given above. All of the forms comply with the first, fifth and sixth requirements.

As to the volume of the briquet, the author's form having a total length of four inches, has about 50 per cent. greater volume than the A. S. C. E. form of 1885.

181. MOLDS. — In the early tests of cement, wooden molds were employed, but they absorb water from the mortar and soon warp out of shape. Iron molds have also been used to a considerable extent, but these are apt to become rusted if not in constant use. Brass, bronze or some similar metal not easily corroded should be used, and molds of this character can be obtained of dealers in testing apparatus.

The molds may be made single, or in "nests" or "gangs" of three to five. The two halves of the mold may be entirely separable, or may be hinged at one end and fastened by a clip at the other end. The gang molds are somewhat cheaper than the single ones. The hinged molds and those held with patent clip are rather difficult to clean, while the gang molds, if made heavy enough to prevent spreading, are unwieldy, and briquets are removed from them with greater difficulty than from the single molds. It is considered, therefore, that the most convenient form is the single mold, in which the two halves are held together by a screw clamp of simple design.

182. To clean these molds, place ten in a row with clamps removed; scrape the upper faces with a piece of zinc, brush with a stiff "horse-brush," and wipe with oily waste. Turn them over and repeat the process. Then separate the two halves of each mold, place the twenty halves in line with inner surfaces up, forming a trough twenty inches long. Wipe this trough thoroughly with oily waste, finishing with some that is only slightly oiled.

183. MOLDING. — Methods of molding briquets vary widely and have a considerable effect on the results obtained by different operators. The mold may be placed on a glass or marble slab, or on a porous bed. This difference in treatment will affect the results chiefly because a porous bed will extract moisture from the briquet, and, unless it is already mixed very dry, will make it give a higher result on a short time test. The use of a porous bed probably originated with a desire to more closely imitate the use of mortar in actual work, but it introduces another source of variation in results and should not be followed.

184. In hand work the whole mold may be filled at once, or small amounts of mortar may be added at a time, and each layer packed; the mortar may be tamped into the mold with a rod, in which case the pressure used may vary widely; or the mortar may be pressed in with the fingers, or with the point of a small trowel; and, finally, the pressure applied on the top of the whole briquet may be light or heavy. It is evident that it is almost impossible to so describe all these details of manipulation that another operator may follow the same system and obtain the same results. The practice of ramming the mortar into the mold by means of a metal rod or a stick faced with zinc is objectionable, because of the possible wide variation in the force thus applied. This method is sometimes used by manufacturers, since by making the mortar quite dry and ramming it into the molds very hard, a high initial strength is obtained. But the foremost cement makers are now eschewing such methods and are aiming to make fair tests. Some experiments made under the author's direction indicate that the pressure applied to the top of the briquet is the salient point in the process of molding, and that the other details are of minor importance.

In Germany a heavy trowel or iron plate weighing about 250 grams, and provided with a handle, is used in making one-to-three mortar briquets. The mortar is made rather dry (about 10 per cent. water), and after the mold is filled and heaped, the mortar is beaten with the trowel until it becomes elastic, and water appears on the surface. The excess of mortar is then scraped off with an ordinary trowel or spatula.

185. Several **machines** have been devised for making briquets, some of which are said to give good results. Among these the most prominent is the Böhme hammer apparatus, which is much used in Germany, although not employed to any extent in the United States. It consists of a plunger which fits the mold and upon which a given number of blows are struck by a hammer. The mortar is first gaged as for hand molding, and placed in the form. A pinion, turned by a hand crank, is geared to a wheel provided with ten cams. These cams operating on the wrought iron handle of the hammer cause a certain number of blows to be delivered to the plunger. The mechanism is automatically shut off after the proper number of blows has been delivered. The following results were obtained by Professor Böhme with his apparatus: —

TABLE 32

Comparison of Hand Made Briquets with Those Made by Böhme Hammer

No.	Method.	Weight of Briquets.	Mean Tensile Strength at 7 Days in Kgs. per Sq. Cm.
1	By hand	160.0	16.06
2	Hammer, 75 blows	158.0	12.75
3	" 100 "	159.5	13.25
4	" 125 "	159.5	14.56
5	" 150 "	159.0	15.56

186. Several American engineers have devised machines for briquet-making, but none of them has been generally adopted.

An apparatus designed by Prof. Charles Jameson, of Iowa University, is said to work very rapidly. The mortar is packed in the mold by a plunger of the form of the briquet. This plunger works in a chamber of the same shape as the briquet mold. The mortar is placed in a hopper at the side of this chamber, and is delivered to the mold automatically when the plunger is raised. The force is applied to the plunger by hand, but it should be so arranged that this be done by a weight, to prevent variations in pressure. In this method the briquet is removed from the mold as soon as made, and this would appear to be an objectionable feature.

Professor Spalding, of Cornell University, in his excellent little book on "Hydraulic Cement," states that he has found that "a pressure of about 500 pounds upon the surface of the briquet is sufficient to produce a compact and homogeneous briquet, and a crude appliance consisting of a lever arranged to bring a pressure upon the mortar in the mold by means of a weight suspended at the end of the lever, has been found to increase both the rapidity and the regularity of the work, and especially to diminish the variations in results obtained by different men."

A machine which would give more uniform results and work more rapidly than hand molding, would commend itself for general use.

187. Method Recommended. — In making briquets by hand, the mortar may well be packed into the molds by the fingers, which should be protected by rubber tips. When the mold is filled and slightly heaped, the trowel should be placed on top, and the molder put about 60 pounds pressure on the trowel. The excess mortar is then cut off by the trowel and the top of the briquet is smoothed by drawing the trowel across the face. The results obtained by four molders using this method in the same laboratory are given in Table 33.

188. The recent progress report of the Committee of the American Society of Civil Engineers on uniform tests of cement contains the following, under "Molding": —

"Having worked the paste or mortar to the proper consistency, it is at once placed in the molds by hand.

"The Committee has been unable to secure satisfactory results with the present molding machines; the operation of machine-molding is very slow, and the present types permit of molding but one briquet at a time, and are not practicable with the pastes or mortars herein recommended.

TABLE 33

Results Obtained by Different Molders when Using Similar Mortar

Reference.	Sand-Parts to One Cement.	Water (63° to 66°F.) Per Cent Dry Ingredients.	Temperature of Air where Gaged.	Age.	Mean Tensile Strength. Molder N.	Molder M.	Molder T.	Number Averaged for Each Molder	Date.	Weather.
	a	b	c	d	e	f	g	h	i	
1[1]	0	31.6	62–65	7 days	81	92	89	5	10–22	Clear
2	0	"	"	28 "	197	213	220	5	"	
3	1	18.7	67–62	7 "	79	91	89	5	"	
4	1	"	"	28 "	235	257	259	5	"	
5	1	"	63–68	3 mo.	515	541	519	5	"	
6	1	"	"	1 year	558	569	555	5	"	
7	2	15.2	70–65	28 days	196	186	197	5	"	
8	2	"	"	3 mo.	423	383	406	5	"	
9	3	13.3	65–61	3 mo.	253	263	239	5	"	
10	3	"	"	1 year	260	232	236	5	"	
11	Sum of Means				2797	2827	2809			
						Molder S.	Molder T.			
12	0	31.6	62–65	7 days	. .	60	60	5	10–28	Cloudy
13	0	"	"	28 "	. .	145	167	5	"	
14	1	18.7	65	7 "	. .	67	71	5	"	
15	1	"	"	28 "	. .	223	211	5	"	
16	1	"	"	3 mo.	. .	435	449	5	"	
17	1	"	"	1 year	. .	504	491	5	"	
18	2	15 2	67	28 days	. .	182	179	5	"	
19	Sum of Means				. .	1616	1628			

Cement, Brand Gn, Sample 21 R. Sand, Crushed Quartz 20 to 40.

All briquets in same line received same treatment after made and were immersed in same tank until broken.

[1] Mean of ten specimens.

"Method. The molds should be filled at once, the material pressed in firmly with the fingers and smoothed off with a trowel without ramming; the material should be heaped up on the upper surface of the mold, and, in smoothing off, the trowel should be drawn over the mold in such a manner as to exert a moderate pressure on the excess material. The mold should be turned over and the operation repeated.

"A check upon the uniformity of the mixing and molding is afforded by weighing the briquets just prior to immersion, or upon removal from the moist closet. Briquets which vary in weight more than 3 per cent. from the average should not be tested."

189. Marking the Briquets. — The briquets made in a given laboratory should be numbered consecutively, so that no confusion can arise, and this one number is all that should be placed on the briquet. The record of the brand of cement, the proportions used, etc., should be placed in a book opposite the briquet number. The briquets should be numbered on the face, near the end. Steel stamps furnish a ready means of numbering, and when mortar contains more than two parts of sand to one of cement a thin strip of neat cement paste plastered across one end of the briquet will aid in making the numbers legible.

ART. 24. STORING BRIQUETS

190. The Time in Air before Immersion. — As soon as the briquets are molded they should be covered with a damp cloth

TABLE 34

Variations in Length of Time Briquets are Left in Moist Air before Immersion — Natural Cement

Cement.		Parts Crushed Quartz, 20-30° to 1 Cement.	Age When Broken.	Tensile Strength, Pounds per Sq. Inch. Hours in Moist Air before Immersion.					
Brand.	Sample.			8	12	24	48	72	168
Gn	15 R	0	7 days	123	...	139	151	161	237
"	"	1	7 days	91	...	106	114	114	182
"	16 R	0	28 days	110	...	106	109	89	113
"	"	1	28 days	142	...	138	139	152	175
"	"	2	28 days	102	...	105	112	113	115
An	G	0	7 days	...	168	181	194	185	238
"	"	0	28 days	...	200	210	224	241	243
"	"	1	7 days	...	108	137	141	157	160
"	"	1	28 days	...	278	283	297	297	301
"	"	3	28 days	...	120	130	137	139	152

NOTE: — All briquets made by same molder. Each result is mean of ten specimens.

until they are ready to be removed from the molds, when they should be transferred to a "damp closet," lined with zinc or other non-corroding metal. It was formerly the practice to immerse the briquets as soon as they were considered to be sufficiently set; but for the sake of uniformity, they are now left in moist air for twenty-four hours before immersion, whether the cement is quick or slow setting. Briquets which are to be broken at twenty-four hours, however, are usually immersed as soon as set hard.

Table 34 gives the results obtained by allowing natural cement briquets to remain in moist air different lengths of time before immersion. In general, the strength is greater for seven and twenty-eight day tests the longer the briquets are allowed to remain in the moist air. It appears that, while the time in moist air should be made as nearly uniform as possible, a variation of a few hours will not cause an important difference in strength.

TABLE 35

Gain or Loss in Strength of Natural Cement Briquets by Immersion

Time in Moist Air.	Time in Tank.	Age When Broken.	Tensile Strength, Pounds per Sq. Inch.	
			Neat Cement.	One Part Standard Sand to One Cement.
20 hours	....	20 hours	151	94
18 hours	6¼ days	7 days	147	153
2 days	....	2 days	192	126
2 days	5 days	7 days	160	158
3 days	....	3 days	205	141
3 days	4 days	7 days	177	155
4 days	....	4 days	218	165
4 days	3 days	7 days	191	165
5 days	....	5 days	230	175
5 days	2 days	7 days	192	169

NOTE: — All briquets made by same molder. Each result is mean of five specimens.

Table 35 shows the early action of the water on the briquets. These tests were made in sets of ten; five briquets of a set were immersed after twenty hours, forty-eight hours, etc., while the other five of the same set were broken at the time the first five were immersed. With this sample of natural cement, it appears that the briquets lose part of their strength by immersion, and that some time is required to regain this lost strength. Thus, with neat cement mortar the briquets broken at twenty hours without immersion were as strong as those broken at seven days which had been immersed the last six and one-fourth days. With briquets of one-to-one mortar, it appears that if immersed at the end of four days, the gain in strength during the last three days (in water) is about equal to the loss of strength due to immersion. If immersed earlier than this, the gain is greater than the loss, but if immersed later, the loss is greater than the gain.

191. For storing briquets the required twenty-four hours before immersion a **moist closet** is very convenient, tends to promote uniformity of treatment, and may be very easily made. The use of a damp cloth for covering briquets is inconvenient, as the cloth may dry out. If it is used, the end of the cloth should rest in a pail of water, so it will keep wet by capillarity; it should also be kept from touching the briquets by a wire screen or by wooden slats.

A moist closet may be made of slate, glass or soapstone, or of wood lined with metal. In the bottom of the box is a pan of water, or a sponge kept constantly wet. The shelves may well be of glass, and should be so arranged that any shelf may be removed without disturbing the others.

192. Water of Immersion. — When the briquets are ready to be immersed, *i.e.*, usually, twenty-four hours after made, they are placed in a tank, containing water that is kept fresh by frequent renewals. The water in the tank should also be maintained at a nearly constant temperature. It is sometimes the case that briquets are subjected to considerable variations of temperature while in storage. It also frequently occurs that the water is allowed to become stale. A few of the many experiments made at St. Marys Falls Canal to show the effect, on the tensile strength of natural cement briquets, of variations in the temperature of the water of immersion, are given in Table 36. The details of these experiments, as well as other tests on the same point, may be found in the Annual Report, Chief of Engineers, U. S. A., for 1894, page 2314.

The very marked effect which the temperature of the water may have on the rate of hardening of natural cements is clearly shown. When broken at the age of one day or seven days, the effect on the strength may not be evident, or the briquets stored in cold water may develop a greater strength, but the more rapid hardening of the briquets stored in warm water is usually very evident at twenty-eight days, and increases up to two or three months. Some samples of cement are affected less than others, and a few experiments indicated that the differences in strength due to the temperature of water of immersion decrease after three months and become almost nil at one year.

193. The **conclusion** drawn from these tests may be briefly stated as follows: Between certain limits the early strength of natural cement mortars is usually developed faster in cool

TABLE 36

Variations in Temperature of Water in which Briquets are Immersed

Reference No.	Natural Cement.		Parts Standard Sand to One Cement, by Weight.	Age of Briquets.	Tensile Strength, Pounds per Square Inch, When Immersed in Water of Approximate Temperature, Degrees Fahr.							
	Brand.	Sample.			38°	40°	50°	55°	60°	65°	70°	80°
1	Gn	15 R	0	7 days	146	...	137	125	...	...	126	154
2	"	"	0	14 days	144	...	131	125	131	150	168	208
3	"	"	0	28 days	166	...	178	...	184	...	247	280
4	"	"	1	7 days	83	...	88	84	89	98	97	121
5	"	"	1	14 days	84	...	111	...	123	...	150	191
6	"	"	1	28 days	96	...	156	187	...	221	243	288
7	Ln	31 S	0	1 day	...	143	...	124	120	...	109	109
8	"	"	0	7 days	...	204	201	...	183	...	193	186
9	"	"	0	14 days	...	184	203	...	204	...	229	245
10	"	"	0	28 days	...	221	245	...	254	...	281	303
11	"	"	0	2 mos.	...	261	292	...	348	...	382	429
12	An	G	1	7 days	...	134	140	...	150	...	154	158
13	"	"	1	14 days	...	149	162	...	189	...	182	216
14	"	"	1	28 days	...	198	223	...	250	...	281	296
15	"	"	1	2 mos.	...	251	286	...	337	...	386	403
16	"	"	3	14 days	...	50	58	...	69	...	73	100
17	"	"	3	28 days	...	67	87	...	100	...	102	157
18	"	"	3	2 mos.	...	104	127	...	147	...	194	231

water, but after the first seven days, and sometimes after a shorter time, the strength is developed more rapidly in warm water, and the strength at any time between seven days and three months is approximately proportional to the temperature. After three months, the effect of the temperature seems to diminish, and may entirely disappear in time.

M. Paul Alexandre[1] made quite a number of experiments on this point with Portland cement. In these experiments the

[1] "*Recherches Experimentales sur les Mortiers Hydrauliques.*"

gaging was done in about the same temperature as that at which the water of immersion was maintained, so that a double cause of variation was present. However, it was found that in all cases the higher strength was attained at seven days by the briquets made and stored in the higher temperature (15° to 18° C., 60° to 65° Fahr.) while at twenty-eight days the briquets of the lower temperature (0° to 5° C., 32° to 40° Fahr.) were ahead in the case of neat cement, and nearly as high as the warm briquets in the case of mortar. At three months the differences seemed to disappear.

194. Stale Water. — Some experiments made to compare the strength of briquets which were alike in all other respects, but were immersed in different tanks in which the water had not been frequently renewed, showed very clearly the possible variations from this source. Natural cement briquets, neat, and with one and two parts sand, gave, when immersed in one of the tanks, only from 40 to 60 per cent. of the strength attained in another tank by briquets entirely similar.

To store briquets in running water is going to the other extreme; this appears to be the best method, at least for short-time acceptance tests, provided the temperature can be regulated. However, in some cases where this has been adopted, the strength of the briquets is said to have fallen off very much after four or five years. Whether this is due to the action of running water is a very interesting point, and a valuable one from the practical standpoint of the use of cement, but it has not yet been thoroughly investigated.

195. It appears from the foregoing that variations in the temperature and freshness of the water in which the briquets are immersed is an uncertain contingent, and therefore that all such variations should be carefully avoided. As a matter of convenience, the tanks may well be maintained at 60° to 70° Fahr., but if one does not care for a comparison of his results with those obtained in other laboratories, then any other constant temperature between 40° and 75° may be adopted. The water in the tanks should be renewed at least once a month, and preferably once a week.

196. Storing Briquets in Sea Water. — When the cement under test is to be used for constructions in the sea, some of the briquets should be stored in sea water to indicate the behavior in this medium. Many tests have been made in this way by several experimenters, but the varied results obtained only indicate the different effects of such treatment on different samples of cement. One of the effects of storing in sea water has been touched upon under the head of consistency of mortar, where it is shown that porous briquets may disintegrate in this medium. A small specimen like a briquet will of course be more quickly affected than a large mass of concrete, but on the other hand, the concrete in work is likely to be more porous than the briquet. The effect of sea water upon cement will be taken up in another place.

197. Other Methods of Storing Briquets. — It has been thought that briquets, made to test cement that is to be used in air, should be hardened in the same medium in order that the tests should more nearly approach the conditions of use. Several points, however, should be borne in mind in interpreting the results obtained with air-hardened specimens. In actual work the mortar is usually in a large mass, or is protected from the influence of a warm, dry atmosphere, so that it remains moist for a long time, whereas a briquet placed in the open air is much more affected by changes in atmospheric conditions. If the briquets are allowed to harden in a room, such a small quantity of mortar may become quite dry in a few days, and, unless the amount of moisture in the air is regulated, another source of variation is introduced in the tests.

It has been found impossible to obtain uniform results from briquets made as nearly alike as possible and stored side by side in the air of the laboratory. The regular acceptance tests should, therefore, it is thought, be made in the ordinary manner, but if cement is to be used in locations where it is likely to become very dry, a few special tests should be made to assure one that the brand of cement in question is one that will yield good results in such exposure. It may be found that certain kinds or brands should be entirely avoided for use in such locations. A few tests of this character are given in Tables 72 and 73, §§ 359, 360. The results in any given line of the table are from briquets made the same way but treated differently in the method of storing. It is seen that these brands harden well in dry air. The effect of the amount of water used in gaging appears to follow somewhat the same law, whether the briquets are stored in air or water.

A method more nearly approaching conditions that frequently prevail in practice is to bury the briquets in damp sand. Table 120, §409, gives the results obtained with a large number of briquets stored in this way. While the results are somewhat more irregular than those for water-hardened specimens, since the conditions cannot be made so nearly uniform, yet this method gives better results than dry air storage.

ART. 25. BREAKING THE BRIQUETS

198. THE TESTING MACHINE. — The function of the testing machine is simply to furnish a means of applying the tensile stress, and of measuring the amount of force required to break the briquet. Aside from the clips, which hold the briquet, any contrivance which may be conveniently operated, and which will accurately measure the force applied, may be used for this purpose.

There are several forms of testing machines on the market, all designed on the lever principle, though differing slightly in the method of application. The force is applied either by allowing water or shot to run into or out of a vessel suspended at the end of the longer arm of a lever, or a weight is made to run along the lever arm, which is graduated so that the force applied may be read from the beam.

199. In machines of the first class the delivery of shot is cut off automatically the instant the briquet breaks. The advantage of this style is that the flow of shot may be so adjusted as to approximately regulate the rate of applying the stress; but little skill is required to operate it, and, since in its best form two levers are used, the shorter arm of one acting on the longer arm of the other, the machine occupies but little space. This machine does not permit rapid operation, since the shot must be weighed each time a briquet is broken. One of the main disadvantages of this form has been that in the case of strong briquets, a certain initial strain had to be applied in order that the stretch of the briquet and the slipping of the clips should not allow the shot to be cut off before the briquet broke. This objection, however, has recently been met by the makers, who have provided means of taking up this slip by a hand crank.

200. Another objection urged against the short-lever shot machines is the fact that as the stream of shot flowing into the scale pan is cut off by the breaking of the briquet, a certain amount of shot on its way to the pan falls into the pan after the briquet breaks, and is weighed, although not acting on the briquet at the time of the break. A form of shot machine is now on the market, however, in which this objection has been overcome. The load is applied by means of a weight hanging from one end of a lever. This weight is at first counterbalanced by a pail of shot at the other end of the lever, but as the shot is allowed to run out of the vessel, the unbalanced portion of the weight acts, through suitable levers, upon the briquet. The flow of shot is shut off automatically by the breaking of the briquet, and the shot that has escaped is weighed on a special scale to determine the load acting on the briquet.

201. In the other form of machine the weight is made to move along the arm by means of a cord and hand-wheel. This style may be operated much more rapidly, but some skill is required to use it properly, and as now made it occupies too much space. These machines are preferable for laboratories, while the shot machines may well be used in cement factories and small works where a foreman does the testing.

202. It would seem that a machine could easily be made which would combine the desirable features of both of these forms, by placing a heavy weight provided with rollers upon the upper lever arm of the shot machine, and using it in the same way that the hand power machine is now used. This would involve placing a hand wheel and cord upon the machine to operate the moving weight, the shot attachment being removed. Such a machine would combine the compactness of the shot machine, with the accuracy and speed of the single lever machine; the graduations on the beam could represent five pounds each, instead of two pounds, the value of the graduations now on the single lever machines.

203. FORMS OF CLIP. — Since cement has been tested by tensile strain, it has ever been a problem to obtain a clip which would give a perfectly true axial pull on the briquet. Various forms of clips have been used from time to time, but none of them has proved satisfactory in all respects. To trace the history of the development of the clip is not warranted by its interest, but it may be said that in some of the early forms the head of the briquet was held between two plates and clamped tight enough to develop sufficient friction to transmit the stress. The later forms of briquets are made with a shoulder or with wedge-shaped ends to allow the clip to grasp them. Mr. John Grant, Mr. Alfred Noble, General Gilmore, Mr. J. Sondericker and Mr. D. J. Whittemore have each designed or adapted different forms, and more recently Mr. S. Bent Russell and Mr.

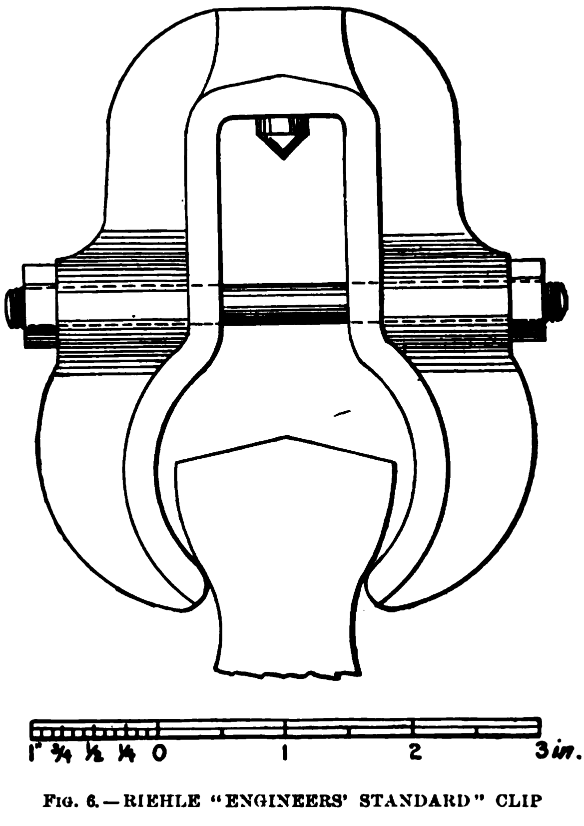

FIG. 6.—RIEHLE "ENGINEERS' STANDARD" CLIP

W. R. Cock have each devised a clip which will be mentioned below.

204. Form in Most General Use. — The clip in most general use in the United States is of the general style shown in Fig. 6. It differs only in detail from the form recommended by the Amer. Soc. C. E. Committee of 1885, which has been called the "Engineers' Standard." The general form is pear shaped; the briquet is grasped at the points of reverse curve at the side of the briquet, giving an area between opposite gripping points of about one and a quarter square inches. The gripping points are rather too sharp, when new, as they have a tendency to crush the briquet locally. The width of the bearing increases with the amount of wear the clip sustains. The clip is provided with a conical pivot, which rests in a cone-shaped cavity attached to the machine, so that the two parts of the clip are free to swing. In a form which was previously used to a considerable extent, each bearing surface was designed to be about an inch square, the jaw being made to conform to the outline of the briquet. This form, however, did not give satisfactory results; a particle of sand between the briquet and the bearing surface of the clip would give an eccentric pull, and strong briquets would sometimes break in the head of the briquet transverse to the axis, in several curved layers joining opposite gripping surfaces.

205. CLIP-BREAKS. — When a briquet is inserted in the ordinary clip, the gripping points will not, in general, grasp the briquet symmetrically. The gripping points have a tendency to slide on the surface of the briquet in order to assume a symmetrical position; there is friction to resist this sliding, and when this resistance overcomes the tendency to motion, the two clips and the briquet become a rigid system, and bending strains may be introduced. Again, if the briquet is not too badly adjusted in the clips, it is apt to break in a line joining two opposite gripping points, instead of at the smallest section; this is called a "clip-break." The tendency to form clip-breaks is greater if the gripping points are very narrow or have sharp edges; neat cement briquets exhibit this tendency much more than briquets from sand mortars, and some samples of cement are much more likely to give clip-breaks than others.

206. Cause of Clip-breaks. — When a briquet breaks in this manner, the broken section is usually about normal to the side of the briquet at the point where the jaw was in contact. This indicates that a clip-break is caused by compression at that place; there is evidently compression along the plane joining the two opposite gripping points, and tension at right angles to that plane, and the briquet fails here as a result of the two stresses. If the briquet is not properly adjusted in the clips, but is so placed that its longest axis is at one side of the line joining the points of application of the forces (in the "Engineers' Standard" clip, the line joining the pivot points), then the bending strain that is introduced is greatest at the central section of the briquet; this may cause the briquet to break at the smallest section, when if it were properly adjusted in the clips it would develop a clip-break. The bearing surfaces of the clip should not be too small, as this increases the intensity of pressure, but on the other hand there appears to be no practical advantage in making this area more than $\frac{3}{16}$ to $\frac{1}{4}$ inch wide (the length being limited by the thickness of the briquet, one inch).

207. Prevention of Clip-breaks. — The method most frequently adopted to prevent clip-breaks is to cushion the gripping points with some compressible material, such as thin rubber or blotting-paper. This device prevents clip-breaks, but the result of about three hundred tests made under the author's direction showed clearly that it also lowered the apparent strength very materially.[1] Briquets broken with the bare clips showed a mean strength of 606 pounds per square inch, while the cushioned clips gave an apparent strength of but 521 pounds, or 86 per cent. of the strength without the cushion; of the briquets broken with the bare clips, 33 per cent. were clip-breaks; with the cushioned clips no clip-breaks occurred. The rubber was applied by slipping two rubber bands over each end of the briquet, giving cushions about $\frac{1}{16}$ inch thick.

208. Strength of Briquets that Develop Clip-breaks. — It was also found in breaking 277 briquets with two styles of clips without cushions that 129 of them that gave clip-breaks averaged 611 pounds per square inch, while 148 which did not develop clip-breaks had a mean strength of 590 pounds. This result is easily accounted for by saying that some of the briquets that broke in the small section were made to do so by the cross-strain introduced by imperfect adjustment in the clips.

When a briquet breaks at other than the smallest section, it is certain that the smallest section has a greater strength per

[1] For a report of these tests in detail, see Annual Report Chief of Engineers, U. S. A., 1895, p. 2913. Also "*Municipal Engineering*," Dec., 1896, Jan., Feb., 1897.

square inch than is shown by the result obtained; how much greater cannot be told. But it follows that if clip-breaks could be eliminated in a proper way, one which would not cause center breaks by the introduction of cross-strains or other undesirable conditions, the strengths thus obtained would be greater than when clip-breaks occur. The fact that the use of a rubber cushion gives lower strengths, shows that this is not the proper method of preventing clip-breaks.

209. Mr. **W. R. Cock** has devised a clip, with rubber-covered gripping points, which has attracted some attention. It has

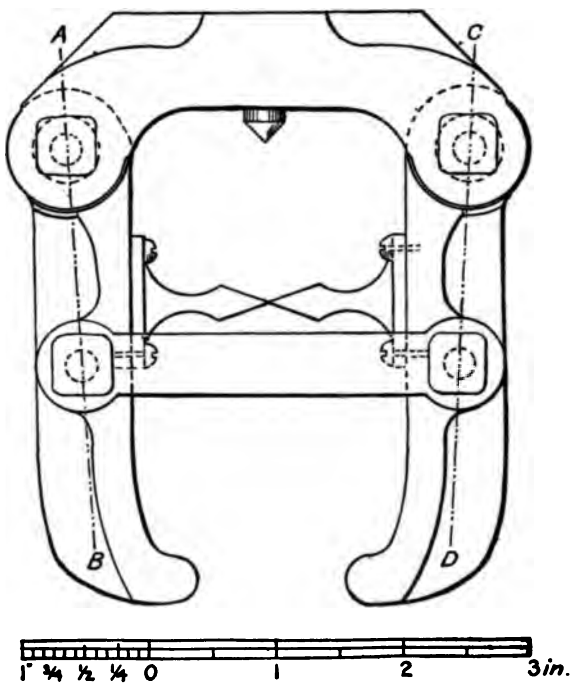

FIG. 7.—RUSSELL CLIP

sometimes been assumed that because this clip eliminated clip-breaks it must give a higher apparent strength than the rigid form. No extensive series of experiments have been published which permit of comparing this clip with other forms, but from the results obtained above, in using rubber cushions, it would appear that the Cock clip may give lower apparent strengths.

210. The form of clip designed by Mr. **S. Bent Russell** is constructed on the "evener" principle, each clip having freedom of motion imparted by four pin-connected joints (see Fig. 7). It is sought to prevent any but an axial pull being applied to the briquet. On account of details of construction, into which it is not necessary to enter here, the clip must be in its normal position when the briquet is inserted, in order that the possibility of cross-strain shall be effectually removed. As a result of many tests with this form and the ordinary "En-

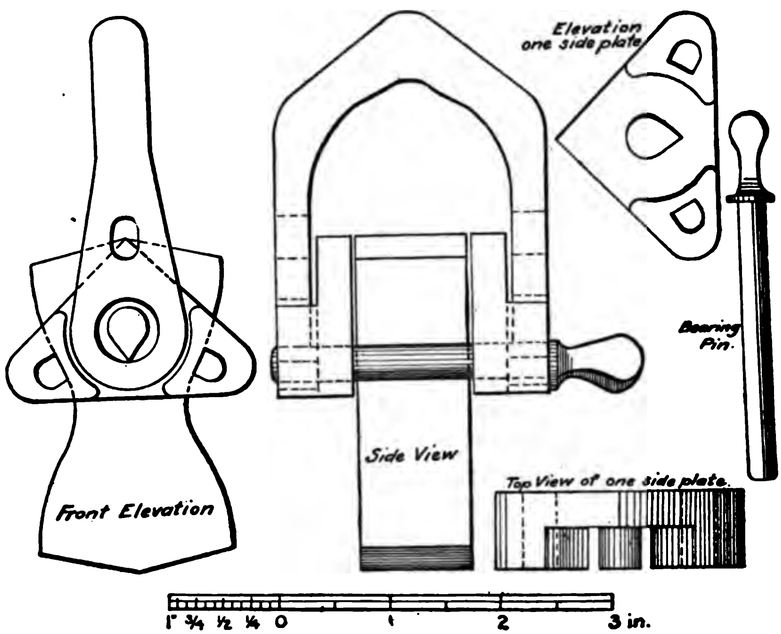

FIG. 8.—SINGLE GIMBAL CLIP

gineers' Standard," it was found that they gave very nearly the same strength. But that the evener motion itself was of some value was shown by a series of experiments in which part of the briquets were broken by this form of clip without modification, while part were broken by the same clip when it had been changed to a rigid form by means of a clamp that eliminated the evener motion. It is believed that with some modifications this clip will give good results, and it may be used almost as rapidly as the ordinary rigid form.

211. Several experiments were made with a clip in which the gimbal principle was applied, the stress passing from the machine to the gripping points through knife edges placed in the line joining opposite gripping points and midway between them[1] (Fig. 8). Higher results were obtained with this form, the "**Single Gimbal,**" than with any of the styles with which it was compared, but it was made only for experimental purposes, and unless modified is not convenient enough to be recommended for general use.

212. In the course of these experiments it was shown that to increase the distance between gripping points, grasping the briquet nearer the head, increased the apparent strength and diminished the number of clip-breaks. With the Russell clip, increasing this distance from $1\frac{3}{16}$ inches to $1\frac{7}{16}$ inches gave an increase of about six per cent. in the apparent strength; and a similar increase in the width between jaws of the Gimbal clip, from $1\frac{3}{16}$ to $1\frac{6}{16}$ inches, gave an increase in apparent strength of about five per cent. It was found later that Mr. J. Sondericker had previously arrived at similar results,[2] and as the form of briquet used by the latter had permitted extending the experiment, he found that when the points were about $1\frac{3}{4}$ inches apart (making the area of the briquet about $1\frac{3}{4}$ square inches between opposite gripping points), nearly all the fractures occurred at the smallest section.

213. Effect of Improper Adjustment. — The effect of not properly adjusting the briquets in the clip was also investigated. In some cases the briquets were placed in the proper position as nearly as possible. In the other cases they were in a decidedly distorted position, much worse than they would be placed with the most careless manipulation. It was found that if the briquet was so placed in the "Engineers' Standard" clip that the gripping points on one side of the briquet were farther apart than those on the other side, the decrease in breaking strength was very marked (about 35 per cent.), while if the planes determined by the lines of contact of the gripping points of each clip were parallel, there appeared to be no effect. The

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[1] This clip was devised by the author at the suggestion of Mr. E. S. Wheeler, M. Am. Soc. C. E.

[2] Jour. Assoc. Eng. Soc., Vol. vii, p. 212.

reason of this is evident: in the former case the line of force, joining the two pivot points, does not pass through the center of the smallest section of the briquet, and transverse stresses are introduced, while in the latter case the line of force does pass through the center of the smallest section, though not at right angles to its plane. With the Russell and Gimbal clips the distortion seemed to have little effect, provided, that in the case of the former, the clip was itself in its normal position when the briquet was inserted.

214. Conclusions Derived from Tests of Several Styles of Clips. — From the tests described above,[1] the following conclusions may be drawn: —

1st. When using the ordinary form of clips with metal gripping points, the briquets which break at the places of contact of the jaws give higher apparent strengths than those which break at the smaller sections.

2d. A rubber cushion between the briquet and the jaw of the clip prevents clip-breaks, but materially lowers the stress required to break the briquet.

3d. The form of clip designed by Mr. S. Bent Russell gives somewhat less irregular results than are obtained with the Riehlé "Engineers' Standard" rigid clip. Although the results given by the Russell clip in its present form are a trifle lower than those given by the Riehlé, it seems probable that these lower results are due to defects in detail which may readily be eliminated.

4th. By the application of the gimbal principle to cement testing clips, higher, as well as more nearly uniform, results may be obtained.

5th. In using the rigid form of clip, careless manipulation in adjusting the briquet may result in serious error due to the introduction of cross-strains, while with either the Single Gimbal or Russell clip slight deviations in adjustment are not important.

6th. With the form of briquet recommended by the committee of the American Society of Civil Engineers in 1885, the breaking stress may be somewhat increased, and the number of clip-

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[1] These tests were described in greater detail and discussed by the writer in "*Municipal Engineering*," Dec., 1896, Jan. and Feb., 1897.

breaks may be very materially decreased, by such a modification of the clip as to allow grasping the briquet nearer the head.

215. Requirements for a Perfect Clip. — As a logical result of these conclusions, the ideal clip should fulfill the following requirements: —

1st. It should impart a true axial pull to the briquet without subjecting it either to cross-strains or to compressive forces

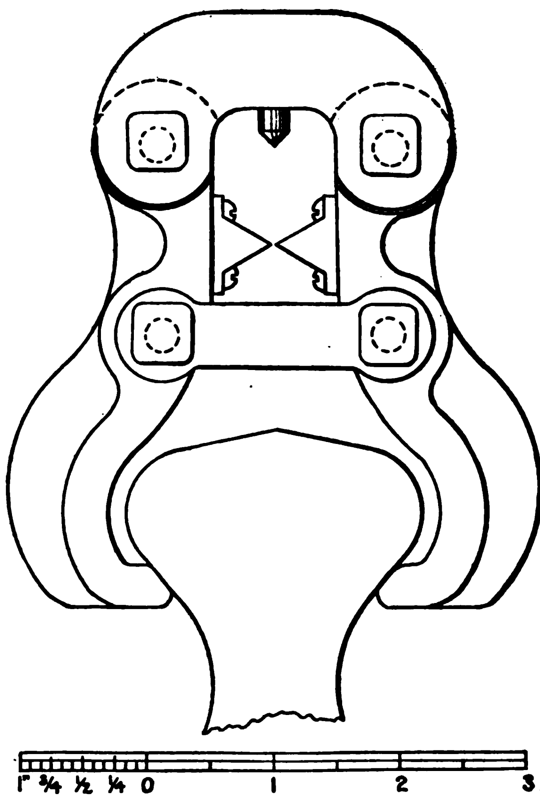

FIG. 9.—FORM OF ARTICULATED CLIP SUGGESTED FOR USE

sufficient to cause it to break at other than the smallest section.

2d. The bearing surfaces of the gripping points should not ore than about one-fourth of an inch wide, since this is ient to prevent crushing the briquet at these places, and wide a jaw will not usually bear uniformly over its whole face.

3d. Its parts should have sufficient strength and stiffness, so that they will not bend appreciably when in use.

4th. It should permit rapid operations, and

5th. It should be as light as consistent with the above requirements.

216. Form Suggested. — Fig. 9 shows a style of clip which closely conforms to the above specifications. The evener form devised by Mr. Russell has been selected for modification. The S. G. clip would more nearly meet some of the requirements, and, so far as the principle is concerned, this form is considered quite the equal of the evener clip. But no method of applying the gimbal principle has commended itself as affording such rapid manipulation as does the evener motion, and since it is thought that either form will obviate cross-strains in a plane parallel to the face of the briquet, the evener form has been adopted on account of convenience.

The defects in detail of the Russell clip which have already been mentioned have been obviated in the present form. The gripping points are made one-fourth of an inch wide, and a little more material has been used between the gripping points and the first pin to stiffen the clip. This form is designed for use with the briquet shown in Fig. 5 (see § 179).

217. Rate of Applying the Tensile Stress. — Table 37 gives the results of several hundred experiments made by Mr.

TABLE 37

Relation of Apparent Tensile Strength to Rate of Applying Stress

Rate of Applying Stress, Pounds per Minute.	Tensile Strength Obtained, Pounds per Sq. Inch.
50	400
100	415
200	430
400	450
6,000	493

Henry Faija [1] to show the effect on tensile strength of varying the rate of applying the stress.

A few of the results obtained from nearly 900 tests, made

[1] "Cement for Users," by Mr. Henry Faija.

under the author's direction to illustrate this point, are given in Table 38. Some of these results accord very well with those given in Table 37, but the results in the latter table were doubtless obtained from neat Portland briquets only, while the experiments given in Table 38 were made with briquets neat and with two parts sand, and on natural as well as Portland cement mortars.

TABLE 38

Relation of Apparent Tensile Strength to the Rate of Applying the Stress

Cement.	Proportions.	Age of Briquets.	Tensile Strength, Pounds per Square Inch, for Stress Applied at Rate of Pounds per Minute.				
			100	300	500	700	900
Portland	Neat cement	7 and 14 days	453	485	521	520	528
"	Neat cement	3 months	...	590	617	622	640
"	1-2	3 months	445	467	487	507	510
Natural	Neat cement	7 days	150	169	186	...	202
"	Neat cement	3 months	300	351	363	378	390
"	1-2	3 months	255	299	327	329	354

218. It appears from all these results that the increase in the breaking strength due to increasing the rate of applying the stress is considerable in the case of low rates of speed, but when a rate of 500 or 600 pounds per minute has been reached, a further increase in rapidity does not make a material increase in the apparent strength. Since certain variations in rate are sure to occur, until some device is used to automatically regulate it, a rate should be adopted which would allow of slight variations without materially changing the result of the test. A rate of 600 pounds per minute would fulfill this requirement, and, with certain machines at least, would be still more convenient than the rate of 400 pounds per minute which has heretofore been quite generally used.

An analysis of the experiments made to determine the degree of uniformity obtained by using each of the given rates, showed there was but little difference in this regard, but if any choice could be made on this basis it seemed to lie with the more rapid rate.

219. With the shot machines it is not difficult to approximately regulate the rate at which the stress is applied. In operating a machine in which a handwheel moves a weight along the graduated beam, it must be remembered that the rate at which the weight moves is the controlling factor, and not the movement of the lower wheel, which simply serves to take up lost motion, the stretch of the briquet under strain, and the slipping of the briquet in the jaws of the clip. A mistaken idea concerning this matter has sometimes led to the adoption of a device to regulate the motion of this lower wheel. Until one is accustomed to applying the stress at a given uniform rate, he will find it an aid to hang near the machine a pendulum of such a length that a certain number of vibrations correspond to a complete revolution of the handwheel.

220. Treatment of the Results. — The number of briquets which are made to test the strength of a given sample of cement will depend on the accuracy which it is desired to attain. If but two briquets are made, neither of the results may be rejected; however widely they may differ one from the other, the mean of the two must be considered the result of the experiment when nothing is known as to their comparative value. But if several briquets are made from the same sample, and they vary one from another, the final result is sometimes obtained by rejecting certain of the observations. In some cases if five or six specimens are made, the highest and the lowest ones are omitted, while sometimes the two lowest are rejected, and the mean of the three or four highest is taken.

221. While the absolute mean of all of the observations will ordinarily be quite sufficient, and should usually be considered the result of the test, yet where tests are very carefully made to compare two samples, or two methods of manipulation, it may be desired to reject certain observations that appear to be abnormal. The beginner in cement testing, unfamiliar with observations of this character, may not feel confidence in his own judgment as to what observations may be rejected, and the criteria sometimes used in more accurate work are entirely too complicated for this purpose. To serve as a guide in such cases, the writer would suggest the following simple method which, though entirely arbitrary, is more justifiable than either of the methods mentioned above. As the experimenter becomes more familiar with the work, he will doubtless prefer to depend on his own judgment in the rejection of observations, taking into account the general accuracy of the work.

First obtain the absolute mean and the difference between this mean and each individual result; let us call this difference the "error" for each result. Reject any observations whose error is, say, ten per cent. of the absolute mean, and obtain the mean of the remaining observations as the true result.

222. For example, suppose that we have broken ten briquets obtaining the strengths given below, and wish to determine the result of the test. The absolute mean is found to be 213.9 pounds, or, the nearest whole number, 214 pounds.

TABLE 39

Rejection of Observations

Number of Briquets.	Observed Strength.	Error.	Observed Strength.	New Error.
1	209	5	209	1
2	226	12	226	16
3	227	13	227	17
4	184	30	. . .	. . .
5	217	3	217	7
6	252	38	. . .	. . .
7	200	14	200	10
8	195	19	195	15
9	193	21	193	17
10	236	22	. . .	. . .
Sum . . .	2,139	177	1,467	83
Mean . .	213.9	17.7	209.6	11.9

The "errors" are given in the third column, and it is seen that three of them are greater than ten per cent. of the mean. Omitting the results having these large errors, we obtain a new mean of 209.6 pounds, which is to be considered the result of the test. An inspection of the first column of errors shows that the mean of the errors is 17.7 pounds; if we divide this by the mean of the tensile strengths, we obtain 17.7 ÷ 213.9 = .0827. Expressing this as a percentage, we may call 8.27 per cent. the "average error." The same result is, of course, obtained by dividing the sum of errors by the sum of the strengths. Now if we consider column five, we see that the new average error will be but 83 ÷ 1467 = 5.66 per cent.

223. In giving the results of a series of tests, it is a common practice to state only the absolute mean, but it is of considerable interest to know the variations that occurred in breaking in order that one may judge of the reliability of the results, or, in other words, to make a rough approximation as to the probable error. For this purpose the highest and lowest result may be given, but a much better index to reliability would be to give the "average error" as explained above. However, in reporting a large number of tests, the extra labor involved in obtaining this "average error" is usually considered too great to be attempted, and in such cases the absolute mean and the highest and lowest results must serve the purpose.

224. Accuracy Obtainable. — When an operator has become expert and is working under good conditions, he may expect to obtain results within the following limits: The extreme variations between the results in a set of ten briquets (the difference between the highest and lowest) not exceeding 20 per cent. of the mean strength of the set, the maximum variation from the mean not exceeding 12 per cent. of the mean, and the "average error," as explained above, not exceeding 8 per cent.

ART. 26. THE INTERPRETATION OF TENSILE TESTS OF COHESION

225. One of the problems presented in the inspection of cement is to foretell the ultimate relative strengths of two samples from the results of short time tests. Formulas have been presented purporting to solve this problem, such formulas being based on the assumption that the strength gained at the end of months or years is a function of that developed in a few days. In fact, the *raison d'être* of tensile or other short-time strength tests for the acceptance of cement, rests, in a sense, upon this same assumption.

The value of strength tests as one of the guides in determining in a short time the probable quality of a cement is unquestioned. One is apt, however, to seek too close an agreement between the results of such tests and the actual quality of the cement. It would be easy to select examples illustrating the harmony between short and long time tests; but it will be of greater value to show, rather, some of the many exceptions to such a rule, and thereby emphasize the fact that it is only by a close analysis of all of the information obtainable concerning a sample, and a general knowledge of the behavior of the different grades of cement, that one may hope to arrive at a tolerably accurate opinion.

226. Comparative Tests of Portland Cements. — In Table 40 are given the results of tests on four brands of Portland cement at seven days, twenty-eight days and two years. From the tests at two years it appears that T and U are the best cements, V is nearly as good, but W gives a much lower result. Turning now to the seven and twenty-eight day tests of briquets maintained at the ordinary temperature, it is seen that W gave in every case higher results than T, and nearly as high as U or V. Among the short time tests it is only the results of briquets maintained at 80° C. that indicate the inferiority of Brand W.

TABLE 40

Interpretation of Short Time Tests of Portland Cement, Several Brands

Parts Sand to 1 Cement by Weight.	Temperature Water of Immersion.	Age of Briquets.	Tensile Strength, Pounds per Square Inch.			
			Brand.			
			T	U	V	W
2	Hot, 80° C.	7 days	339	278	284	222
3	" "	"	221	191	180	134
3	" 60° C.	"	144	142	169	144
0	Ordinary	"	426	510	487	565
1	"	"	327	425	400	396
2	"	"	172	275	256	236
3	"	"	73	150	160	150
1	"	28 days	526	577	557	556
2	"	"	312	394	387	332
3	"	"	142	241	223	247
1	"	2 years	719	753	763	654
2	"	"	554	553	513	407
3	"	"	386	373	340	287

227. Comparative Tests of Natural Cements. — From the nature of natural cements a much greater variation in strength among different brands, and even among different samples of the same brand, is to be expected. With Portland cements made in accordance with ordinary methods, the variations in strength among ten or twenty brands will usually be comparatively small. One of them may possibly prove unsound, and one or two others may give inferior strength, but the variations in strength among three-fourths of the samples will not generally exceed 20 per cent. With the same number of brands of natural cements, variations of 50 to 200 per cent. may be expected.

TABLE 41

Interpretation of Short Time Tests of Natural Cement, Several Brands

Parts Sand to 1 Cement.	Temperature Water of Immersion.	Age of Briquets.	Tensile Strength, Pounds per Square Inch. Brand.					
			Jn	Hn	Bn	Mn	Nn	Kn
2	Hot, 50° C.	7 days	152	102	84	133	160	277
2	Hot, 60° C.	"	170	270	79	154	164	254
2	Hot, 80° C.	"	58	136	128	179	166	221
0	Ordinary	"	174	203	130	189	210	189
1	"	"	125	198	103	164	169	164
0	"	28 days	208	314	293	203	316	289
1	"	"	237	342	247	247	252	385
2	"	"	132	223	148	158	184	217
3	"	"	64	113	85	93	104	101
1	"	2 years	177	271	358	631	665	532
2	"	"	106	157	195	515	550	561
3	"	"	99	130	117	340	328	372

In Table 41 six brands of natural cement are compared by tests at seven days, twenty-eight days and two years. These six brands have been arranged in the table according to their value as shown by the two year tests, and it is seen that the first three, Jn, Hn and Bn, are especially poor, while the last three, Mn, Nn and Kn, are exceptionally good. In the short time tests of briquets maintained at ordinary temperature, Jn and Bn gave low results and Nn and Kn gave fairly high results, in harmony with the long time tests; but Hn, which proved to be one of the poorest samples, gave in every case the highest, or next to the highest, result in seven and twenty-eight day cold tests. In this table we find again that the results of the briquets maintained at 80° C. for seven days gave, in a general way, the best indication of the relative values of the six brands.

228. Several Samples of One Brand. — To show that short time tests do not always indicate the relative values of several samples of cement, even when all of the samples are of the same brand, Tables 42 and 43 are given. All of the results in these tables are from samples of the one brand of natural cement.

TABLE 42

Comparison of Short and Long Time Tests of Samples of One Brand of Natural Cement

Series.	Sand.		Age.		Tensile Strength, Lbs. per Square Inch.				
	Kind.	Parts to 1 Cement.							
				Number of Samples Tested.	3	7	2	3	5
A	. . . .	0	28 days	. .	84	123	177	220	207
	. . . .	0	6–7 months	. .	121	186	241	301	381
				Number Samples.	17	20	17	16	. .
B	Std.	1	7 days	. .	62	74	86	146	. .
	"	1	6 months	. .	462	468	442	367	. .
				Number Samples.	50	50	19	19	. .
C	P.P.	1	7 days	. .	49	54	73	128	. .
	"	1 and 2	6 months [1]	. .	473	426	381	321	. .
	"	2	7 days [2]	. .	273	249	265	283	. .
				Number Samples.	13	48	38	18	. .
D	. . . .	0	7 days	. .	66	80	95	147	. .
	P.P.	2	1 year	. .	473	422	377	325	. .
	"	2	7 days [2]	. .	257	234	277	215	. .
				Number Samples.	12	21	18	9	. .
E	. . . .	0	7 days	. .	74	83	120	167	. .
	. . . .	2	6 months	. .	535	477	424	373	. .
				Number Samples.	287	170	41	. .	. .
F	. . . .	0	28 days	. .	135	191	235	. .	. .
	Cr. Qtz. 20 to 40	2	6 months and 1 year	. .	565	454	367	. .	. .

[1] Mean one-to-one and one-to-two mortars.
[2] Briquets immersed six days in water maintained at 60° C.

In Table 42 the results are selected from a large number of tests of this brand, and are arranged in groups according to the strength shown at a certain age. For instance, in Series A the results of twenty samples are given, arranged according to the strength at twenty-eight days. Three of the samples gave less than 100 pounds per square inch, neat, at twenty-eight days; the same three samples gave a mean strength of 121 pounds per square inch, neat, six to seven months. Seven samples, the strength of which fell between 100 and 150 pounds at twenty-eight days, gave a mean strength of 186 pounds at six to seven months. The results of this series show the harmony between short and long time tests when it is a question of comparing neat cement mortars.

In Series D of this table the samples are arranged in order according to the strength developed by one-to-two mortars one year old. Thirteen samples had a strength at this age of between 450 and 500 pounds, average 473 pounds. The same samples gave but 66 pounds, neat, seven days. Forty-eight samples, giving between 400 and 450 pounds, average 422 pounds, gave but 80 pounds, neat, seven days, while eighteen samples that developed only 300 to 350 pounds mean, 325 pounds at one year, showed a mean strength of 147 pounds, neat, seven days.

A little study of this table will show that the samples which were comparatively weak in seven and twenty-eight day tests, either neat or with sand, gave the best results in the long time tests of sand mortars. Series A shows that the neat tests at seven days and at six months are consistent, but in all cases where sand mortars are tested at six months to one year, the highest results are given by the samples showing the lowest strength in the short time tests in cool water. It is very seldom that this conclusion has not been indicated by the author's tests of this brand. It is not invariably true, however, for some samples which were selected as being defective in burn, gave low results both in short and long time tests. The conclusion stated above must therefore be understood to have limits even for this brand, and may not apply at all to many brands.

As to the results of short time tests of briquets stored in hot water, Series C and D indicate that such results are more nearly consistent with the long time tests, yet it is evident that even with hot tests one could not readily and accurately differentiate the best from the mediocre samples.

TABLE 43

Natural Cement: Rate of Increase in Strength, Hardening in Water and Dry Air

Sand, Parts to One Cement.	Age of Briquets When Broken.	Tensile Strength per Sq. In., of Samples.					
		Hardened in Water.			Hardened in Air of Room.		
		84	U′	O′	84	U′	O′
1	7 days.	74	53	103	107	68	187
1	28 days.	228	180	228	188	95	256
1	3 mos.	415	345	331	158	100	248
1	6 mos.	506	381	307	425	161	359
1	2 years.	446	383	200	151	147	403
3	28 days.	99	97	64	112	61	180
3	3 mos.	244	241	129	153	81	194
3	6 mos.	255	232	162	92	69	173
3	1 year.	274	204	186	229	70	144
3	2 years.	258	208	167	274	152	228

Sample	84	U′	O′
Fineness: Per cent. passing Sieve No. 120, Holes .0046 inch square	80.5	87.8	89.7
Time Setting—to bear $\frac{1}{12}''$ $\frac{1}{4}$ lb. Wire, min.	54	23	97
Specific Gravity	3.012	2.950	3.145

U′, underburned, O′, overburned. All samples same brand, Gn.

229. The results in Table 43 will serve to illustrate the same point by showing the very different rates of increase in strength of three samples when the briquets are stored in water and in dry air. One of these samples, 84, was taken at random from a shipment, while U′ and O′ were supposed to be defective in burn. Of the water-hardened specimens, No. 84 gained in strength up to six months or one year and then suffered only a slight falling off. The underburned sample showed a continuous gain, but the overburned cement showed a marked decrease in strength after six months or one year. The air-hardened specimens were very irregular in strength, but the underburned sample gave very low results throughout.

Table 44 gives similar results obtained with several samples, the briquets being hardened in water as usual. 16 R is a fair sample of the best cement of this brand, and its rate of increase in strength with one to three parts sand is shown. Samples M and L were tested together, as were CC and DD. M and CC are of the class giving comparatively high results at seven days, while L and DD give high results at seven days, but develop only a moderate ultimate strength.

TABLE 44

Natural Cement: Difference in Rates of Increase in Strength of Several Samples of the Same Brand

Reference.	Cement.		Sand.		Tensile Strength, Pounds per Sq. In. at Age of							
	Brand.	Sample.	Kind.	Parts to One Cement by Weight.	7 days.	28 days.	2 mos.	3 mos.	6 mos.	1 year.	2 years.	3 years.
1	Gn	16 R	Crushed Qtz. 20–30	1	94	142	334	399	430	500	445	. . .
2	"	"	"	2	59	101	289	341	335	386	354	. . .
3	"	"	"	3	. . .	73	204	243	252	268	262	248
4	"	M	. . . .	0	118	199	. . .	256	248	300	. . .	. . .
5	"	L	. . . . .	0	40	88	. . .	148	146	167	. . .	. . .
6	"	M	Point aux Pins	2	63	155	. . .	216	241	252	. . .	. . .
7	"	L	"	2	30	150	. . .	296	415	369	. . .	. . .
8	"	CC	"	1	123	232	. . .	276	269	. . .	317	. . .
9	"	DD	"	1	77	218	. . .	327	337	. . .	474	. . .
10	"	CC	"	2	. . .	185	. . .	268	242	279	279	. . .
11	"	DD	"	2	. . .	189	. . .	326	303	373	359	. . .

230. Conclusions. — From the above tables one should not draw the conclusion that all strength tests are valueless because likely to be misleading. Some lessons, however, seem to be plain; conclusions drawn from the results of short time tests of strength alone are likely to be far from infallible. This is especially true of natural cements. The correctness of one's conclusions concerning the value of a sample is likely to depend very much upon his knowledge of the behavior of that particular brand, and the beginner in cement testing should not have too great confidence in his early conclusions. Samples under inspection should be tested in comparison with other samples of known quality, and the results of the strength tests studied in connection with all the information obtainable from the other tests of quality already outlined.

CHAPTER X

THE RECEPTION OF CEMENT AND RECORDS OF TESTS

ART. 27. STORING AND SAMPLING

231. STORAGE. — The storage houses provided for the cement should be such as will effectually preserve it from dampness, the floor being dry and strongly built. A circulation of air under the floor will insure dryness.

In building houses for storage, due regard should be given to the ease of getting the cement in and out, and facilities provided for the use of block and tackle in tiering.

When the cement is received, whether in sacks or barrels, it should, if possible, be so tiered in the warehouse that any package is accessible for sampling. In the case of barrels this may readily be attained by tiering in double rows, the barrels lying on the side. It has been found that ordinary cement barrels will withstand the pressure if tiered five high with a "binder" row on top; and when so piled, a warehouse 32 feet wide and 100 feet long will readily hold 2,200 barrels, an allowance of about one hundred fifty square feet of floor space for one hundred barrels.

232. Where storage space is limited, the barrels may be numbered and sampled before they are placed in the warehouse, and they may then be piled solid, but this should be avoided if practicable. Sacks cannot be quite so neatly stored, and since a smaller quantity is contained in a sack, they may be tiered so that every third or fourth sack is accessible. It is desirable where work is executed with the greatest care that every package be numbered for future identification, but this may sometimes prove impracticable, especially when the cement is in sacks, and in such cases the sampled packages only may receive numbers.

233. Percentage of Barrels to Sample. — The amount of cement which shall be accepted on the test of a single sample must be determined by each user of cement according to his knowledge as to the uniformity and reliability of the brand in use, and according to the character of the work in which the cement is to be used. In a few isolated cases every barrel is tested, while sometimes several tons of cement are accepted on a single test. As the improvements in methods have decreased the work involved in making the simpler tests, the tendency has been to test a larger percentage of the packages.[1]

The report of the committee of the Amer. Soc. C. E. in 1885, contains the following concerning sampling: "There is no uniformity of practice among engineers as to the sampling of the cement to be tested, some testing every tenth barrel, others every fifth, and others still every barrel delivered. Usually, where cement has a good reputation, and is used in large masses, such as concrete in heavy foundations, or in the backing or hearting of thick walls, the testing of every fifth barrel seems to be sufficient; but in very important work, where the strength of each barrel may in great measure determine the strength of that portion of the work where it is used, or in the thin walls of sewers, etc., every barrel should be tested, one briquet being made from it."

234. Taking the Sample. — The sample should be taken in such a manner as to fairly represent the package, and for this purpose a "sugar trier" may be used, by which is obtained a core of cement about one inch in diameter and eighteen inches long. As any tool used for boring cement barrels soon becomes dull, and as a sugar trier is somewhat difficult to sharpen, the author prefers to use an ordinary bit and brace to penetrate the barrel head, and then extract the sample with a "trier," or a long, slender scoop of similar form provided with a handle.

For storing the sample until it is tested, it has been found convenient to use covered tin cans holding about one pint, the cover of the can being labeled with the number of the package from which the sample is taken.

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[1] In a paper read before the Institution of Civil Engineers in 1865–66, Mr. John Grant states that "after using, during the last six years, more than 70,000 tons of Portland cement, which has been submitted to about 15,000 tests, it can be confidently asserted that none of an inferior or dangerous character has been employed in any part of the work in question." (The Metropolitan Main Drainage, London.) This is an average of one test to twenty-five barrels.

Art. 28. Records of Tests

235. Value of Records. — In conducting work in which the use of cement enters as a prominent factor, it is not only necessary to know that the cement used is of a good quality, but also to be able to show at any future time what tests were made to establish its value. This fact, as well as the convenience of the work, demands that a record shall be kept of all the tests made. These records may be more or less elaborate, according to the kind and amount of the work in hand, but in any case, enough detail should be given to make them intelligible to other engineers.

236. Marking Specimens. — There is sometimes a temptation, in making tensile specimens, to stamp upon them many details of the test, and for this purpose an elaborate cipher system has sometimes been used. But this method is to be strongly deprecated. Each briquet should receive its proper consecutive number, as mentioned in §189, and the details concerning it should be placed in the record book.

237. Records Kept at St. Marys Falls Canal.— In the tests of cement at St. Marys Falls Canal, during the construction of the Poe Lock, a system of records was used that gave entire satisfaction. At the time the largest amount of cement was being used three molders were employed, each making fifty briquets per day of eight hours. Over one hundred thousand briquets were made in five and one-half years. Although the system of records used at this point may be more elaborate than is often necessary, yet the system will be described, and certain modifications will be suggested for places requiring less complete records.

238. Barrel Records. — The barrels receive consecutive numbers after they are tiered up in the warehouse. The "receiving book" is a simple transit book in which are entered the date of the receipt of each cargo, the name of the boat (or the car number, if shipped by rail), the brand of cement, the number of barrels, the first and last barrel number of the cargo and the warehouse in which the cement is placed. The next book to be used is the "barrel book," in which the numbers of the barrels are entered consecutively in a column at the left, each barrel being given one line. This book is also of transit size, but might well be larger. The headings are given below.

SAMPLE PAGE OF "BARREL RECORD"

No. Bbl.	Sampled.		Defects.	Accepted.	Rejected.	Issued.	Remarks.
	M. D.	M. D.		M. D.	M. D.		
88251	*5 16*	*6 5*	*S7 = 48#*	*6 13*	. . .	*July 25*	*S7 = 65#*
2	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
3	. . . .	*6 6*	. . . . . .	*6 13*	. . .	*July 25*	*S7 = 102#*
4	*5 19*	*6 5*	*S7 = 32#* *S7 = 35#*	. . . .	*6 12*	*Sept. 27*	*Removed by Contractor*
5	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
6	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
7	*5 19*	. . .	. . . . . .	*5 26*	. . .	*July 25*	. . . .
8	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
9	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
88260	*5 19*	. . .	. . . . . .	*5 26*	. . .	*July 25*	. . . .
1	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
2	. . . .	*6 6*	. . . . . .	*6 13*	. . .	*July 25*	*S7 = 105#*
3	*5 19*	*6 5*	*S7 = 40#* *S7 = 32#*	. . . .	*6 12*	*Sept. 28*	*Removed by Contractor*
4	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .
5	. . . .	. . .	. . . . . .	. . . .	. . .	*July 25*	. . . .

When the barrels are sampled and briquets made, the date sampled is entered in the second column of the barrel record book. The other columns will be explained later.

239. Molders' Records. — Separate sheets of paper ruled and headed as shown on page 148 are used by the molders to record the details concerning the making of briquets.

Separate sheets properly ruled and headed are also given to the assistants who test time of setting and fineness. These record sheets, when filled in by the assistants, are copied the following day by the bookkeeper, into the permanent "record book." At the end of the month these separate sheets, containing original records of work done, are folded and filed for future reference.

240. Briquet Record. — The briquets are made in sets of ten for convenience. Each set is given a page in the "record book," as is indicated on page 149 where the form for this book is given. The size of page is 9 by 12 inches. Paper having the same ruling and column headings is convenient for reporting tests to the chief engineer.

241. Summary Book. — The data for each set of briquets are copied from the record book, in a condensed form, into the "summary book," one line of the latter containing a page of the former. In the summary book each brand is given a few

SAMPLE SHEET, MOLDERS' RECORD

Date	Brand.	No. Bbls.	No. Briquets.	Mortar.	Made.	Removed.	Tank.	Temperatures, Degrees Fahr.		Weather.	Molder.	Remarks.
								Water.	Room.			
Sept. 6, 1893,	*Milwaukee*	79014 41	61691 700	*80–80–30*	*8.00* A.M.	*10.00* A.M.	*H 2–2*	*65*	*62*	*Cloudy*	*M*	*Standard sand*
	"	79044 71	61701 10	" " "	*9.30* A.M.	*11.30* A.M.	*H 2–3*	*65*	*63*	"	*S*	*P.P. sand 20–30*
	"	79074 101	61711 20	" " "	*9.30* A.M.	*11.30* A.M.	*H 2–4*	*65*	*63*	"	*M*	" " "
	"	79104 31	61721 30	" " "	*11.00* A.M.	*1.00* P.M.	*H 2–5*	*65*	*64*	"	*S*	" " "

SAMPLE PAGE OF "BRIQUET RECORD" BOOK

St. Marys Falls Canal, Mich.

CEMENT TESTS

SAULT STE MARIE, MICH., *Sept. 6*, 189*3*.

Test No. *61691 — 700* of *Natural* Cement.

Received *8/26* 189*3*. From *Milwaukee Cement Co.*
Brand, *Milwaukee* Briquets made, *8.00 A.M. Sept 6*, 189*3*.
Where made, *Milwaukee, Wis.* Briquets broken, *Sept. 13*, 189*3*.
Per cent. of bbls. sampled, *33⅓* Age when broken, *7 days*.
Tests made from cement *as rec'd, with St. Sand.*

No. of Bbl.	No. of Briquet.	Weight of Cubic Foot.		Per Cent. Passing No. 50 Sieve.	Per Cent. Passing No. 100 Sieve.	Time of Setting Neat Cement.			Proportions in Mortar by Weight.			Tensile Strength, Lbs.	Remarks.
		Cement.	Sand.			To Bear Light Wire, Min.	To Bear Heavy Wire, Min.	Difference, Min.	Cement.	Sand.	Water.		
		Lbs.	Lbs.						Gms.	Gms.	C.C.		
79014	*61691*	....	....	...	*86.8*	....	....	...	*80*	*80*	*30*	*179*	*Temperature water, 65°* *Temperature room, 62°* *Weather cloudy* *Molder. Matthews,* *Tank, H 2-2*
7	*2*	....	....	...	...	....	....	...	....	....	....	*207*	
20	*3*	....	....	...	...	*34*	*114*	*80*	....	....	....	*204*	
3	*4*	....	....	...	...	....	....	...	....	....	....	*215*	
6	*5*	....	....	...	...	....	....	...	....	....	....	*226*	
9	*6*	....	....	...	...	....	....	...	....	....	....	*180*	
32	*7*	....	....	...	...	....	....	...	....	....	....	*193*	
5	*8*	....	....	...	...	....	....	...	....	....	....	*108*	
8	*9*	....	....	...	...	....	....	...	....	....	....	*185*	
41	*61700*	....	....	...	...	....	....	...	....	....	....	*228*	
Sum	...	....	....	...	...	....	....	...	....	....	....	*1925*	
Mean	...	....	....	...	...	....	....	...	....	....	....	*192.5*	

SAMPLE PAGE OF "SUMMARY BOOK"

Milwaukee.

No. of Bbl.	No. of Briquets.	Record Book. No.	Record Book. Page.	Briquets Made.	Briquets Broken.	Sand. Kind.	Sand. Fineness.	Proportions in Mortar by Wt. Cement.	Proportions in Mortar by Wt. Sand.	Proportions in Mortar by Wt. Water.	Age.	Tensile Strength. Mean.	Tensile Strength. Highest.	Tensile Strength. Lowest.	No. Averages.	No. below Requirements of Specifications.	Remarks.
				1893 M. D.	1893 M. D.			Gm.	Gm.	C.C.	Days	Lbs.	Lbs.	Lbs.			
79014 41	61691 700	U	170	9 6	9 13	St'd	20/30	80	80	30	7	192.5	228	108	10	0	
79044 71	61701 10	"	171	9 6	9 13	Pt. aux Pins	"	80	80	30	7	146.2	176	106	10	0	
79074 101	61711 20	"	172	9 6	9 13	"	"	80	80	30	7	157.6	200	104	10	0	
79104 31	61721 30	"	173	9 6	9 13	"	"	80	80	30	7	146.2	176	59	10	0	
88200 27	78351 60	AA	38	1894 5 19	1894 5 26	"	"	80	80	30	7	72.6	98	41	10	1	
88230 57	78361 70	"	39	5 19	5 26	"	"	80	80	30	7	84.2	128	48	9	3	
88260 87	78371 80	"	40	5 19	5 26	"	"	80	80	30	7	81.8	118	50	9	0	
88290 317	78381 90	"	41	5 21	5 28	St'd	20/30	80	80	32	7	68.1	82	46	10	2	
88320 47	78391 400	"	42	5 21	5 28	"	"	80	80	32	7	86.4	130	48	9	2	

pages by itself, so that this book corresponds to a ledger in form. By this means a large number of tests on the same brand may be looked over at once. The summary book might be omitted where a smaller number of tests are to be made, or it might be slightly modified and take the place of the record book. A sample page is given below.

242. Records of Fineness, Time of Setting and Soundness. — Although provision is made in the record book for recording time of setting and fineness, it has been found that where a large amount of cement is being tested it is more convenient to have separate books for each test. Especially is this true as it has been judged necessary to test but a very small percentage of the barrels for fineness, while a larger percentage of the barrels are tested for time of setting and soundness. The "fineness book" is as simple as possible and need not be illustrated. A sample page of the "pat book" is given below.

Sample Page of "Pat Book" or Record of Time of Setting and Soundness

Lagerdorfer Portland Cement Pats, Two from Every Third Barrel

No. Bbl.	Special Marks on Pats.	Time Day Made, 7/11/95.	Time to Bear 1/4# Wire, Min.	Time to Bear 1# Wire, Min.	Treatment of Pats.		Examined.		Removed.		Remarks.
					Stmr.	Tank.	Date. Mo. D.	Condition.	Date. Mo. D.	Condition.	
110274	1	9:23	117	337	*Pat. No. 1 in vapor when set hard, immersed 3 hrs. later, temperature 176° F.*	*Pat. No. 2 in tank when set hard.*	8 1	O.K.	7 15	O.K.	*Water 24%.*
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
7	1	9:28	37	232			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
80	1	9:32	15	268			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
3	1	9:34	143	383			8 1	O.K.	7 15	Surface cracked & scale.	
. . .	2	. .	. .	. .			. . .	. . .	8 17	O.K.	
6	1	9:41	24	259			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
9	1	9:50	15	250			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
92	1	9:53	13	247			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
95	1	9:57	123	363			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
98	1	10:28	97	367			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	
301	1	10:32	103	365			8 1	O.K.	7 15	"	
. . .	2	. .	. .	. .			. . .	. . .	8 17	"	

SAMPLE PAGE OF "SERIES BOOK" FOR SPECIAL TESTS

Comparative Strength, Different Samples Same Brand

Number of Briquets.	Cement.	Sand.		Water Per Cent. Dry Ingredients.	Date Made, 1896.	Age.	Tensile Strength.				Molder.	Time in Molds.	Stored.	Remarks.
		Kind.	Parts to One Cement.				Mean.	Highest.	Lowest.	No. Averaged.		Hrs.		
97841— 5	Milwaukee Mix R R	P. P. Pass	0	31.7	2/18	1 yr.	420	452	382	5	S	12	Tank G	Consistency O. K.
51— 5		20 Sieve	1	18.7	"	"	436	462	406	"	"	"	"	" "
61— 5		"	2	15.3	"	"	341	362	314	"	"	"	"	" "
71— 5		"	3	13.2	"	"	242	256	230	"	"	"	"	" "
81— 5		"	4	12.5	"	"	196	210	180	"	"	"	"	" "
97846—50	Milwaukee Mix S S	P. P. Pass	0	31.7	2/18	1 yr.	335	398	290	5	S	12	Tank G	Consistency O. K.
56—60		20 Sieve	1	18.7	"	"	304	324	288	"	"	"	"	" "
66—70		"	2	15.3	"	"	245	280	170	"	"	"	"	" "
76—80		"	3	13.2	"	"	136	164	85	"	"	"	"	" "
86—90		"	4	12.5	"	"	95	140	52	"	"	"	"	" "

243. The Diary. — When the bookkeeper has copied the data contained on the record blanks into the record book and summary book, he turns to the proper page in the diary and records the briquets to be broken. Thus, if briquets made May 17th are to be broken at three months, he enters the numbers of these briquets and the tank in which they have been placed under the date Aug. 17th. This leaves no chance of allowing briquets to go beyond the proper time of breaking.

244. Acceptance or Rejection. — If all of the tests on a given sample are satisfactory, the date of acceptance is placed in the proper column of the barrel book. It only remains then to mark the barrels "O. K.," and issue them when needed, placing the date of issue in the column indicated. If, however, some of the tests have given unsatisfactory results, the failure is noted in the "defects" column of the barrel book, and the barrel is resampled to determine whether the failure was due to faulty manipulation. If finally rejected, the barrel is prominently marked to prevent its being issued for use.

It is seen from the above that the history of each barrel is given in the barrel book, and the record of any brand is given in a condensed form in the summary book.

245. Special Tests. — When special tests are made to investigate the effects of variations in manipulation, or for any other special purpose, such as to test the value of certain kinds of sand, it becomes convenient to have still another form which may be called a "series book." In this the results are so arranged that they may be studied for conclusions, and tables for reports may be copied directly from it. A sample form is given on preceding page. Should extra rulings be needed, they may be placed at the right in the "remarks" column.

PART III

PREPARATION AND PROPERTIES OF MORTAR AND CONCRETE

CHAPTER XI

SAND FOR MORTAR

246. Mortar. — When cement is mixed with sand and water, the resulting paste is called mortar. The term "neat cement mortar" is sometimes used to designate a cement paste without sand, but when the term mortar is not qualified, it refers to the mixture containing sand. The primary function of mortar is to bind together pieces of stone of greater or less size, though it is sometimes used alone to prevent the percolation of water, to make a smooth exterior finish, or in places too confined to permit of placing concrete.

There are comparatively few cases in which it is judicious to use cement without the addition of sand, for such an admixture not only cheapens the mortar, but actually improves it for nearly all purposes. The quality of sand used is only second in importance to the quality of the cement. Indeed, if one does not know how to select either a good cement or a good sand, he is in greater danger of going amiss in the selection of the latter than the former; for the cement has been placed upon the market by a manufacturer who has a reputation to establish or maintain.

ART. 29. CHARACTER OF THE SAND.

247. Various kinds of rock are capable of producing sand of good quality. The natural sands are usually siliceous in character, but calcareous sands are also met with and may give excellent results in mortar. Good artificial sand may be made from almost any kind of rock that is not liable to chemical decay, even though it be only moderately hard. One of the most essential features of a good sand is that the grains should be perfectly sound. Evidences that chemical decay is going on in the grains would indicate that the sand is of very inferior quality.

248. Shape and Hardness of the Grains.— It is generally believed that the grains of sand should be angular in order to give the best results; this is probably true, although in testing three varieties of calcareous sand, M. Paul Alexandre[1] obtained results which seemed to indicate that if rounded grains are disadvantageous, the other properties of the sand may readily counterbalance this disadvantage.

M. Alexandre used three sands which were reduced to the same fineness by sifting into different sizes and then remixing them in fixed proportions (equal parts of five sizes). The three sands were, 1st, white marble, very hard with sharp corners; 2d, moderately hard limestone; and 3d, chalk, very soft with rounded grains. The proportions used were 400 kg. of cement to one cubic meter of sand, the amount of water varying from twenty-five to thirty per cent. of the sand, according to the amount required to produce plasticity. The tensile strength of the mortars, in pounds per square inch, is given in Table 45.

TABLE 45

Results Obtained with Three Varieties of Calcareous Sand

Character of Sand.	Tensile Strength, Pounds per Square Inch at			
	7 da.	28 da.	6 mo.	1½ yrs.
1. Marble	45	107	171	220
2. Limestone	72	148	222	256
3. Chalk	86	120	205	252

As these sands varied in the structure and hardness as well as in the shape of the grains, it cannot be concluded that rounded grains are as good as sharp and angular ones for mortar-making. There is little question that if two samples of pure quartz sand,

[1] "*Recherches Experimentales sur Les Mortiers Hydrauliques.*"

differing in sharpness but alike in all other respects, including the percentage of voids, were tested side by side, the rounded grains would be found inferior. (See also § 253.)

M. Alexandre also made tests on sands differing both in chemical and physical characteristics, but having the same fineness, namely, twenty per cent. each of five sizes of grain. Some of the results are given in Table 46.

TABLE 46

Results Obtained with Various Sands

SAND.	WATER PER CENT. OF VOLUME OF SAND.	TENSILE STRENGTH, IN LBS. PER SQ. IN., OF MORTARS CONTAINING 400 KG. OF CEMENT TO 1 CU. METER SAND, AT AGES OF		
		7 da.	1 yr.	3 yrs.
Sea Sand	21	69	165	245
Calcareous (Renville stone)	28	78	198	267
Granitic	21	65	158	201
Siliceous (cliff quartz)	20	63	174	215
Siliceous (Cherbourg Quartzites)	20	79	178	244
Coke	28	35	99	132

249. Siliceous vs. Calcareous Sands. — The above tests would seem to show that sand to be used in mortar need not be siliceous. In experimenting on different varieties of sand, both natural and artificial, the author has obtained results that point to a similar conclusion. Some of these tests are given in Tables 47 to 50.

Table 47 gives the results obtained with four varieties of siliceous sand. The first was an artificial sand made by crushing sandstone, the second and third were natural sands containing a large percentage of quartz grains, and the fourth appeared to be almost pure quartz. Only the fine particles of the sands were used in the tests given in this table. The differences in strength at the end of two years are not great, but the two natural sands appear to give somewhat lower results.

In Table 48 the two natural sands were again compared, but this time in connection with a calcareous sand formed by crushing limestone. The latter gave the best results. Only the finer grains were used in these tests.

250. Tables 49 and 50 are more valuable in this connection,

TABLE 47

Values of Different Varieties of Fine Siliceous Sand for Use in Portland Cement Mortar

TWO PARTS SAND TO ONE CEMENT BY WEIGHT

REFERENCE.	SAND.	FINENESS.	WATER, Per Cent.	TENSILE STRENGTH, LBS. PER SQ. IN. AT	
				6 Mo.	2 Yr.
	a	*b*	*c*	*d*	*e*
1	Screenings from crushing Potsdam sandstone	Pass 40 sieve .	18.5	388	470
2	Screenings from crushing Potsdam sandstone	Pass 40 sieve, retained on 100	17.5	478	539
3	Bank sand, siliceous	Pass 40 sieve .	13.3	433	445
4	River sand, siliceous	Pass 40 sieve .	12.1	382	437
5	Clean quartz . .	Pass 40 sieve .	13.3	398	506

NOTE. — Holes in No. 40 sieve 0.015 inch square, holes in No. 100 sieve about 0.0065 inch square.

TABLE 48

Different Varieties of Fine Sand for Portland Cement Mortar

REFERENCE.	SAND.	FINENESS.	PER CENT. WATER.		TENSILE STRENGTH, POUNDS PER SQUARE INCH.					
					1 Part Sand to 1 Cement by Wt.			2 Parts Sand to Cement by Wt.		
			1 to 1	1 to 2	6 mo.	18 mo.	3 yr.	6 mo.	18 mo.	3 yr.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*
1	River sand, siliceous . . .	Pass 40 sieve	14.0	12.4	715	725	776	491	575	581
2	Bank sand, siliceous . . .	Pass 40 sieve	14.5	12.6	664	690	759	442	502	524
3	Calcareous sand from crushing limestone . .	Pass 40 sieve	18.2	17.7	721	770	788	531	632	680
4	Calcareous sand from crushing limestone . .	Pass 40, retained on 100	17.5	17.0	753	783	844	597	659	727

since the coarser particles of the sand were used with the fine. The sand was separated into four sizes by sifting, and then remixed in equal proportions. Table 49 gives the results obtained with natural cement, and Table 50 refers to Portland. The superiority of the screenings is very clearly shown, the limestone giving especially good results. Indeed, the strength obtained with three parts limestone screenings to one part of either Portland or natural cement is remarkably high. The mortar made from such sand is peculiarly plastic when fresh, and soon gains a high strength which it appears to maintain.

TABLE 49

Values of Different Varieties of Sand for Natural Cement Mortar

Ref.	Sand.	Fineness.	Per Cent. of Water.	Tensile Strength, Lbs. per Sq. In., 3 Parts Sand to 1 Cement by Wt.			
				28 Da.	6 Mos.	1 Yr.	2 Yrs.
	a	b	c	d	e	f	g
1	Clean crushed quartz . . .	Mx.	15.4	117[1]	344	356	332
2	River sand, siliceous . . .	Mx.	13.3	93	297	339	308
3	Limestone screenings . . .	Mx.	16.7	143	467	526	601
4	Potsdam sandstone screenings	Mx.	18.2	113	316	416	462
5	Clean crushed quartz . . .	20–30	12.5	118	330	342	324

[1] 13.6 per cent. water, trifle dry.

NOTE. — Fineness Mx. means 25 per cent. each of 20–30, 30–40, 40–50 and 50–80.

Expression 20–30 means passing No. 20 sieve and retained on No. 30 sieve.

TABLE 50

Values of Different Varieties of Sand for Portland Cement Mortar

Ref.	Sand.	Fineness.	Per Cent. of Water.	Tensile Strength, Lbs. per Sq. In., 3 Parts Sand to 1 Cement by Wt.			
				28 Da.	6 Mos.	1 Yr.	2 Yrs.
	a	b	c	d	e	f	g
1	Clean crushed quartz . . .	Mx.	12.5	255	327	359	335
2	River sand, siliceous . . .	Mx.	11.1	206	284	329	324
3	Limestone screenings . . .	Mx.	12.5[1]	407	574	667	665[2]
4	Sandstone screenings . . .	Mx.	12.5[1]	321	438	495	492[3]
5	Clean crushed quartz . . .	20–30	11.1	259	344	369	335

[1] Trifle dry, plastic. [2] 13.3 per cent. water. [3] 14.3 per cent. water.

NOTE. — Fineness Mx. means 25 per cent. each of 20–30, 30–40, 40–50 and 50–80.

251. Slag Sand. — To turn to good account some of the immense quantities of blast furnace slag produced yearly, the use of granulated slag in place of ordinary sand has been advocated. In a paper read before the Engineers' Society of Western Pennsylvania, in March, 1904, Mr. Joseph A. Shinn described some experiments he had made, in which it was shown that "slag sand," with Portland cement, natural cement, or common lime, gave a higher strength than the sample of river sand used in the comparison.

The "slag sand" is produced by projecting two flat jets of water into the stream of molten slag, the resulting sand being heavier, finer and more nearly uniform in size of grain than the ordinary slag granulate.

252. Sand for Use in Sea Water. — It has been said that granitic sands when used in sea water do not give good results on account of the felspar of the granite being attacked by the cement when the concrete is impregnated with sea water. M. Paul Alexandre would proscribe the use of argillaceous sands in sea water, but he found that sands containing calcareous marl gave excellent results in the sea, and others have stated that the mixture of crushed limestone with concrete has been known to hinder the action of sea water upon it. Since porous and permeable mortars are most liable to disintegration by sea water, it is evident that it is especially desirable to employ a sand in which the proportion of voids is small.

Art. 30. Fineness of Sand

253. The size and shape of the grains are important elements in the quality of sand. Considering grains of the same shape but differing in size, the larger grain will have a smaller surface area in proportion to the volume than the smaller grain, since the volume varies approximately as the cube of one dimension while the surface varies as the square. Since, in order to obtain the best results in mortar, each grain of sand must be coated with cement, it follows that, other things being equal, the coarser grained sands will give the best results, because they will be more thoroughly coated; this will be especially true when the amount of sand in the mortar is relatively large.

Following the same reasoning given above as to the relative volume and superficial area of sand grains, it would appear that spherical grains would be better than cubical or angular ones (see § 248). This, however, is not thought to be the case, for the better bond obtained with angular grains seems to counterbalance the advantage which the small superficial area would appear to give to the spherical grains. For this reason a lenticular shaped grain, while having a very large area relative to its volume, will give excellent results in mortar if otherwise suited to the purpose.

It is usually desirable to have all of the voids in the sand filled by the cement paste, as this renders the mortar less porous, and makes it more certain that all the grains are coated with cement. On this account a mixture of fine and coarse particles is excellent.

TABLE 51

Effect on Tensile Strength of Varying Fineness of Limestone Screenings Used with Portland Cement

Age Briquets when Broken.	Tensile Strength, Pounds per Square Inch Fineness of Screenings.					
	10-20.	20-30.	30-40.	40-50.	40-80.	Pass 50.
6 months . .	718	657	633	516	. . . .	403
2 years . . .	812	754	656	. . .	516	488
4 years . . .	845	782	714	. . .	571	516

Significance of Fineness

Designation.	Sieve Number.		Approximate Mean Size of Grain.
	Passing.	Retained on.	Inch.
10-20	10	20	.057
20-30	20	30	.028
30-40	30	40	.020
40-50	40	50	.015
40-80	40	80	.012
Pass 50	50	. . . .	.008

Notes. — Three parts screenings to one cement by weight.
All briquets made by one molder and immersed in one tank.
Variations in consistency were slight, the largest percentage of water being used for the finest particles.

254. Tests on Effect of Fineness of Sand. — Many of the experiments made to show the effect of the fineness of sand on the strength of the mortar are defective, because the sand used varies in the shape of the grains and in chemical characteristics as well as in fineness. The experiments given in Table 51 were made with screenings obtained in crushing limestone, and thus all causes of variation aside from the fineness of the sand were absent, except the differences in consistency of the mortar, the uniformity in consistency depending on the judgment of the operator. The results show quite clearly the superiority of the coarser sand.

255. The Relative Effect of Fine Sand on Portland and Natural Cement. — The tests in Table 52 were made to determine

TABLE 52

Coarse and Fine Sand, — Relative Effects with Portland and Natural Cement

Age of Briquets when Broken.	Brand of Natural Cement.	Tensile Strength, Pounds per Sq. In. when Sand is 20–30	Tensile Strength, Pounds per Sq. In. when Sand is 40–80	Percentage Strength, Fine to Coarse.	Brand of Portland Cement.	Tensile Strength, Pounds per Sq. In. when Sand is 20–30	Tensile Strength, Pounds per Sq. In. when Sand is 40–80	Percentage Strength, Fine to Coarse.
28 days . .	Bn	197	145	74	A	406	337	83
	In	89	57	64	U	352	275	78
6 months . .	Bn	216	188	87	A	520	446	86
	In	364	267	73	U	499	415	83
2 years . .	Bn	256	250	98	A	546	451	83
	In	450	419	93	U	567	496	89

Notes. — Sand, limestone screenings; three parts to one cement by weight.

20–30 means sand passing sieve with 20 meshes per linear inch, and retained on sieve with 30 meshes per linear inch.

Columns 5 and 9 show percentage that strength with finer sand is of the strength with coarser sand.

the relative effects of fine sand on Portland and natural cements. Limestone screenings of two sizes of grain were used in connection with two brands of each kind of cement. At twenty-eight days the natural cement shows the decrease in strength due to the use of fine sand more than Portland cement does.

At six months the fine sand seems to have about the same effect on Portland and natural, but the two-year results indicate that the ultimate effect is less on the natural cement than on the Portland; the mean ratio of the strength obtained with fine sand to that given by coarse sand being ninety-six in the case of natural, and only eighty-six in the case of Portland. The effect of fine sand appears to decrease with age, especially with natural cement.

The fineness of sand will be treated further in the following article relating to voids.

ART. 31. VOIDS IN SAND

256. Conditions Affecting Voids. — The voids present in a given mass of sand will depend upon the shape of the grains, the degree of uniformity in size of grains, the amount of moisture present, and the amount of compacting to which the mass has been subjected. If all of the grains in a given mass of sand are of uniform size, the percentage of voids will be independent of what that size may be. In other words, the percentage of voids in a cubic foot of buckshot will be the same as in a cubic foot of bird shot; but if we take a cubic foot of a mixture of buck and bird shot we will find that the voids are much less.

257. Effect of Shape of Grain. — M. Feret has published in France the results of a large number of experiments made by him as to the voids in sand and broken stone.[1] Table 53 gives the results he obtained concerning the effect of the shape of the grains on the percentage of voids present. He first divided each sand into three parts by means of three sieves, which we will call A, B and C. Sieve A had four meshes per sq. cm. (about five meshes per linear inch), sieve B had 36 meshes per sq. cm. (about fifteen meshes per linear inch), and sieve C had 324 meshes per sq. cm. (about forty-five meshes per linear inch). The grains that passed A and were retained on B were designated G, the grains that passed B and were retained on C were designated M, and the grains that passed C were designated F. These different sizes were then recombined by taking five parts of G, three parts of M and two parts of F, and

[1] Abstracted in *Engineering News*, Vol. XXVII, p. 310.

the resulting sand was designated $G^5 M^3 F^2$. Thus, all of the sands tested had the same "granulometric" composition.

TABLE 53

Voids in Sands Having Different Shaped Grains

FROM M. FERET

Nature of Sand.	Volume of Voids Remaining in One Liter of Sand.	
	Unshaken. C.C.	Shaken to Refusal. C.C.
Natural sand with rounded grains.	359	256
Cherbourg quartzite, angular grains.	421	274
Crushed shells, flat grains.	443	318
Residue of Cherbourg quartzite crushed between jaws, laminated grains.	475	346

It is seen that the rounded grains have the smallest percentage of voids, or about thirty-six per cent. unshaken, while the laminated grains gave the largest percentage. It may also be noticed that the angular grains were compacted more by shaking than any of the others.

258. Effect of Granulometric Composition of Sand on the Percentage of Voids. — To determine the effect of uniformity of size of grain upon the percentage of voids and the strength of mortars, the author has experimented with an artificial sand formed by crushing limestone. That portion of the product that passed the coarse screen of the crusher varied in fineness from particles three-eighths of an inch in one dimension to a very fine powder, the particles of which were less than .0065 inch in one dimension. Such material admits of division into parts that differ widely in fineness, but which are essentially of the same composition, and it is therefore excellent for an experiment of this kind.

The four sieves used in first separating the material into parts had, respectively, 10, 20, 40 and 80 meshes per linear inch, the sizes of the holes being, respectively, about as follows: 0.08 inch, 0.033 inch, 0.017 inch, and 0.007 inch square. The several sizes of grain are designated as follows: —

"C," Coarse, passing No. 10, retained on No. 20.
"M," Medium, " " 20, " " 40.
"F," Fine, " " 40, " " 80.
"V," Very fine, " " 80.

M. Feret's method of designating the granulometric composition, namely, to represent by exponents the number of parts of each size of grain, has been adopted.

259. The voids were obtained by first weighing a given volume of the sand; dividing the weight by the specific gravity of the limestone, as previously determined, gives the amount of solid material in the measure, and this subtracted from the volume of the measure, gives the voids. This method is considered more nearly accurate than the usual one of measuring the amount of water required to fill the voids in a measure of sand, especially so for a sand of uniform character and one which absorbs water quite freely.

TABLE 54

Voids in Limestone Screenings, Showing Effect of Variations in Granulometric Composition

Fineness of Granulometric Composition.	Weight of One Liter of Sand, Dry, Grams.		Volume Solid Sand in One Liter (Sp. Gr. = 2.667) Cu. Cent.		Per Cent. Voids in Sand.	
	Loose.	Shaken.	Loose.	Shaken.	Loose.	Shaken.
a	*b*	*c*	*d*	*e*	*f*	*g*
C = Coarse 10 to 20	1126	1358	422	509	57.8	49.1
M = Medium 20 to 40	1140	1362	428	511	57.2	48.9
F = Fine 40 to 80	1150	1392	431	522	56.9	47.8
V = Very fine, pass 80	1165	1609	437	603	56.3	39.7
C	...	1395	...	523	...	47.7
M	...	1439	...	540	...	46.0
F	...	1459	...	547	...	45.3
V	...	1656	...	621	...	37.9
C^{65}, M^{25}, F^{15}, V^{5}	...	1606	...	602	...	39.8
C^{40}, M^{30}, F^{20}, V^{10}	...	1732	...	649	...	35.1
C^{25}, M^{25}, F^{25}, V^{25}	...	1912	...	717	...	28.3
C^{30}, M^{25}, F^{15}, V^{30}	...	1850	...	694	...	30.6
C^{50}, M^{0}, F^{0}, V^{50}	...	1991	...	746	...	25.4

The results obtained are given in Table 54. Comparing the voids in C, M, F and V, it is seen that the first three have nearly the same percentage, but V has less voids than the others. This is explained by the fact that this sample was made up of all sizes smaller than the holes in No. 80 sieve, down to the fine powder. Comparing the mixed sands, it is seen that the sample made up of equal parts of coarse and very fine had the least voids, the percentage being only a little more than half of that obtained with coarse particles alone. The next lowest percentage was given by the sample having equal parts of four sizes.

It is apparent that the granulometric composition has a very important effect on the percentage of voids. When one desires to make a compact mortar with as small a quantity of cement as possible, similar tests might well be made with the materials available for use.

260. Effect on Strength of Mortars of Varying the Granulometric Composition of Sand. — Table 55 gives the results of tensile tests of mortars made with limestone screenings of various granulometric compositions. The differences in strength are not very great, but it appears that with one-to-three mortars the highest strength is developed at six months, with the coarse grains alone, but when poorer mortars are in question the result is affected by the percentage of voids in the sand.

TABLE 55

Limestone Screenings with Portland Cement. Effect on Tensile Strength of Variations in Granulometric Composition of Sand

Granulometric Composition of Sand. Per Cent. of Each Size Grain.				Voids. %	Tensile Strength at 6 Mos. Pounds per Sq. In. with Parts Sand to One Cement by Weight.		Weight of Briquets in Grams.	
C	*M*	*F*	*V*		3	5	3	5
0	100	0	0	46	509	324	1465	1438
40	30	20	10	35	505	392	1466	1480
25	25	25	25	31	470	356	1445	1455
30	25	15	30	28	496	391	1448	1470
50	0	0	50	25	487	349	1455	1460

Cement. — Portland, Brand R. For significance of composition of sand, see text.

261. Table 56 gives the results of similar tests of both Portland and natural cement with Point aux Pins sand dredged from St. Marys River and containing a very large percentage of quartz grains. The sand was divided into but three parts by sifting, and was then remixed, the proportion of each size being indicated in the table. The results verify the conclusions already drawn that the coarser sands give the higher strength. It appears that not more than one-half of the grains should be very fine if the best results are desired.

TABLE 56

Varying the Granulometric Composition of River Sand. Effect on Value of, for Use in Cement Mortar

Composition of Sand as to Fineness.			Tensile Strength, Pounds per Square Inch.							
Parts Used that Passed No. 20 Sieve and Retained on No. 30.	Parts Used, 30-40	Parts Used that Passed No. 40 Sieve.	Portland Cement with Two Parts Sand to One Cement by Weight, at age of				Natural Cement with Three Parts Sand to One Cement by Weight, at age of			
M	*F*	*V*	28 da.	6 mo.	1 yr.	2 yr.	28 da.	6 mo.	1 yr.	2 yr.
10	0	0	342	471	560	591	77	267	348	341
4	1	5	300	448	515	507	77	237	304	319
2	4	4	290	425	494	503	79	278	291	325
1	3	6	246	384	455	442	46	222	234	251
1	2	7	271	366	456	438	67	226	247	251

Note. — River sand, mostly quartz, obtained at Point aux Pins. Each result mean of five briquets, all made by one molder.

262. Effect of Moisture. — The effect of a small amount of moisture on the bulk of a given weight of sand is not usually appreciated, but it may easily be shown that it is very marked. The results in Table 57 were obtained by adding small amounts of water to a given bulk of dry sand. Each time, after the water was added, the sand was stirred up and the weight of a given volume of the moist sand was obtained. It appears that the finer sands are affected more than coarse ones.

In the case of the limestone screenings 40–80, if we add but 3.7 per cent. water to a given quantity of dry sand, the bulk of the sand is so increased that if we take 1,000 c.c. of the moist sand it will contain but 720 c.c. of dry sand. The voids are, of course, correspondingly increased from 54.5 per cent. to 67.2 per cent.

The cause of this increase in bulk is that each grain of sand is surrounded by a film of water which prevents the grains from lying close together after they have been disturbed. A large amount of air is also imprisoned in the mass. It may be noticed that the difference in bulk between moist and dry sand is greater when the measurements are made "loose."

TABLE 57

Volume of Sand and Voids as Affected by the Addition of Water

Reference.	Sand.		Water Expressed as Per Cent. of Dry Sand by Weight.	Weight of Dry Sand in One Liter of Moist Sand.		Volume of Dry Sand in One Liter of Moist Sand.		Per Cent. Voids in Sand by Volume.	
	Kind.	Fineness.		Loose, Grams.	Shaken, Grams.	Loose, Cu. Cent.	Shaken, Cu. Cent.	Loose.	Shaken.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*
1	Crushed Limestone.	10–20	0.0	1288	1489	1000	1000	. .	. .
2	"	"	4.8	1094	1367	849	919	. .	. .
3	"	"	7.7	1023	1295	794	869	. .	. .
4	"	"	11.9	996	1276	773	857	. .	. .
5	"	40–80	0.0	1214	1481	1000	1000	54.5	44.5
6	"	"	0.85	1124	1489	926	1005	57.9	44.2
7	"	"	1.5	1059	1470	872	993	60 3	44.9
8	"	"	2.2	950	1383	782	934	64.4	48.2
9	"	"	3.7	875	1298	720	877	67.2	51.4
10	"	"	6.3	824	1274	679	860	69.1	52.3
11	"	"	7.8	799	1266	658	855	70.0	52.6
12	"	"	12.3	817	1280	672	864	69.4	52.0
13	"	"	16.8	829	1306	683	881	69.0	51.1
14	"	"	20.2	836	1274	689	860	68.6	52.3
15	"	"	25.3	891	1357	783	916	66.6	49.1
16	"	"	30.3	1049	1270*	864	858*	. .	. .
17	"	Pass 80	0.0	1185	1500	1000	1000	. .	. .
18	"	"	2.4	1038	1394	873	929	. .	. .
19	"	"	5.1	835	1281	704	854	. .	. .
20	"	"	12.2†	806	1310	680	873	. .	. .
21	"	"	17.7†	806	1260	680	840	. .	. .
22	Point aux Pins.	‡	0.0	1725	. .	1000	. .	. .	. .
23	"	‡	2.0	1405	. .	815	. .	. .	. .
24	"	‡	4.0	1400	. .	810	. .	. .	. .
25	"	‡	6.0	1400	. .	810	. .	. .	. .
26	"	‡	10.0	1415	. .	820	. .	. .	. .
27	"	‡	11.6	1425	. .	825	. .	. .	. .
28	"	‡	18.4	1485	. .	860	. .	. .	. .

* Not jarred down in measure as much as usual. Water rose to surface.

† Sand crumbled like damp earth.

‡ Fineness of Point aux Pins Sand

	20	30	40	50	80
Sieves No.	20	30	40	50	80
Approx. size holes =	.033	.022	.017	.012	.007
Per cent. passing	96.0	82.3	46.6	6.7	1.2

Note. — 10–20 = passing No. 10 sieve (holes about .08 in. sq.) and retained on No. 20 sieve.

263. This subject is of great importance in proportioning mortars, because, in construction, the amounts of cement and sand are usually measured. Suppose it is desired to use a mixture of one hundred pounds of cement to four hundred pounds of sand, and for convenience we will suppose the packed cement and dry sand each weigh one hundred pounds per cubic foot. If now we use damp sand, containing about 3.5 per cent. water, instead of dry sand, and measure the materials, we would have four cubic feet of damp sand to one cubic foot of cement; but damp sand would contain only about $4 \times 75 = 300$ pounds of dry sand, and we would really have a one-to-three mixture instead of a one-to-four.

Art. 32. Impurities in Sand

264. The usual specification for sand is that it shall be "clean, sharp and siliceous." We have shown that it need not be siliceous, and we have also noted that one authority considers that it need not be sharp, though this latter does not appear to be proven; let us see what interpretation should be given to the word "clean" if it must be retained in all specifications for sand.

Mr. E. C. Clarke, in the tests for the Boston Main Drainage Works, showed that "clay in moderate amounts" (ten per cent. to thirty per cent. of the sand) "does not weaken cement mortars." Calcareous marl might be considered an impurity, but we have seen that M. Alexandre found that sands containing this material gave excellent results. On the other hand, there seems to be no doubt that loam, peaty matter or humus will very materially decrease the strength of mortars, or even destroy them entirely. Likewise, decayed particles of some kinds of stone, or grains which readily break up into thin scales, should be strenuously avoided.

265. Detection of Impurities. — Clean sand when rubbed in the hand will not leave fine particles adhering to it, but should the sand not prove to be clean, the character of the impurities should be investigated before finally rejecting it. When there is not time for making proper tests, it will, of course, be safest to use only such sand as has no foreign matter whatever; but when strictly pure sand can only be obtained at great cost, tests may show that a small percentage of impurities may be tolerated.

Another simple test, beside the one of rubbing in the hand, is to place a little of the sand in a test tube filled with water; if any impurities are present, they may separate from the sand on account of their lighter weight, or if in a very fine state of division, the water may be rendered murky in appearance. This test is not absolute, however, especially for calcareous sand, as the fine particles of limestone will give the murky appearance to the water, although not objectionable except on account of their extreme fineness.

The use of poor sand will result in a larger proportionate decrease in strength for a mortar containing a large amount of sand than for one made with a small amount. The effect of incorporating various foreign substances in cement mortar is treated in Art. 49. As some of these substances may occur in sand, the article referred to should be read in connection with this subject.

266. SAND WASHING. — When impurities occur, they may sometimes be removed by washing, but such work must be carefully inspected if the foreign matter be of a really dangerous character.

In the construction of the Canal at the Cascades, Columbia River, Oregon, quite an elaborate concrete plant was established, which had in connection a sand and gravel washer and separator.[1] This consisted of a tube about two and one-half feet in diameter and seventeen feet long, made of one-quarter-inch boiler iron and revolving about an axis slightly inclined to the horizontal. Angle irons were riveted on the inside of the tube to carry the material up on the side and drop it again, while a spray of water issued from a perforated pipe inside the tube. The materials were separated by screens near the lower end of the tube. The material contained considerable earthy matter and is said to have been fairly well washed by this process.

Another style of sand washer was designed by the contractors for the construction of Lock No. 3, improvement of Alleghany River.[2] The sand contained earthy matter and some coal, the latter being hard to remove by ordinary processes. A

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[1] Report of Lt. Edw. Burr, Report Chief of Engineers, 1891, p. 3334.

[2] W. H. Rober, *Engineering News*, Feb. 16, 1899.

large barrel or tank, nine feet in diameter and seven feet high, was provided with double floor, the upper one being pierced with one-inch holes. Paddles were attached to a vertical shaft in the axis of the tank and revolved by suitable gearing, while water was forced into the space between the two floors. The water finding its way through the holes in the upper floor, passed up through the sand and overflowed at the top, carrying with it the coal and sediment. The cost of washing is said to have been about seven cents per cubic yard, but it is evident that methods of handling would have to be quite perfect to keep the cost at so low a figure.

ART. 33. CONCLUSIONS. WEIGHT. COST

267. REQUIREMENTS FOR GOOD SAND. — In conclusion, then, we may say that good sand may consist of grains of almost any moderately hard rock that is not liable to future alteration in the work. The grains may be of any shape, but preferably should be sharp and angular or lenticular in form, not rounded and smooth. The sand should not contain such impurities as loam or humus, but for most purposes a small percentage of clay or fine rock dust is not objectionable. Clay should not, however, be permitted in sand for use in sea water.

Coarse grained sands are better than fine grained ones, but a mixture of fine and coarse is excellent, especially where but a small amount of cement is used, because such a mixture contains less voids and will make a less permeable mortar, while giving a good strength. As might be expected, the deleterious effect of poor sand is more apparent the larger the dose of sand used.

268. Weight of Sand. — It is evident from what has preceded that the weight of sand per cubic foot will vary greatly, not only with the character of the rock from which it came, but also with its physical condition. Natural sand, as it ordinarily occurs, will weigh about as follows, according to its condition: —

Moist and loose	70 to 90	pounds per cu. ft.	
Moist and shaken	75 to 100	"	"
Dry and loose	75 to 105	"	"
Dry and shaken	90 to 125	"	"
When settled in water, weight of wet sand, voids full	100 to 140	"	"

If the rock from which the sand is made weighs, say, one hundred sixty pounds per cubic foot solid (specific gravity, 2.56), then the sand will weigh per cubic foot 120, 100, and 80 pounds, for voids of 25, 37.5 and 50 per cent., respectively.

269. Cost of Sand. — The cost of sand will, of course, vary with the locality. In exceptional cases where it is found directly at the works, it may not cost more than twenty to thirty cents per cubic yard to deliver it on the mixing platform. If it has to be pumped from the bed of a river or lake and can be conveyed to the work in scows with a tow of not more than ten miles, it may be delivered at the work for from forty to sixty cents per cubic yard. If it must be hauled in wagons for some distance, it may cost from fifty cents to one dollar per yard; and again, if sand is so difficult to obtain that it must be made by crushing rock, it may cost from one dollar to three dollars per yard. Usually from sixty cents to a dollar is a fair price for sand. Several examples of cost of sand will be given in connection with the subject of cost of concrete.

CHAPTER XII

MORTAR: MAKING AND COST

ART. 34. PROPORTIONS OF THE INGREDIENTS

270. CAPACITY OF CEMENT BARRELS. — Since there is no standard size for cement barrels, the capacities vary considerably, Portland cement barrels ranging from 3.1 to 3.6 cu. ft., while natural cement barrels contain from 3.4 to 3.8 cu. ft. In Germany cement is packed to weigh three hundred ninety-six pounds per barrel, gross, the net weight being about three hundred seventy-five pounds. American Portland usually weighs four hundred pounds gross or about three hundred eighty pounds net.

In 1896 the Boston Transit Commission had a number of measurements made of the capacity of Portland cement barrels, and these have been compiled by Mr. Sanford E. Thompson.[1] Table 58 presents some of the averages obtained from this series of tests. It is seen that the capacity of the barrels varied from 3.12 to 3.50 cu. ft., the mean volume being 3.29 cu. ft. The difference between the capacity of the barrel and the volume of the packed cement contained is due to the fact that there is usually a small space beneath the head not filled with cement. A barrel of packed cement makes about 1.25 barrels, measured loose.

271. Natural cements made in the East are packed to weigh three hundred pounds net, while some of the Western natural cements weigh but two hundred sixty-five pounds per barrel net. Any of the natural cement factories will doubtless pack their cement to suit customers on large orders, and there seems to be little reason for this variation in weight between the West and the East. There would perhaps be some trouble in getting three hundred pounds of a very light, finely ground, natural cement in the ordinary sized barrel, but two hundred

[1] *Engineering News*, Oct. 4, 1900.

TABLE 58

Capacity of Portland Cement Barrels

	HIGHEST.	LOWEST.	MEAN.
Height of barrel between heads, feet	2.19	2.01	2.00
Capacity between heads, cubic feet	3.50	3.12	3.29
Volume of packed cement in barrel, cubic feet .	3.48	3.03	3.18
Volume of loose cement in barrel, cubic feet . .	4.19	3.75	4.07
Net weight of cement in barrel, pounds . . .	387.0	370.7	377.4
Weight per cubic foot of cement as packed in barrel, pounds	123.16	113.81	118.79
Weight per cubic foot, loose, pounds	100.49	88.52	92.63

NOTE. — Results are averages of thirty-one tests with seven brands, four of which were American. The above data compiled by Sanford E. Thompson and published in *Engineering News* of Oct. 4, 1900.

eighty pounds may be put in a barrel without difficulty, and it would seem that a compromise might be made on this weight.

272. QUANTITY OF SAND. — The amount of sand to be used in mortar will depend entirely on the character of the work and the quality of the cement and sand. If it is merely a matter of strength to be developed, no special care need be taken to have the voids in the sand filled with cement, but if an impervious mortar is desired, the mortar must not be too poor in cement, even though only a moderate strength is required.

In France the proportions of cement and sand are usually given in terms of kilograms of cement to one cubic meter of sand. In England and America the proportions are usually given by volume, as so many parts of cement to one of sand, while in Germany the proportions are given by weight. The bulk of cement varies so much according to the degree of packing, and the volume of sand is so varied by the amount of moisture contained, that the German method of stating proportions by weight seems to be the most logical one to adopt.

273. Proportions by Volume. — It has been shown that the volume of a given quantity of cement may vary twenty-five per cent. according as it is measured packed or loose, and that likewise the volume of sand may vary twenty per cent. according to the amount of moisture contained. This makes it necessary to take great precaution in proportioning mortars by volume if the desired richness of the mortar is to be assured. Nevertheless, mortars for use in actual construction are usually proportioned by volume. The usual method is to state the proportions as one part of packed cement (as it comes in the barrel or bag) to so many parts of loose sand, but proportions are sometimes stated as volumes of loose sand to one volume of loose cement.

274. Equivalent Proportions by Weight and Volume. — As cement is now so frequently sold in sacks of one-fourth barrel each, in which the cement is not so compact as in a barrel, we have assumed the contents of a barrel to be 3.45 cu. ft. for Portland, and 3.75 cu. ft. for natural, which are somewhat higher than the mean actual capacities of stave barrels as shown by tests. At three hundred eighty pounds and two hundred eighty pounds net weight respectively for Portland and natural, this is equivalent to one hundred ten pounds per cubic foot and seventy-five pounds per cubic foot packed. If we also assume that loose cement weighs eighty-five pounds per cubic foot for Portland and sixty pounds per cubic foot for natural; and that loose, dry sand weighs one hundred pounds per cubic foot, while loose, damp sand weighs eighty pounds per cubic foot, we may obtain the following comparisons, Table 59.

275. It is evident that in all specifications and in reports of tests, as well as in the use of cement, the method of stating proportions should be made clear, and in interpreting the results of tests this must be borne in mind. For instance, in tests to compare the value of limestone screenings with quartz sand, proportions by weight will favor the quartz, while proportions by volume will favor the screenings, since the latter are lighter.

276. Richness of Mortar. — Mortars containing small amounts of sand are often stronger than neat cement mortars. Especially is this true of most natural cements. Some of these will give as high strengths when mixed with two parts sand by weight as when neat, and usually the one-to-one mortars are stronger than the neat mortars. These remarks refer to tensile tests where a good quality of sand is used and the mortars are three months old or more. The neat cement mortars gain their strength more rapidly, short time tests usually not showing the results mentioned. Portland cements of good quality

TABLE 59

Comparison of Proportions by Weight and Volume

Parts Dry Sand to One Cement by Weight.	Equivalent Parts Sand, Proportions Stated by Volume.							
	Portland Cement.				Natural Cement.			
	Parts Loose Dry Sand to One of Packed Cement.	Parts Loose Damp Sand to One of Packed Cement.	Parts Loose Dry Sand to One of Loose Cement.	Parts Loose Damp Sand to One of Loose Cement.	Parts Loose Dry Sand to One of Packed Cement.	Parts Loose Damp Sand to One of Packed Cement.	Parts Loose Dry Sand to One of Loose Cement.	Parts Loose Damp Sand to One of Loose Cement.
1	1.10	1.38	0.85	1.06	0.75	0.94	0.60	0.75
2	2.20	2.75	1.70	2.12	1.50	1.88	1.20	1.50
3	3.30	4.12	2.55	3.19	2.25	2.81	1.80	2.25
4	4.40	5.50	3.40	4.25	3.00	3.75	2.40	3.00
5	5.50	6.88	4.25	5.31	3.75	4.69	3.00	3.75
6	6.60	8.25	5.10	6.38	4.50	5.62	3.60	4.50

In preparing the above table the following assumptions are made:

Material.	Weight in a Barrel.	Volume of a Barrel.	Weight per Cubic Foot.		
			Packed.	Loose Dry.	Loose Damp.
Portland cement .	380	3.45 cu. ft.	110	85	. .
Natural cement .	280	3.75 cu. ft.	75	60	. .
Sand	. .	. . . .	. .	100	80

usually give about the same tensile strength neat and with one part sand by weight. Tests showing the rate of decrease of strength with added sand are discussed in §§363 to 365.

Portland cements are usually mixed with from one to three parts sand by weight, and natural cements are mixed with from one to four parts by weight (or three-fourths part to three parts by measure). For certain special purposes poorer mortars are sometimes employed. To arrive at the proper proportion to use in mortar for a given purpose, the tables of strength given in Chapter XV will be of value.

277. Effect of Pebbles. — If the sand contains pebbles, the proportions should be considered in a little different way. Suppose we make a one-to-three mortar with sand that contains ten per cent. of pebbles. We have in reality, then, $3 \times .90 = 2.7$ parts of sand to one of cement, and .3 part pebbles embedded in this richer mortar. This point is of special significance in making concrete from gravel containing some sand, or from broken stone from which the fine particles or screenings have not been removed. Such fine particles serve to weaken the mortar by increasing the dose of sand, while the proportion of aggregate is diminished. In using aggregates containing some fine material, then, or in using sand containing pebbles or fine gravel, one should not permit himself to be deceived as to the actual richness of the resulting mortar or concrete.

278. AMOUNT OF WATER FOR MORTAR. — The amount of water required for mortar will vary with the proportion of sand to cement, the character and condition of the ingredients, the weather, and the purpose which the mortar is to serve. If the water is stated as such a percentage of the combined weight of cement and sand, the amount required for a rich mortar will be greater than for a poor one, since the cement requires more water than the sand. Fine cement will require more water than coarse; the same is true of sand. Sand from absorbent rock will require a larger amount of water. On a hot, dry day, more water must be used to allow for evaporation; and again, if the mortar is to be placed in contact with brick or porous stone, the mortar must be more moist than when used in connection with metal, or with hard rocks such as granite. All of these points must be borne in mind when determining the proper consistency for a given purpose.

279. We may arrive at the approximate amount of water required in the following manner: find what proportion of water is required for the neat cement. This will vary among different samples, and especially between Portland and natural cements; the former requiring twenty to twenty-eight per cent. of water (by weight), and the latter thirty to forty per cent. Then find the amount of water required to bring the sand alone to the consistency of mortar. This will vary considerably, fine sand requiring much more water than coarse, etc., as mentioned above. Having these two quantities, we may find the amount of water required for a mortar having any given proportions of these samples of cement and sand. Thus, suppose we find that the neat cement requires twenty-five per cent. water and the sand ten per cent. water to bring them to the proper consistency. If we wish to make a one-to-three mortar from these ingredients, using one hundred pounds of cement, the required amount of water is $(100 \times .25) + (100 \times 3 \times .10) = 25 + 30 = 55$ pounds.

280. However, it will usually be better to experiment directly upon the mixture which it is proposed to use, and for this purpose the following rule will be found of value. For ordinary purposes, that amount of water should be used which for given weights of the dry ingredients will give the least volume of mortar with a moderate amount of packing. In the actual use of mortars it is not practicable to state that a certain definite amount of water shall always be used with given quantities of the dry materials. It is the resulting consistency of the mortar that must be specified and insisted upon, while the amount of water required to produce this consistency will vary from day to day and must be left to the discretion of the inspector or foreman. For a discussion of the relation of consistency to the tensile strength of the mortar, see Art. 46.

ART. 35. MIXING THE MORTAR

281. Having decided upon the proportions of cement, sand and water, it remains to incorporate these into a plastic, homogeneous mass. The size of the batch should be so adjusted, if possible, that a full barrel of cement shall be used, and for careful work the amount of sand should be weighed instead of measured. Where this is impracticable, the condition of the sand from day to day, as regards the amount of moisture contained, should be taken into account (see §§ 262 and 263).

Mortar is usually mixed by hand, but where large amounts are to be used, machine mixers may profitably be introduced.

282. HAND MIXING. — For hand mixing, a water tight platform or shallow box should be used, of such a size that the given batch will not cover the bottom more than four inches deep.

If the sand is measured, a bottomless box, provided with two handles at each end, will be found more convenient than the bottomless barrel which is often employed for this purpose. When the sand is delivered on the mixing platform in barrows, the latter may be fitted with rectangular boxes to avoid remeasuring. A two-wheel cart, the box of which may be inverted to discharge the contents on the mixing platform, will also be found very serviceable when the runway is suited to such a vehicle.

The proper amount of sand is evenly spread on the platform, the cement is then dumped on top of the sand and spread out over it to an even thickness. With either hoes or shovels the dry materials are then thoroughly mixed, until, when a small amount is taken in the hand, it will appear of uniform color throughout. From two to five turnings of the materials, according to the expertness of the workmen, will be required to produce this result. The dry mixture is then drawn to the edges of the platform to form a ring, and the requisite amount of water is added at one time in the center. The mixture is then gradually incorporated with the water, and the mass is thoroughly worked until plastic and homogeneous. Should it be found that too little water has been used, a small amount may be added from a sprinkling pot or rose nozzle, but the mass should always be worked over again after such addition. Four shovels may be used at one platform, but if the mixing is done by hoes, not more than two can be used to advantage with a batch of ordinary size.

Some engineers prefer one method and some the other, but in whatever manner done, the mixing should not be stinted. From two to four turnings of the mass are usually considered sufficient, but as a general rule it will be found that further mixing, beyond that required to just give the mass a uniform appearance, will be amply repaid in the strength of the resulting mortar. (See Art. 47.)

283. Machine Mixing. — Where large quantities of mortar are required, machine mixers are sometimes used. A very complete plant for mortar-making was used in building the Titicus Dam.[1] In this case machinery was used in measuring the proportions of cement and sand as well as in making the mortar. The measuring apparatus consisted of two cylindrical troughs, one for cement and one for sand. Each trough was divided, by means of six radial vanes and four discs, into eighteen equal compartments. These cylinders revolved in cast iron boxes which were so constructed as to serve as hoppers for filling the compartments. Three compartments were presented to the hoppers at once, and slides were provided by which any of the hoppers could be cut off at will. The cylin-

[1] *Engineering Record*, August 3, 1895.

ders being geared to the same pinion, it was possible, by means of the slides, to make any desired proportion of cement and sand from neat cement, to three parts sand to one cement.

The mixing machine "consisted essentially of a semi-cylindrical wrought-iron trough with extended flaring sides, with elements slightly inclined to the horizontal, and in its axis a revolving shaft with oblique radial blades set at an incline of ninety degrees to each other and of a length to just clear the bottom of the trough."

284. Another form of machine that is sometimes employed consists of a semi-cylindrical trough in which rotates an axis carrying a blade in the form of a screw. The materials are fed to the mixer at one end and the screw mixes them while working the mass toward the other end.

ART. 36. COST OF MORTAR[1]

285. INGREDIENTS REQUIRED FOR ONE CUBIC YARD OF MORTAR.—The character of the ingredients used in making cement mortar varies so much that it is difficult to accurately determine the quantities of materials required for a proposed mortar except by experimenting with the materials that are to be employed. It has been shown that the weights per cubic foot of both cement and sand vary greatly according to the conditions of packing, the moisture, etc. The percentage of voids in the sand is one of the most important variations affecting the amount of mortar made with certain materials mixed in given proportions. The consistency of the mortar also has a marked effect, and different cements show a considerable variation in the volume of mortar that a given weight will yield. In any general treatment of the question, then, we may expect only approximate results, and the tables given in this connection must be considered in this light.

286. Results of Experiments. — The tests from which Tables 60 and 61 were derived, were made with a natural sand weighing about one hundred pounds to the cubic foot, dry, and having about three-eighths of the bulk voids. The grains varied in size from 0.01 in. to 0.1 in. in diameter with a few grains out-

[1] Portions of this article were contributed to "*Municipal Engineering*," and appeared in that magazine, Feb., 1899.

TABLE 60

Ingredients Required for One Cubic Yard of Mortar, Portland Cement

SAND WEIGHS ABOUT 100 LBS. PER CUBIC FOOT. VOIDS THREE-EIGHTHS OF VOLUME

Parts Sand to 1 of Cement.	Proportions by Weight, Dry Sand and Cement.			Proportions by Volume Dry Loose Sand to Packed Cement, Packed Cement Assumed at 104 lbs. per Cu. Ft. or 380 lbs. per Bbl. of 3.65 Cu. Ft.			Proportions by Volume Dry Loose Sand to Packed Cement, Cement Assumed at 114 lbs. per Cu. Ft. or 380 lbs. per Bbl. of 3.33 Cu. Ft.			Proportions by Volume Dry Loose Sand to Loose Cement, Loose Cement Assumed at 85 lbs. per Cu. Ft.		
	Cement.		Sand Cu Yd.	Cement.		Sand Cu. Yd.	Cement.		Sand Cu. Yd.	Cement.		Sand Cu Yd.
	Pounds.	Bbls. of 380# Net.		Pounds.	Bbls. of 380# Net.		Pounds.	Bbls. of 380# Net.		Pounds.	Bbls. of 380 Net.	
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*
0	2810	7.40	0.00	2810	7.40	0.00	2810	7.40	0.00	2810	7.40	0.00
1	1555	4.08	0.57	1585	4.17	0.56	1640	4.32	0.54	1440	3.79	0.64
2	1050	2.76	0.78	1080	2.84	0.77	1140	3.00	0.74	930	2.45	0.81
3	760	2.00	0.84	785	2.06	0.84	850	2.24	0.82	660	1.74	0.87
4	600	1.58	0.88	615	1.62	0.88	665	1.75	0.87	515	1.36	0.90
5	490	1.29	0.91	505	1.33	0.90	550	1.45	0.89	425	1.12	0.92
6	420	1.10	0.93	435	1.14	....	470	1.24	0.91	.....	....	....
7	.....	....	....	.....	....	....	410	1.08	0.93	.....	....	....

TABLE 61

Ingredients Required for One Cubic Yard of Mortar, Natural Cement

SAND WEIGHS ABOUT 100 LBS. PER CUBIC FOOT. VOIDS THREE-EIGHTHS OF VOLUME

Parts Sand to 1 of Cement.	Proportions by Weight, Dry Sand and Cement.					Proportions by Volume Dry Loose Sand to Packed Cement, Cement Assumed at 71# per Cubic Foot or 265# Net per Bbl.			Proportions by Volume Dry Loose Sand to Packed Cement, Packed Cement Assumed at 75# per Cu. Ft. or 280# Net per Bbl.			Proportions by Volume Dry Loose Sand to Packed Cement, Cement Assumed 80# per Cu. Ft. or 300# Net per Bbl.			Proportions by Volume Dry Loose Sand to Loose Cement, Loose Cement Assumed at 60# per Cubic Foot.				
	Cement.					Cement.			Cement.			Cement.			Cement.				
	Pounds.	Bbls. of 265# Net.	Bbls. of 280# Net.	Bbls. of 300# Net.	Sand, Cubic Yard.	Pounds.	Bbls. of 265# Net.	Sand, Cubic Yard.	Pounds.	Bbls. of 280# Net.	Sand, Cubic Yard.	Pounds.	Bbls. of 300# Net.	Sand, Cubic Yard.	Pounds.	Bbls. of 265# Net.	Bbls. of 280# Net.	Bbls. of 300# Net.	Sand, Cubic Yard.
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*	*t*
0	2240	8.45	8.00	7.47	0.00	2240	8.45	0.00	2240	8.00	0.00	2240	7.47	0.00	2240	8.45	8.00	7.47	0.00
1	1380	5.21	4.93	4.60	0.51	1180	4.45	0.61	1210	4.32	0.60	1250	4.17	0.58	1080	4.08	3.86	3.60	0.67
2	970	3.66	3.46	3.23	0.72	750	2.83	0.78	780	2.79	0.77	825	2.75	0.76	660	2.49	2.36	2.20	0.81
3	720	2.72	2.57	2.40	0.80	540	2.04	0.85	570	2.03	0.84	600	2.00	0.83	470	1.77	1.68	1.57	0.87
4	570	2.15	2.03	1.90	0.84	425	1.60	0.89	450	1.60	0.88	470	1.57	0.87	...	...	...	...	...
5	470	1.77	1.68	1.57	0.87	...	...	...	...	...	...	390	1.30	0.90	...	...	...	...	...
6	400	1.51	1.43	1.33	0.89	...	...	...	...	...	...	...	...	...	...	...	...	...	...

side of these limits. The consistency of the mortar was such that when struck with the shovel blade the moisture would glisten on the smooth surface thus formed. In the experiments the proportions were determined by weight, and the results for proportions by volume were deduced from them. The results for neat natural cement mortar and for the natural cement mortars containing more than four parts sand by weight were derived by analogy.

287. Explanation of Tables. — The first section of Table 60 gives the amount of materials required for Portland cement mortar when the proportions are stated by weight; the second and third sections refer to proportions by volume of loose sand to packed cement when the size of the cement barrel is assumed at 3.65 cu. ft. and 3.33 cu. ft., respectively. The fourth section gives the materials required when the proportions are given in terms of loose sand to loose cement. Likewise, the first section of Table 61 for natural cement refers to proportions by weight; the second, third and fourth sections, to proportions by volume of loose sand to packed cement when the cement weighs 265 pounds, 280 pounds and 300 pounds, net. per barrel, respectively; while the fifth section refers to proportions of loose sand to loose cement.

As has been shown, the method of stating proportions by weight is the most accurate, but when the sand does not approximate the weight of 100 pounds per cubic foot when shoveled dry into a measure, the sections of the tables referring to weight proportions may require a correction, and it may be simpler to use the sections giving proportions by volume of loose sand to packed cement. The method of stating proportions by volumes of loose sand to loose cement is to be deprecated, but since it is occasionally used, provision is made for it in the tables.

In using those portions of the tables where the proportions are stated by volume, it should be borne in mind that if the sand is damp when used it will weigh less per cubic foot, and hence more, by measure, will be required to make a cubic yard of mortar.

288. Estimating Cost of Mortar. — With the data given in Tables 60 and 61 and a knowledge of unit prices of the materials used in the mortar, one may estimate the cost of the materials in a given quantity of mortar. The cost of the mixing will, of course, depend upon the cost of labor, the method employed, etc., and may vary from fifty cents to a dollar and fifty cents per cubic yard. If we assume, for illustration, that natural cement can be delivered on the mixing platform for $1.10 per barrel of 280 pounds net, that sand costs 60 cents per cubic yard, and the mixing costs $1.00 per yard of mortar, then we have for the cost of a mortar composed of one part cement to two parts sand by weight: —

3.46 bbls. cement at $1.10	$3.80
0.72 cu. yd. dry sand at .60	.43
Cost of mixing per cu. yd.	1.00
Total cost of one cu. yd. of mortar	$5.23

289. For approximate results, Tables 62 and 63 give the cost of the materials used in a cubic yard of mortar for different prices of cement. In Table 62 the proportions by weight only are indicated, since for Portland the proportions by volume of loose sand to packed cement vary so little from proportions by weight.

TABLE 62

Cost of Portland Cement Mortar

COST OF CEMENT AND SAND IN ONE CUBIC YARD OF PORTLAND CEMENT MORTAR. SAND, 75 CENTS PER CUBIC YARD

COST OF PORTLAND CEMENT PER BARREL OF 380 POUNDS NET.	COST OF INGREDIENTS IN MORTAR, IN DOLLARS. Proportions in Mortar by Weight, — Parts Sand to One of Cement.						
	0	1	2	3	4	5	6
$1.20	8.90	5.33	3.89	3.03	2.56	2.23	2.02
1.30	9.62	5.73	4.17	3.23	2.72	2.36	2.13
1.40	10.36	6.14	4.44	3.43	2.88	2.49	2.24
1.50	11.10	6.55	4.72	3.63	3.03	2.62	2.35
1.60	11.84	6.96	5.00	3.83	3.19	2.75	2.46
1.70	12.58	7.37	5.27	4.03	3.35	2.88	2.57
1.80	13.32	7.77	5.55	4.23	3.51	3.01	2.68
1.90	14.06	8.18	5.82	4.43	3.67	3.13	2.79
2.00	14.80	8.59	6.10	4.63	3.82	3.26	2.90
2.10	15.54	9.00	6.38	4.83	3.98	3.39	3.01
2.20	16.28	9.41	6.65	5.03	4.14	3.52	3.12
2.30	17.02	9.81	6.93	5.23	4.30	3.65	3.23
2.40	17.76	10.22	7.20	5.43	4.46	3.78	3.34
2.50	18.50	10.63	7.48	5.63	4.61	3.91	3.45
2.60	19.24	11.04	7.76	5.83	4.77	4.04	3.56
2.70	19.98	11.45	8.03	6.03	4.93	4.17	3.67
2.80	20.72	11.85	8.31	6.23	5.09	4.30	3.78
2.90	21.46	12.26	8.58	6.43	5.25	4.42	3.89
3.00	22 20	12.67	8.86	6.63	5.40	4.55	4.00

TABLE 63

Cost of Natural Cement Mortar

COST OF CEMENT AND SAND IN ONE CUBIC YARD OF NATURAL CEMENT MORTAR. SAND, 75 CENTS PER CUBIC YARD

Method of Stating Proportions, and Weight of Cement in One Barrel.	Parts Sand to 1 of Cement.	Cost of Cement per Barrel, Dollars.									
		0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50
Proportions by weight. Barrel 265 lbs. net.	0	5.07	5.92	6.76	7.60	8.45	9.30	10.14	10.98	11.83	12.68
	1	3.50	4.02	4.54	5.06	5.59	6.11	6.63	7.15	7.67	8.19
	2	2.74	3.10	3.47	3.83	4.20	4.57	4.93	5.30	5.66	6.03
	3	2.23	2.50	2.78	3.05	3.32	3.59	3.86	4.14	4.41	4.68
	4	1.90	2.12	2.33	2.54	2.76	2.98	3.19	3.41	3.62	3.83
Proportions by weight. Barrel 300 lbs. net.	0	4.48	5.23	5.98	6.72	7.47	8.22	8.96	9.71	10.46	11.20
	1	3.14	3.60	4.06	4.52	4.98	5.44	5.90	6.36	6.82	7.28
	2	2.48	2.80	3.12	3.45	3.77	4.09	4.42	4.74	5.06	5.38
	3	2.04	2.28	2.52	2 76	3.00	3.24	3.48	3.72	3.96	4.20
	4	1.75	1.94	2.13	2.32	2.51	2.70	2.89	3.08	3.27	3.46
By volume; parts dry loose sand to packed cement. Cement assumed 265 lbs. per bbl. of 3.75 cu. ft.	0	5.07	5.92	6.76	7.60	8.45	9.30	10.14	10.98	11.83	12.68
	1	3.13	3.58	4.02	4.46	4.91	5.36	5.80	6.24	6.69	7.14
	2	2.29	2.57	2.85	3.14	3.42	3.70	3.99	4.27	4.55	4.84
	3	1.83	2.04	2.24	2.45	2.65	2.86	3.06	3.26	3.47	3.67
	4	1.63	1.79	1.95	2.11	2.27	2.43	2.59	2.75	2.91	3.07
By volume; parts dry loose sand to packed cement. Cement assumed 300 lbs. per bbl. of 3.75 cu. ft.	1	2.94	3.36	3.77	4.19	4.61	5.03	5.44	5.86	6.28	6.70
	2	2.22	2.50	2.77	3.05	3.32	3 60	3.87	4.15	4.42	4.70
	3	1.82	2.02	2.22	2.42	2.62	2.82	3.02	3.22	3.42	3.60
	4	1.59	1.75	1.91	2.06	2.22	2.38	2.53	2.69	2.85	3.00

In Table 63 the cost of materials in one cubic yard of natural cement mortar is given, 1st, for various parts of sand to one of cement by weight when the cost of cement refers to a barrel of 265 pounds; 2d, when this cost is for a barrel of 300 pounds net; 3d, for various parts sand to one cement when the proportions are expressed as parts by volume, dry loose sand to one volume of packed cement weighing 265 pounds per barrel; and 4th, when the proportions are expressed as parts of dry loose sand to one volume of packed cement weighing 300 pounds per barrel. The quantities in the table are based upon the assumption that the sand used is similar to that used in the experiments from which Tables 60 and 61 were derived, and that the cost of sand is seventy-five cents per cubic yard.

290. Example. — To indicate the use of these tables, let us determine the cost per cubic yard of natural cement mortar composed of one volume of packed cement to three volumes of loose dry sand when the cement weighs 300 pounds per barrel, net, and costs $1.25 per barrel, while sand costs $1.00 per cubic yard. In the fourth section of Table 63, opposite three parts sand and under $1.20 and $1.30, we find, respectively, $3.02 and $3.22; then with cement costing $1.25 and sand $0.75, we should have cost of mortar per cubic yard $3.12. But in our example sand is assumed to cost $1.00 per cubic yard, or twenty-five cents more than the price for which the tables are computed, and from Table 61 we find that for this mortar 0.83 cubic yard of sand is required. We must therefore add to $3.12, .83 × 25 = 21 cents, giving $3.33 as cost of materials in one cubic yard of the mortar. The cost of mixing the mortar must be added to obtain the total cost per cubic yard.

CHAPTER XIII

CONCRETE : AGGREGATE

291. Cement concrete is composed of a mixture of cement mortar and fragments of stone, brick or other moderately hard substances to which the mortar may adhere. Put in place while plastic, it soon obtains a strength and hardness equal to good building stone. This property, combined with its cheapness and adaptability to monolithic construction, renders it one of the most useful of engineering materials.

ART. 37. CHARACTER OF AGGREGATE

292. MATERIAL FOR AGGREGATE. — Many of the points mentioned concerning the selection of a good sand are also applicable to broken stone. The latter may be produced from almost any moderately hard rock, provided it is not subject to decay. The best material for broken stone is a rather hard and tough rock, which breaks into angular fragments with surfaces that are not too smooth.

Gravel makes a good aggregate, although its surfaces are too smooth and rounding to give the best results. Coarse gravel may be improved by running it through a rock crusher to render some of the fragments angular and rough. A mixture of gravel and broken stone gives excellent results (see § 454). The gravel assists the compacting of the mass, and the fragments of broken stone furnish a good bond. A mixture of this kind also leaves but a small percentage of voids in the mass, and this decreases the amount of mortar required.

293. Sandstones are sometimes said to be better than limestones, but this will depend on their relative hardness and structure, and the use to which the concrete is to be put; no general rule will apply. Some limestones seem to be particularly adapted to concrete-making, as the cement adheres to the surface so firmly. Granite, syanite and trap are excellent for the purpose. Fragments of brick and of other burnt clay products give good results up to the limit of the strength of the pieces, but this limit is not high. Table 155 gives the results of transverse tests of concrete bars made under the author's direction, to show the comparative value of different kinds of stone. The results of these tests are discussed in § 454.

Mr. E. L. Ransome[1] has pointed out that "for fireproof work, care should be taken to avoid such aggregates as contain feldspar," and that limestone should not be used if the concrete is likely to be subjected to a long continued red heat. The same writer mentions the fact that finely crushed granite may be inferior to finely crushed limestone for use in concrete; one reason for this being that, "owing to the brittle quality of granite, in crushing it is not only broken into small pieces, but many of these pieces are so bruised or contused that upon a little pressure being exerted upon them, such, for instance, as can be applied by the finger or thumb, they will crumble."

294. The care required in the selection of a proper quality of broken stone or gravel will depend upon the required strength of the concrete. If a strong concrete is required, rich mortar will not be able to make up a deficiency in the strength of the stone; but if a low strength is sufficient, and consequently a poor mortar is to be used, but little will be gained by having a very strong rock from which to obtain broken stone. In this case a rock which presents a good surface to which mortar may adhere is the principal requirement, and a very hard rock need not be insisted upon.

295. PRESENCE OF SCREENINGS IN BROKEN STONE. — It is frequently required that the broken stone shall be freed from all fine material, resulting from the crushing of the stone, before the mortar is added to form concrete. The wisdom of this requirement is not always clear and depends upon the kind of stone. It has already been stated that some forms of crusher dust or screenings give, if not too fine, most excellent results in mortar; this is especially true of limestone screenings. Again, to retain in the broken stone all of the screenings, will result in diminishing the percentage of voids in the aggregate, and thus decrease the amount of mortar necessary.

On the other hand, if a stone is covered with a layer of

[1] *Engineering Record*, Nov. 17, 1894.

moistened, floury dust, it cannot be so readily brought in direct contact with the mortar, and if the mortar does reach the stone it is made less rich by the dust, which acts as so much fine sand. It must be said, however, that so far as our experiments go, they do not confirm this latter theory when a moderate amount of fine material is in question, especially with crushed limestone. There is a reason, however, in some cases why the very fine material which acts as sand should be screened out of broken stone, even if it is again used in the mortar for the concrete; the fine material collects in certain parts of the bin or pile, making the proportions irregular, so that one batch of concrete may have a rich mortar with a comparatively large amount of stone, while another may have a poor mortar with but little stone. If, therefore, all of that portion of the broken stone finer than, say, one-eighth of an inch, be screened out and used as so much sand in making the mortar, the resulting concrete will be better and more nearly uniform in quality.

296. Impurities. — Material that is really foreign, such as vegetable mold or loam, will be detrimental to the strength of the concrete. Even clay is not permissible here if it adheres to the stone, because if the surface of a piece of stone is smeared with clay, the mortar will not be able to adhere as well to that surface. Clay in a granulated form and not adhering to the stone may be permitted, however, in small amounts, possibly as much as ten per cent., without seriously injuring the concrete for many uses.

When old masonry is torn down, the stones are sometimes crushed for use in concrete, but such stones, having particles of mortar adhering to the surfaces, will not be of first quality for the purpose; their cheapness, however, will frequently outweigh such objections.

ART. 38. SIZE AND SHAPE OF THE FRAGMENTS AND THE VOLUME OF VOIDS

297. As in the case of sand, the shape of the fragments and the degree of uniformity in size have an important effect on the proportion of voids in the mass, and all of these elements affect the value of broken stone for use in concrete. As in mortar each grain of sand should be completely covered with cement, so in concrete should each piece of stone be completely covered with mortar. As the pieces in a given volume of broken stone will have a smaller total superficial area when the fragments are large than when they are small, we should conclude that the larger fragments will require less mortar or be more thoroughly coated with a limited amount. From the same point of view we should expect that round fragments would require less mortar than those of irregular shape.

It is found however, in practice, that these theoretical considerations must be modified to correspond with the facts.

TABLE 64

Voids in Broken Stone and Gravel Varying in Granulometric Composition

Character Stone.	Granulometric Composition.	Weight of Broken Stone, Lbs. per Cu. Ft.	Per Cent. Voids.
Limestone . . .	K	83	47
"	V	89	44
"	F	90	43
"	M	91	42
"	C	85	46
"	F^{30}, M^{70}	91	42
"	F^{50}, C^{50}	94	40
"	K^{30}, F^{20}, M^{50}	102	35½
"	K^{20}, V^{20}, F^{20}, $M^{2)}$, C^{20}	104	34
"	C, 120½ lbs., K, 33½ lbs.	111½	29
Potsdam sandstone	V	86	45
" "	M	84	44
" "	V^{33}, F^{67}	88	43
" "	V^{33}, F^{33}, M^{33}	92	40
" "	K^{25}, V^{25}, F^{25}, M^{25}	97½	36½
Gravel	V	110	32
"	F	108	33
"	M	106	34
"	V^{33}, F^{33}, M^{33}	112	30
"	V^{50}, M^{50}	114	29
Potsdam sandstone and gravel . .	P. 6 cu. ft. on ½ in. screen G. 2 " " ¼ in. to ½ in. "	100	39
	P. 4 cu. ft. on ½ in. screen G. 4 " " ¼ in. to ½ in. "	109	33

NOTE. — Stone jarred down in measure for all trials.
K passed holes ¼ inch square, failed to pass holes $\frac{1}{10}$ inch square.
V " ½ " " ¼ "
F " 1 " " ½ "
M " 2 " " 1 "
C " 3 " " 2 "

When the pieces of broken stone are too large, they do not bed themselves well in the matrix of mortar, but become wedged one against another, leaving voids in the concrete. While round fragments have a small superficial area in relation to their volume, have a small percentage of voids, and pack together readily, yet they are lacking in ability to form a good bond, and hence do not give the best results.

298. Relation of Size of Stone to Volume of Voids. — As illustrating the effect of the size of fragments and granulometric composition of stone on the volume of voids, Table 64 gives a number of results obtained at St. Marys Falls Canal.

Table 65 gives some of the results obtained by M. Feret in similar tests.[1]

TABLE 65

Size of Stone and Volume of Voids

Composition, by Weight, of Small Stone.				Per cent. of Voids by Volume.	
Fragments Passing a Ring of				Rounded Pebbles.	Broken Stone.
90 mm.	60 mm.	40 mm.	20 mm.		
and Retained on a Ring of					
60 mm.	40 mm.	20 mm.	10 mm.		
1	0	0	0	41.4	52.1
0	1	0	0	40.0	53.4
0	0	1	0	38.8	51.7
0	0	0	1	41.7	52.1
0	1	0	1	35.6	47.1
1	4	1	1	33.5	48.8
1	1	1	4	35.6	46.4

The percentage of voids in a mass of broken stone of uniform size should be independent of what the size may be, and the first few lines in Table 65 show this to be nearly the case with the four samples tested. It is seen from both tables that the more complex mixtures give smaller percentages of voids, and that for all sizes the voids are much less in the gravel than in the broken stone.

[1] "Sand and Stone Used for Cement Mortar and Concrete," by M. Feret. Abstracted in *Engineering News*, March 26, 1892.

299. M. Feret's Experiments. — To show the effect of the variation in sizes of fragments on the strength of the concrete made, M. Feret experimented with four mixtures of three sizes. The proportions used in the mortar were one part by weight of Portland cement to three parts of Boulogne gravel, gaged with an amount of water equal to seventeen per cent. of the total weight of cement and sand. The volume of mortar used in each case was made equal to the volume of the voids in the stone. The concrete was thoroughly mixed and then rammed into a large cylindrical mold. After four months' exposure to the air, twelve cubes were cut from the cylindrical block, four cubes being cut from each of three consecutive horizontal layers. These cubes were placed in sea water and crushed after one month, being then five months old. The results of the tests are given in Table 66.

TABLE 66

Strength of Concrete. Varying Size Stone

Granulometric Composition of Broken Stone.			Vol. of Voids per Cu. Meter.	Vol. of Mortar per Cu. Meter of Stone.	Weight of Concrete per Cu. Meter.	Mean Resistance in Kg. per Sq. Cm.			
						Of 4 Cubes from			Of 12 Cubes from Same Blocks.
						Top.	Middle.	Bottom.	
G	M	F	Cu. Meter.	Cu. Meter.	Kg.				
4	1	1	0.492	0.492	2296	144	143	173	153
1	4	1	0.494	0.494	2272	141	141	154	145
1	1	4	0.486	0.486	2276	106	121	133	120
2	2	2	0.478	0.478	2264	115	132	151	133

Size "G" of broken stone passed a ring 60 mm. (2.4 inches) in diameter and was held by a ring 40 mm. (1.6 inches) in diameter; "M" passed 40 mm. (1.6 inches) ring and was held by a ring 20 mm. (0.8 inch) in diameter; while "F" passed the 20 mm. (0.8 inch) ring and would not pass a ring 10 mm. (0.4 inch) in diameter.

The following conclusions are drawn from this table: (1) In each block the lower layers, which had been submitted to longer continued ramming than the upper layers, offered a greater resistance. (2) The mean resistance varied according to the granulometric composition of stone used, and was greater with the increasing proportion of large stone in each block. Since the amount of mortar used was in all cases equal to the volume of voids in the stone, the effect of voids on the strength was not noticeable.

300. Further Experiments. — Tables 153 and 155 give the results of some experiments made under the author's direction to test the effect of size and character of broken stone. In these tests the proportions are generally 35 pounds of cement to 105 pounds of sand and 3.75 cubic feet of broken stone, the stone being measured after jarring it down in the vessel. The amount of mortar made was sufficient to fill the voids in the stone when the latter did not exceed about thirty-three per cent (§§ 452, 454).

It is seen that, in general, a higher result was given by mixtures of various sizes than by any one size alone, and the fine stone gave higher results than the coarse. In these tests the effect of voids is shown, since in some cases there was not sufficient mortar to fill the voids.

301. GRAVEL VS. BROKEN STONE AS AGGREGATE. — The elements entering into the analysis of the superiority of one kind of aggregate over another are given above, but since the question of the relative merits of gravel and broken stone is so frequently discussed, a word may be added here to show the special points involved in such a comparison.

Gravel is composed of hard, rounded pebbles, the surfaces of which are usually quite smooth. On account of the manner of its formation and occurrence, the sizes of the pebbles are usually graded from coarse to fine. Occasional beds of gravel are found, however, in which the sizes of the several fragments are nearly the same. In broken stone the fragments are angular and usually have rough surfaces, though the degree of roughness depends upon the kind of stone. The sizes of the fragments as they come from the stone crusher vary from coarse to fine, but by regulating the crusher jaws and by screening, any desired size may be obtained.

302. In determining the value of a certain material for aggregate, at least six characteristics are to be considered,— the strength and durability of the stone, the size and shape of the fragments, the volume of the voids, and the character of the surface to which the cement must adhere. As gravel is usually from the igneous rocks, its strength and durability are not often open to question. This may or may not be so in the case of broken stone, but the question of relative value of gravel and broken stone, which is so frequently conclusively settled either one way or another, seldom hinges on this point. As to the average size of the fragments, it is evident that as a general proposition it must be allowed that by proper screening either broken stone or gravel may be obtained of any desired size.

Of the three remaining characteristics, the shape of the fragments, volume of voids, and character of surface, the first is probably the least important and the third of the greatest moment. The round pebbles of the gravel slide readily one on another, and do not interlock to give a good bond. The angular fragments of broken stone give a better bond, but on the other hand, if not thoroughly tamped, are likely to bridge, or arch, and thus leave holes in the mass. On account of the shapes of the fragments and because the sizes are usually more varied in gravel, the latter has generally a smaller percentage of voids; thirty to thirty-seven per cent. voids in gravel, and forty to fifty per cent. in broken stone, may be considered to give, in a general way, some comparative figures. Coming now to the character of surface, cement will not usually adhere so firmly to the smooth surface of the gravel as to the freshly broken surface of the fragments of stone, but this cannot be considered a universal rule, for the strength in adhesion is not simply a matter of smoothness or roughness as it appears to the eye or the touch. The adhesion to limestone may be very much stronger than to a sandstone which has a rougher appearance.

303. Summing up the relative advantages, we find that the gravel is suitable for concrete because, first, it is not likely to bridge and leave holes in the concrete; if mixed rather wet, very little tamping is required to compact it; and second, the usual smaller percentage of voids makes it possible to secure a compact concrete with a smaller amount of mortar than would be required for broken stone. On the other hand, the angular fragments of broken stone will knit together, as it were, to form a strong concrete if properly tamped, and the very important question of a suitable surface for adhesion is usually in favor of the broken stone. It is evident, then, that this matter must resolve itself into a question of relative cost and suitability, and a general statement that either gravel or broken stone is superior, is not tenable. One experimenter using a small percentage of mortar in the concrete, so that the voids in the broken stone are not nearly filled, may conclude that gravel is the better, while another experimenter using a larger amount of mortar, filling the voids in the broken stone but giving a large excess of mortar for the gravel, will conclude that broken stone is much to be preferred.

ART. 39. STONE CRUSHING AND COST OF AGGREGATE

304. Breaking Stone by Hand. — When but a small quantity of concrete is to be made, and broken stone cannot be purchased in the vicinity, the stone for concrete may be broken by hand. This is an extremely tedious process, however, and is generally avoided, since broken stone prepared in this way will cost from two dollars and a half to four dollars per cubic yard. In the reconstruction of the breakwater at Buffalo, the cost of breaking stone by hand was two dollars and eighty-six cents per cubic yard, and loading on boat cost thirty-nine cents, making total cost about three dollars and twenty-five cents per cubic yard.[1]

305. STONE CRUSHERS. — The most common forms of rock crushers are the gyratory and the movable jaw types. The jaw breaker, or Blake crusher, consists of one fixed plate or jaw and one movable one. The latter is hinged at the upper end and the lower end is moved backward and forward through a short space by means of a toggle joint or other mechanism. The jaws are several inches apart at the upper end, depending on the size of the machine, and converge toward the bottom. The distance between the jaws at the bottom regulates the size of fragments delivered, and this distance may be adjusted at will.

The Gates crusher is of the gyratory type and consists of a corrugated cone of chilled iron, called the breaking head,

[1] Report of Capt. F. A. Mahan in *Report Chief of Engineers, U. S. A.*, 1888, p. 2034.

within a larger inverted cone, or shell, which is lined with chilled iron pieces. The vertical shaft bearing the breaking head is pivoted at the upper end while the lower end travels in a small circle; an eccentric motion is then imparted to the head, so that it approaches successively each element of the shell. The size of opening can be regulated by raising or lowering the breaking head.

Stone crushers are made of various sizes having capacities up to one hundred tons per hour. The cost of running a stone crusher is not great, the principal expense being incurred in breaking the stone into pieces of proper size to feed the crusher, the delivery of the stone to the crusher, and taking it away when broken.

Crushing plants are usually provided with revolving screens into which the broken stone is delivered from the crusher. These screens are usually made of perforated steel plate, the holes being such as to separate the material into the sizes desired.

Where large amounts of concrete are required, and the stone is to be crushed on the work, the arrangement of the crusher plant should receive careful study to facilitate the transportation of the rock to and from the crusher. The broken stone should be discharged from the crusher into bins, from which the carts or cars may be filled by gravity, or from which the material may be led directly to the mixer through a chute or other form of conveyor. In quarries preparing aggregate for sale, and on important works, very complete stone crushing plants are erected.[1]

306. COST OF AGGREGATE. — The cost of aggregate varies greatly according to the proximity of the stone to the crusher, the character of the stone, and the amount required. In exceptional cases gravel suitable for use in concrete is so near at hand that it may be delivered on the mixing platform for from twenty-five to forty cents per cubic yard. When it must be brought from a distance, the cost is correspondingly increased. Where a considerable quantity of stone is to be broken, the cost of crushing, aside from transportation of the materials

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[1] The stone crushing and sand and gravel washing plant used in the construction of the Canal at the Cascades of the Columbia, Ore., is described and illustrated in Report of Chief of Engineers, 1891, p. 3332.

to and from the site of the work, would usually be from thirty to forty cents per cubic yard.

In one case where the stone was delivered to the crusher in carts after having been sorted from spoil banks containing much poor stone that had to be handled over, the cost per cubic yard of crushed stone was approximately as follows for about six thousand cubic yards crushed in one season:

Labor, including sorting and delivering to crusher, per cubic yard of crushed stone	$.67
Rent of power plant	.04
Fuel	.05
Tools, supplies, breakages, etc.	.12
Interest and depreciation of plant	.12
Total cost per cubic yard	$1.00

307. The following data concerning the cost of breaking a large amount of stone for road material are given by Messrs. Spielman and Brush.[1] "The stone was broken by a ten-inch Blake stone crusher at the rate of about twenty cubic yards in ten hours. The size of the stones as they came from the crusher was: fifty per cent., two inches size; twenty-five per cent., one and one-half to one inch size; twenty-five per cent., screenings and pea dust. The cost of the crusher, engine, boiler, etc., set up complete, was about twenty-five hundred dollars. The cost of working per day independent of the original cost of the machinery and interest thereon, and also independent of any royalty on the stone, was found by the contractor to be as follows: —

Repairs, lubricants, wear and tear on crusher and engine, about	$6.00
1 engineman, $2.50; 1 feeder, $1.50; 1 screener, $1.50; 5 laborers quarrying and breaking up stone at $1.00	10.50
1 team hauling stone	5.00
½ ton coal	2.50
Cost of preparing and crushing 20 cu. yds. of stone,	$24.00
Cost of one cubic yard, $1.20.	

308. The cost of breaking trap on the Palisades is given as follows:[2] "Two crushers deliver thirty-five cubic yards of two-

[1] Trans. Am. Soc. C. E., April, 1879.

[2] "Construction and Maintenance of Roads," by Mr. Edward P. North, M. Am. Soc. C. E., Trans. A. S. C. E., April 16, 1879.

inch stone per day, when working well, the stone being sledged to go into the jaws readily; fifteen per cent. of the time is lost by breakdowns: —

1 engineman and fireman	$2.50
2 laborers feeding, at $1.25	2.50
2 laborers screening, at $1.25	2.50
Coal, 1 ton	3.50
Oil and waste	1.00
Breakages	5.00
	$17.00

or about fifty-seven cents per cubic yard.

"On Snake Island, three crushers were arranged in a row, and the broken stone was carried by an endless belt to the revolving screen, whence it fell into the bins, so that no screeners were employed. The engine had one cylinder, eight inches by twenty-four inches, and was running with eighty pounds of steam. The product was said to be one hundred eighty cubic yards per day when there was no breakdown." The cost was as follows:[1] —

1 engineman and fireman	$2.50
3 laborers feeding, at $1.25	3.75
2½ tons coal, at $3.50	8.75
Oil, etc.	2.00
Breakages	15.00
	$32.00

"Allowing for the fifteen per cent. lost by breakdowns, the cost would be about twenty-one cents per cubic yard."

At another place on the Hudson, two crushers, set face to face, nine-inch by fifteen-inch jaws, could deliver at the rate of one hundred twenty cubic yards per day when no trouble occurred, but one hundred cubic yards was a fair average.

Cost.

1 engineman and fireman	$2.50
3 feeders	3.75
2 screeners	2.50
1½ tons coal, at $4.00	6.00
Oil, etc.	2.50
Repairs	10.00
	$27.00

or twenty-seven cents per cubic yard."

[1] "Construction and Maintenance of Roads," by Mr. Edward P. North, M. Am. Soc. C. E. Trans. A. S. C. E., April 16, 1879.

It is noticeable that in all the above cases the item for repairs is very large. The wages paid are lower than at present.

309. The following data concerning the cost of **quarrying and crushing** about five thousand six hundred yards of broken stone at Baraboo, Wis., is taken from an article by Mr. W. G. Kirchoffer, C. E.[1]

Cost per Cubic Yard of Crushed Rock

ITEMS.	1901.	1902.
Stone in quarry	$ .040	$ .027
Dynamite, at 24 to 27 cents pound . . .	.056	.110
Tools, repairs, depreciation, supplies and improvements	.200	.218
Labor, quarrying and tending crusher . .	.714	.544
Fuel, at $4.60 per ton, and oil	.078	.053
Rent of engine	.085	.066
Superintendence, including livery . . .	.086	.165
Hauling stone to city	.500	.500
Total cost per cubic yard . . .	$1.76	$1.68

The cost of common labor was fifteen cents an hour, quarrymen and drill runners, seventeen and one-half to twenty cents, engineers and engine, thirty-five cents, and team and driver, thirty cents.

310. The cost of crushing **cobble stone** with a rented plant at Port Huron, Mich., is given by Mr. Frank F. Rogers, C. E., from which the following data have been derived.[2]

	JULY AND AUGUST.	OCTOBER AND NOVEMBER.
Hours run	171.5	94
Stone crushed, cubic yards	1145.	522.0
Average cubic yards crushed per hour . .	6.67	5.55
Average rental cost per cubic yard . . .	11.6 cents	16.1 cents
Average fuel cost per cubic yard. . . .	3.7 "	7.1 "
Average labor cost per cubic yard . . .	22.2 "	27.9 "
Average total cost of crushing per cu. yd.	37.5 "	51.1 "

[1] *Engineering News*, Jan. 15, 1903.

[2] Michigan Engineers' Annual, 1902, abstracted in *Engineering News*, March 6, 1902.

In the construction of the defenses at Portland, Me.,[1] a No. 5 Champion Crusher was used, driven by a thirty horse-power portable engine. **Granite** was purchased at one dollar per ton on the wharf. Hauling to crusher cost thirteen cents per ton. Cost of crushing, twenty cents per cubic yard of crushed stone, making total cost of crushed stone in bin at crusher one dollar eighty-three cents per cu. yd.

[1] Report of Charles P. Williams; Officer in charge, Maj. Solomon W. Roessler, Corps of Engineers, U.S.A.; *Report Chief of Engineers*, 1900, p. 757.

CHAPTER XIV

CONCRETE MAKING: METHODS AND COST

ART. 40. PROPORTIONS OF THE INGREDIENTS[1]

311. Concrete is simply a class of masonry in which the stones are small and of irregular shape. The strength of the concrete largely depends upon the strength of the mortar; in fact, this dependence will be much closer than in the case of other classes of masonry, since it may be stated as a general rule, that the larger and more perfectly cut are the stone, the less will the strength of the masonry depend upon the strength of the mortar.

In deciding, then, upon the proportions of ingredients to use in a given case, the quality of the mortar should first be considered. If the concrete is to be subject to but a moderate compressive stress, the mortar may be comparatively poor in cement; but if great strength is required, the mortar must be of sufficient richness; while if imperviousness is desired, the mortar must also possess this quality and be sufficient to thoroughly fill the voids in the stone.

312. THEORY OF PROPORTIONS. — The usual method of stating proportions in concrete is to give the number of parts of sand and aggregate to one of cement. These parts usually refer to volumes of sand and stone, measured loose, to one volume of packed cement. However, there is no established practice in regard to this and a "1-2-5 concrete" may mean five volumes of loose stone to two volumes loose sand to one volume loose cement, or any one of several combinations.

This method of stating proportions leads to confusion unless one is careful to explain what is meant by such an expression as "1-3-6 concrete." The evils of similar methods of stating proportions in mortars, and the desirability of fixing upon some standard system of weight or volume, have already

[1] Portions of this article were contributed to *Municipal Engineering* by the author and appeared in that magazine, May, 1899.

been pointed out. The only circumstances under which such expressions as the above may be used with propriety are when one wishes to give only an approximate idea of the character of concrete used.

From tests of strength it is known that to obtain the strongest concrete with a given quality of mortar the quantity of the latter should be just sufficient to fill the voids in the aggregate. The strength is notably diminished if the mortar is deficient, and is also impaired by a large excess of mortar. This last statement is subject to one exception: if the mortar is stronger than the stone, then an excess of mortar does not weaken the concrete. This case, however, should never be allowed to occur, since it is evident that the strength of the stone should be at least equal to the required strength of the concrete. Further, the ordinary uses of concrete are generally best served by a compact mixture containing as few voids as possible.

For these reasons, then, one should consider concrete not as a mixture of cement, sand and stone, but rather as a volume of aggregate bound together by a mortar of the proper strength. The volume of voids in the aggregate, the per cent. of this volume filled with mortar, and the strength of this mortar become then the important considerations in proportioning concrete. When thus considered, it is an easy matter to determine the required volume of mortar for a given volume of stone, and the amount of cement and sand required for a given volume of mortar has already been considered.

313. Determination of Amount of Mortar to Use. — The bulk of a given quantity of broken stone is not so variable as the volume of sand. The volume of the stone, and consequently the voids, will vary with the degree of packing, but the packing is not influenced appreciably by the amount of moisture present.

The proportion of voids in the broken stone may be obtained as follows: Find the weight per cubic foot of the broken stone in the condition in which the volume of voids is sought, being careful to use a measure holding not less than two or three cubic feet. Also obtain the specific gravity, and hence the weight per cubic foot of the solid stone. Then one, less the quotient obtained by dividing the weight per cubic foot of the broken stone by the weight per cubic foot of the solid stone, will be the proportion of voids in the aggregate.

For example, suppose the weight per cubic foot of the broken stone is 102 pounds. The specific gravity of the solid stone determined in the ordinary manner is found to be 2.724. Then weight per cubic foot of solid stone is $62.4 \times 2.724 = 170$ pounds and $1 - \frac{102}{170} = .40$, voids in stone.

Another method is to fill a vessel of known capacity with the stone to be used, and to pour in a measured quantity of water until the vessel is entirely filled. The volume of water required indicates the necessary amount of mortar to use. The stone should be moistened before placing in the vessel, to approximate more nearly its condition when used for concrete, and to avoid an error from absorption of the water used to measure voids.

314. As to the degree of jarring or packing to which the stone should be subjected in filling the measure, if the stone is filled in loose, and it is proposed to ram the concrete in place, the amount of mortar indicated will be a little more than the required quantity. If the concrete is to be placed without ramming (as in submarine construction), the amount of mortar indicated will not be too great. On the other hand, if the stone is shaken down in the vessel to refusal, the voids obtained will be less than the amount of mortar which should be used, because it is not possible to obtain a perfect distribution of mortar in a mass of concrete, and because the concrete will usually occupy a greater space than did the stone when shaken down. And again, for perfect concrete, pieces of stone should be separated one from another by a thin film of mortar, and hence the volume of the concrete will be greater than the volume of the stone measured in a compact condition without mortar. A deficiency of mortar is usually more detrimental than an excess. It is safer, therefore, to measure the voids in the stone loose, or when but slightly packed, and make the amount of mortar equal to, or a trifle in excess of, the voids so obtained.

315. Aggregates Containing Sand. — If in the case of broken stone all of the fine particles are used, or if gravel which contains a considerable amount of sand is employed, then this fine material or sand must be considered as forming a part of the mortar. This will not change the method of obtaining the amount of mortar required for such broken stone or gravel, but it will change the composition of the mortar used. Thus, suppose we have a gravel ten per cent. of which is sand (grains smaller than one-tenth inch in diameter) and we find the voids to be thirty-three and one-third per cent. To three cubic yards of this gravel we will add one cubic yard of a one-to-three mortar. The voids will be filled, but instead of having three cubic yards of stone imbedded in one cubic yard of a one-to-three mortar, we will in reality have a little less than that amount of stone imbedded in a mortar composed of one part of cement to about three and three-tenths parts sand.

316. Required Strength. — In the paragraphs just preceding, an attempt has been made to indicate the general principles to be applied in proportioning the materials in concrete. To decide on the actual proportions of the ingredients to use for a given purpose, one must have clearly in mind the strength that will be demanded and any special condition to which the concrete is to be subjected. A reference to Art. 57 concerning the strength of concrete, will be of service in deciding on the proper proportions to use in a given case.

ART. 41. MIXING CONCRETE BY HAND

317. Necessity of Thorough Mixing. — Too much stress can hardly be laid upon the necessity of thoroughly mixing the concrete if the best results are to be attained. It has already been shown that thoroughness in mixing mortar is repaid by greatly increased strength, and the result is even more marked in the case of concrete. Every grain of sand should be coated with cement, and every piece of stone should be covered with mortar. In general, the cost of mixing is from one-tenth to one-fifth of the total cost of the concrete in place. If by doubling the cost of mixing we can increase its strength more than one-tenth or one-fifth in these respective cases, or permit a corresponding decrease in the amount of cement necessary for a given result, the additional labor in mixing is justified.

318. Concrete may be mixed by hand or by machine. Opinions vary as to the comparative merits of the two systems, but as a machine properly installed usually furnishes much the cheaper method of mixing, it is usually employed. The saving by this method, however, will evidently depend upon the cost of labor, the total amount of work to be done, and the degree of concentration of the work, or facilities for distributing the concrete. In certain sections where cheap labor is abundant, the cost of hand mixing may be as low as machine mixing.

With proper supervision, hand mixing may be thorough, and the chief argument against it, aside from its cost, is that such hard work is likely to be slighted. The best forms of mixers now on the market, however, give results quite equal to the best hand work.

319. Method of Hand Mixing. — We will assume that the materials have been brought within easy reach of the mixing place. If the concrete is to be mixed near the point where it is to be deposited, the mixing platform must be made portable. Three platforms, each 8 by 14 feet, built of two-inch plank or of two layers of one-inch boards, nailed to four 2 × 6 inch longitudinal scantlings laid flat, will be suitable for such a case. The platforms should be made without vertical sides, though if desired a narrow piece of one-inch board may be laid flat around the edges and nailed. A short piece of rope attached to each corner of the platforms, or to the ends of the longitudinal scantlings, will be found convenient in moving them. These mixing boards are placed side by side.

The sand, which may be delivered to the mixing platform in wheelbarrows, is first dumped on the board and spread evenly over the surface. If the sand is measured, the barrows should be so arranged as to hold the required amount after "striking" with a straight edge. This will make the measurement independent of the judgment of the shoveler. If the sand is delivered in cars, bottomless boxes of two or three barrels capacity, according to the proportions used, will be found more convenient for measuring than barrels. If the sand is determined by weight, which as has been shown is the more accurate method, the scales should be set at a weight which is a factor of the total weight, and but little time will be required to bring the scales to a balance for each barrow.

If it is possible, the batch should be of such a size as to take either one or two full barrels, or a certain number of full sacks of cement. This will obviate the necessity of measuring or weighing the cement. The sand having been spread over the surface of the mixing board, the cement is dumped upon it and spread evenly over the sand. These ingredients are then mixed dry, the required amount of water is added at one time in the center of a ring formed of the dry materials, and the whole is thoroughly mixed as described under the head of mortar-making.

320. The mortar having been spread evenly over the board, the broken stone is dumped upon it and evenly distributed over the surface. Four shovelers then mix the concrete. Each shoveler starts at a corner of the board and turns each shovelful completely over, casting toward the end and spreading the mortar a little as he draws the shovel toward him. The two shovelers at each end work toward each other, and meeting at the axis of the platform, return to the side and repeat. When the four shovelers meet at the center of the board, they turn the mass again by casting toward the center in a similar manner. If in mixing the concrete it is found that sufficient water has not been used, more may be added from a rose nozzle, or sprinkling pot, previous to the last turning of the mass. The shovel should always be used at right angles to either the side or the end of the board, never diagonally; and it should always scrape the mass clean from the board, never cut it at mid-depth. From three to five turnings are required to thoroughly mix the concrete.

The mode of mixing has been thus minutely described, because if a gang of men are started properly they will soon become expert, working in unison; whereas if each man is allowed to mix according to his notion, confusion is sure to result. It is sometimes preferred to spread the stone on a separate board and cast the mortar upon it, but this necessitates one handling of the mortar which does not appear to contribute much to the incorporation of the ingredients.

While the shovelers are engaged in mixing the concrete on one platform, the mortar mixers have proceeded to the next platform to mix another batch of mortar, and the cement and sand are being placed upon the third platform. Thus the work proceeds in regular progression without delays. The shoveling of concrete is hard work, and it will be found necessary not only to pick good men for this duty, but to cull them until the evolution results in the proper men for the work. An extra compensation for men who perform satisfactory service in the mixing of concrete will usually be repaid in the character and quantity of the output.

321. With the method described above, a working gang would consist of the following men under ordinary conditions: —

Measuring and supplying cement and sand	1
Mixing mortar	2
Delivering stone from bin, one man with horse and cart, or two men with barrows	2
Shovellers to mix concrete and cast or wheel to place	4
Water boy	1
Spreading and tamping concrete	1
Total men required	11

If it is found impracticable to mix the concrete near the place of deposition, it may be necessary to put on two or more extra men to wheel the concrete to place. This gang of eleven men may be doubled and still work on the same three platforms when so desired.

With a moderate length of wheel for the materials and the finished concrete, a gang of eleven picked men, working according to system, will be able to make from twenty-five to thirty cubic yards per day of ten hours, or about two and a half yards per man. The double gang of twenty-two men may not work to quite as good advantage, and will probably not put in more than from forty to fifty cubic yards per day. It would therefore be somewhat more economical to work two gangs of eleven men each on separate sets of platforms, especially as in this way a rivalry is created. Lack of room, however, will frequently preclude this arrangement.

322. COST OF MIXING BY HAND. — The amount of concrete stated above, two and a half yards per man, may be taken as a maximum. With wages at $1.75 per day this would correspond to a cost of about seventy cents per yard, exclusive of the wages of a foreman. Numerous examples might be cited where the mixing costs more. Colonel Mendell, in writing of the fortifications at Fort Point, California,[1] states that a foreman (at $4 per day) and twenty laborers (at $2 per day) made forty-five cubic yards per day of eight hours, the cost of mixing being thus about $1 per cubic yard. It is stated that "the circumstances were exceptionally favorable."

As an instance where hand mixing was done at a very low cost, the Lonesome Valley Viaduct[2] may be mentioned. At

[1] Jour. Assn. of Engr. Soc., March, 1895.

[2] Construction of Substructure for Lonesome Valley Viaduct, Gustave R. Tuska, Trans. A. S. C. E., Vol. xxxiv, p. 247.

this point colored labor was used at a cost of $1 for eleven hours' work. A gang of men, distributed as follows, would mix and lay forty cubic yards of concrete per day: —

Filling sand barrows and handling water	1
Filling rock barrows	2
Mixing sand and cement	4
Mixing stone and mortar	4
Wheeling concrete	2
Spreading concrete in the molds	1
Tamping concrete in the molds	1
Foremen	1
Total	16

Fifteen men at $1 per day, and foreman at $2.50 per day, makes a cost of $17.50 for forty yards of concrete, or at the rate of forty-four cents a yard for mixing. Had the laborers received $1.75 per day, however, the cost would have been 72 cents per yard.

323. In the construction of the Forbes Hill Reservoir and standpipe at Quincy, Mass.,[1] all concrete was mixed and placed by hand. "The ordinary concrete gang was made up of a sub-foreman, two men gaging materials, two men mixing mortar, three men turning the concrete, three men wheeling concrete, one man placing, and two men ramming. Two gangs were ordinarily employed, placing about twenty cubic yards per day each, or about 1.43 cubic yards per man. The concrete was turned at least three times before placing." With labor at $1.75 per day, this would give the cost of mixing and placing $1.22 per cubic yard. The actual cost of mixing and placing varied from $0.97 to $1.53, according to the character of the work.

ART. 42. CONCRETE MIXING MACHINES

324. General Classification. — Concrete mixing machines may be divided into two general classes, batch mixers and continuous mixers. In the former, sufficient materials are proportioned to make a convenient sized batch for the mixer. They are then charged into the machine at once, given a certain amount of mixing, and then discharged at once. In the continuous mixers

[1] Described by C. M. Saville, M. Am. Soc. C. E., *Engineering News*, Mar. 13, 1902.

the materials are dumped on a platform, and after being properly proportioned, are delivered gradually to the mixer, and if fed uniformly, the concrete is discharged continuously by the machine. In the latter method care must be taken to feed the cement, sand and stone together and at a uniform rate. If one man shovels cement, two men shovel sand and four men handle the stone, and the cement man stops to fill his pipe, there is likely to be a poor streak of concrete. It is therefore desirable in feeding a continuous mixer to spread the measured quantity of stone on the platform, and on top of this place the weighed quantities of sand and cement. Then if each shoveler gets his shovel blade under the whole mass, he will have some of each ingredient.

325. There are many styles of concrete mixers of both classes on the market. One of the oldest, as well as one of the best, is the **cubical box mixer** which consists of a box four or five feet on a side, supported by trunnions at opposite corners, and made to revolve about this axis. A hinged door is provided near one corner of the box by which the latter is charged and emptied. The dry materials may be first charged and mixed and the water added later, either through the door or through a perforated pipe in the axis, or the water may be added with the dry materials; after from ten to thirty revolutions of the box, the mixed concrete is discharged into a skip or on a car, to be conveyed to the place of deposition.

The great merit of this mixer is that the materials are thrown back and forth from one side of the cube to another and a thorough commingling results. The chief disadvantage is the difference in elevation between the receiving hopper and point of delivery, making it necessary to elevate the materials; one other defect is that the batch is not in view while being mixed, so that the amount of water cannot be regulated according to slight variations that may occur in the moisture of the sand and stone when charged.

326. To obviate this latter difficulty as well as to facilitate to some extent the charging and dumping of the batch, a form of box mixer is made in which the corners of the box in the axis of revolution are truncated, and the trunnions are replaced by collars which support the box, and through which the materials may be fed and discharged. The collars are supported in a tilting cradle which permits the delivery end to be depressed after the batch is mixed. The advantage of having the batch visible during mixing is perhaps somewhat offset by the greater difficulty of thoroughly cleaning the box when discharged.

Mixers working on the same principle are sometimes made in other forms than the cube. One of these is the **cylindrical mixer,** which is made of boiler plate and may be four or five feet in diameter and five or six feet long. This is rotated about a diagonal axis. It is said to be more easily and cheaply made than the cubical mixer, and dumps more quickly and cleanly, while the cost of operation is about the same, and the mixing is as satisfactorily done as in the cubical form.

327. The so-called **"Dromedary Mixer"**[1] is a batch mixer specially designed for use on street work. The mixing chamber is a cylindrical steel drum with closed ends, mounted between two wheels. It is hinged along an element of the cylinder so that it opens into two halves like a clam shell bucket, to discharge. A trap door is provided for filling. The cart is drawn by a horse, and the chamber may be thrown in or out of gear with the cart wheels. The cement and sand being first added and the trap door closed, the horse draws the cart to the stone pile. The stone and water are here added and the cart is drawn to the work; the concrete, mixed on the way, is dumped by the driver, who merely raises a lever which not only separates the two halves of the mixer, but throws it out of gear so that it stops revolving. The chamber may be thrown out of gear at any time without dumping if desired.

328. The **Ransome Concrete Mixer**[2] "consists of a hollow rotary dome, having upon the inner surface of its periphery directing guides or flanges, and hinged shelves, by means of which the materials are thrown together and perfectly commingled. A discharge chute, or spout, is arranged to deliver the material into the barrow or cart when properly mixed." The mixer is also provided with an automatic device for proportioning the materials, and a conveyor to carry them to the mixer. Water is supplied to the mixer through a pipe with facilities for regulating the supply.

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[1] Fisher and Saxton, 123 G St., N. E., Washington, D. C.

[2] Ransome Concrete Machinery Co., 11 Broadway, N. Y.

329. The **Smith Mixer**[1] is a batch machine made of two truncated cones placed base to base, and provided on the interior with deflecting plates designed to throw the materials from one end of the mixer to the other as the machine is revolved. At the junction of the two cones, on the outer circumference, is a spur gear by which the chamber is actuated. The latter rests upon rollers in a swinging frame, so arranged that the machine may be tilted for dumping while the drum is revolving. In operating this mixer it has been found advantageous to charge the broken stone or gravel first, and give one or two revolutions before adding the cement and sand, as this cleans the mortar from the corners. This form seems to be particularly adapted for a portable machine. They may be had mounted on trucks, with or without an engine, as desired.

330. The **McKelvey Mixers**[2] are made in two styles, continuous and batch. Both styles are cylinders revolving on friction rollers, and having, on the interior, deflecting blades and a patent "gravity shovel" which lies against the rising side of the drum and casts the materials downward when the cylinder has revolved far enough to overturn the blade. The batch mixer has a shorter cylinder and can be discharged at will. These mixers may be fed by shovels, or they may be provided with a hopper into which the materials may be dumped from carts or barrows. They discharge directly into wheelbarrows. The mixer, and an engine and boiler to run it, are mounted compactly on a truck, or the mixer is furnished on a steel frame without an engine.

331. The **pan mixer**[3] consists of a large shallow pan into which may be lowered a framework carrying a series of plows. The materials are spread in the pan in layers, the plows are lowered into it, and the pan is revolved about its vertical axis, the plows remaining stationary. The plows are so arranged as to move the materials radially toward and away from the center of the pan. The water may be added from a rose nozzle. For dumping, an opening is made in the bottom of the pan by withdrawing a slide. Were the plows made to revolve in a

[1] Contractors' Supply Co., 232 Fifth Ave., Chicago.
[2] McKelvey Concrete Machinery Co., N. Y. Life Bldg., Chicago.
[3] Clyde Iron Works, Duluth, Minn.

stationary pan, the concrete would be more conveniently dumped in a pile, or in a car, instead of being scattered about under the pan.

332. The **Cockburn**,[1] a continuous mixer, is in the form of a long box square in cross-section, surrounded at either end by circular rings supported on friction rollers. By suitable gearing the mixer is revolved about its longest axis, which has a slight inclination toward the discharge end. The materials are added through a hopper at one end, and fall from one side of the box to the adjacent side as the machine revolves, working gradually toward the delivery end, which is open. The water is added through a pipe at about one-third of the length of the box from the feed end. While this machine has no complicated system of blades to become clogged, the mortar has a tendency to stick in the corners of the mixer, making the interior cylindrical, and thus much less effective in mixing. Striking the sides of the box with a heavy hammer will detach the mortar, and this requires occasional attention.

333. A common form of continuous mixer consists of a **screw** working in a cylinder. The materials are fed to the cylinder near one end and are mixed while being gradually worked toward the other end by the screw. The water is added through a fixed perforated pipe at a point about one-third of the distance from the feed end of the cylinder, and the mixed concrete falls from the outlet at the other end. This style is frequently made in a light form and mounted on wheels, and is then convenient in the laying of concrete for pavements.

A modification of the screw mixer consists of a semi-cylindrical **trough**, in which revolves a shaft carrying blades set at right angles to the shaft and to each other. The trough is sometimes given a slight inclination to the horizontal, and the blades are so shaped as to assist in working the materials toward the delivery end.

334. The **Drake Mixer**[2] is of the general form just described. One of the machines made by this company is a semi-cylindrical trough in which revolve in opposite directions two shafts, each carrying some thirty blades. Most of the blades are straight,

[1] Cockburn Barrow and Machine Co., Jersey City, N. J.

[2] Drake Standard Machine Works, 298–302 W. Jackson Boul., Chicago.

but some of them are curved to work the material toward the delivery end.

335. Gravity Mixer. — An appliance recently devised, which is called a concrete mixer, consists of a steel trough provided with staggered pins and deflecting plates. The trough is supported in an inclined position and has a hopper at its upper end. Water is supplied through spray pipes at the side of the trough. The materials, stone, sand and cement, are spread in layers on the mixing platform, with the stone at the bottom. The materials are then thrown into the hopper; they are mixed as they descend through the pins, and the product is caught in barrows or carts at the bottom.

336. In a very able article on concrete mixers,[1] Mr. Clarence Coleman, M. Am. Soc. C. E., makes an analytical discussion of the relative efficiencies of the several forms. In this analysis he gives the following weights to the several requirements for a perfect mixer. That the entire mass of concrete shall be so commingled that the cement shall be uniformly distributed throughout the batch is given a weight of forty; that the amount of water shall be subject to control is given a weight of twenty-five; perfect dry mixing and relative time of mixing, each ten; and receiving materials, discharging concrete and self-cleaning, are each given a weight of five.

The first three requirements, with a combined weight of seventy-five, relate to the production of good concrete, while the remaining requirements, with a combined weight of twenty-five, pertain to economy in use. In short, the first requisite is that a machine shall be capable of producing a perfect mixture; then the machine that accomplishes this result at the lowest cost per cubic yard is the best. The choice of a machine will depend frequently on the character of the work to be done, as some machines can only be used economically where large quantities of concrete are to be used in a restricted area, while others are particularly adapted for portable plants.

Art. 43. Concrete Mixing Plants and Cost of Machine Mixing

337. Coosa River Improvement. — The concrete plant used at Lock No. 31, Coosa River Improvement,[2] was erected in a

[1] *Engineering News*, Aug. 27, 1903.

[2] Major F. A. Mahan, Corps of Engineers, U. S. A., in charge.

three-story shed. The top story served as a cement storage room and two hoppers were arranged in the floor to receive the cement for the mixers below. Level with the floor of the second story were two other hoppers immediately below the cement hoppers, to receive the sand and broken stone, while in the first story or basement the mixers were suspended at a height sufficient to allow concrete cars to pass under them. The following description is from the report of the designer, Mr. Charles Firth, U. S. Asst. Engineer:[1]

"The cars used in handling the sand and broken stone are of the side dump pattern and are brought into the charging room on either side of the hoppers. The cement is drawn from the cement room overhead in proper quantities, through vertical chutes arranged somewhat on the principle of the old-fashioned powder flask.

"The water is added to the materials as they enter the mixers, and the quantity, which will probably be variable with the temperature, is controlled by valves on the mixing floor, the operators being governed by indicators, which show the quantity used. The mixers are cubical boxes four feet on each side, inside measurement, made of steel plate five-sixteenths of an inch thick, with 2½ by 2½-inch angle irons. Each mixer is provided with a door in one corner, twenty-two inches square, fastened with a tempered steel spring catch, and held open when required with a hinged screw bolt. The shaft which revolves the mixers is three inches square. It is securely fastened to them by trunnion castings at diagonally opposite corners. The whole is driven by a 10 by 16 inch horizontal engine, and thrown in and out of gear by ordinary friction gearing with friction and brake levers.

"After a sufficient number of revolutions in the mixers, the concrete is dumped into the concrete cars below, which are of the center dump pattern."

The method given of measuring the cement is not recommended, as the charge of cement, if not a full barrel, should always be weighed. The three-story arrangement by which the materials were handled almost entirely by gravity was made possible by the high bank at the side of the lock pit.

[1] *Annual Report, Chief of Engineers, U. S. A.*, 1894, p. 1292.

The total cost of the plant, exclusive of the boilers, is stated to have been about $8,000, and the average output about two hundred cubic yards of concrete per day of eight hours. The cost of mixing, depositing and ramming 8,710 cubic yards of concrete in the construction of lock walls was at the rate of $0.884 per cubic yard.

338. Portland, Maine, Defenses. — In the construction of the defenses at Portland, Maine,[1] a five-foot cubical mixer was used. Sand and stone were delivered, by bucket conveyors, in bins directly over the mixer. "Immediately under these bins were two measuring hoppers for stone and sand, respectively, and an additional hopper for cement. From these measuring hoppers the charge was dumped into the mixer and thence, when mixed, into a car immediately under it. This car delivered the mixed batch by means of a hoisting engine and an inclined track to the site of the battery under a fifty-five foot derrick, which placed it in the work at the point required. Two barrels of cement, sixteen cubic feet of sand, and thirty-two cubic feet of stone constituted a batch. * * * The usual number of men engaged in the operation of mixing and placing was as follows: — Two master laborers, three steam engineers, two stokers and twenty-five laborers." It is said that 200 barrels of cement, or 100 batches, could be mixed and placed in a day of eight hours. This would make the labor cost of this portion of the work 50 or 60 cents per cubic yard. The cost stated, however, varies greatly according to the amount of detail in construction, and the lowest cost given for "labor of mixing and placing" is $1.15 per cubic yard.

339. San Francisco Defenses. — A cubical mixer used in the construction of the defenses at San Francisco[2] mixed 250 cubic yards per day with seven men, engineer, fireman, and five men to feed and dump mixer, at a labor cost of $14.67 per day, or about six cents per cubic yard, exclusive of cost of transportation and ramming. The materials and concrete were handled on cars run almost entirely by gravity.

340. Buffalo Breakwater. — In the construction of the Buf-

[1] Report of Charles P. Williams to Maj. Solomon W. Roessler, Corps of Engrs., U. S. A., in charge. *Report Chief of Engineers*, 1900, p. 745.

[2] Maj. Charles E. L. B. Davis, Corps of Engineers, U. S. A., *Report Chief of Engrs.*, 1900, p. 980.

falo Breakwater,[1] the mixing plant, consisting of a cubical mixer with necessary engines and boilers and two derricks,was mounted on a dismantled lake schooner which could be placed beside the section of the breakwater under construction. The broken stone was delivered in a canal boat which could be tied up alongside the schooner, and outside of the canal boat lay the material scow. The latter was made from an old dump scow, the decked pockets serving as bins for cement, sand and gravel.

Into a steel bucket on the scow were loaded, by wheelbarrows, the following materials:

5.4 cu. ft. (1½ bbls.) cement.
10.8 cu. ft. sand.
5.4 cu. ft. gravel.
21.6 cu. ft. total.

Into a similar bucket on the canal boat 21.6 cubic feet of broken stone were shoveled. As these buckets were filled, they were hoisted by one of the derricks and dumped into the cubical mixer. The latter discharged the mixed concrete into a skip and a derrick deposited the concrete in place. The cost of labor per cubic yard of concrete is as follows:

Items.	No. Men.	Cost per Hour.	Cu. Yds. per Hour.	Cost of Labor per Cu. Yd.
Loading material into buckets from scows	18	$3.17½	18.2	$0.174
Mixing, including engine men and derrick men	11	2.35	18.2	0.129
Placing, including foreman	13	2.65	18.2	0.146
Total labor	42	$8.17½	18.2	$0.449

The above does not include cost of fuel, nor of transporting materials from the storehouses or yards to the site of the work.

341. Quebec Bridge. — The plant used in the construction of the Quebec Cantilever Bridge[2] consists of a No. 5 rotary stone crusher, with a maximum capacity of thirty cubic yards per hour, discharging into a bucket conveyor which delivered the crushed stone in a small storage bin directly over the concrete mixer. The latter was of the cubical form, five feet on a side, with a capacity of two cubic yards of concrete per batch.

[1] Emile Low, U. S. Asst. Engr., *Engineering News*, Oct. 8, 1903.
[2] *Engineering News*, Jan. 29, 1903.

The cement warehouse and the sand supply were near the mixer. Cement and sand were hoisted to the top of the machine in boxes, with bottoms inclined at forty-five degrees, each holding a batch, and dumped into the charging hopper of the mixer as required. The mixer was elevated sufficiently to permit dumping the concrete directly in a skip on a car, the latter being run to the work. The skip was handled by guy derricks. This plant made the remarkable record of two hundred eighty-five batches in ten hours, and on one occasion turned out one hundred fifty batches in five hours, or, if all were two-yard batches, at the rate of sixty yards per hour.

342. Galveston. — For the construction of the Galveston sea wall two concrete mixing and handling machines were designed,[1] each consisting of a double-deck car, on eight wheels, with two revolving derricks, one on either side for handling materials and concrete, respectively. The materials are delivered on tracks beside the mixer car track which is parallel to the sea wall. One derrick hoists the loaded skips from the material cars and deposits them on the upper deck of the mixer car, whence they are delivered in measured quantities to the Smith Rotary Mixer located on the lower deck. When mixed, the concrete is dumped into a skip, which is handled by the second derrick and dumped into the forms.

343. For work having similar requirements to that just described, namely, for **retaining walls** on track elevation, Chicago & Western Indiana R. R. at Chicago, the problem was met in a somewhat different manner.[2] An ordinary flat car was double decked and the space between decks inclosed to protect the machinery, including the Drake Concrete Mixer. Cars containing cement, sand and stone were coupled in the rear of the mixer car. These material cars were fitted with removable wheeling platforms, making a complete runway along the sides of the cars. The materials were delivered at the mixer car in wheelbarrows and dumped into measuring boxes, and thence fed to the mixer. The concrete was delivered on a belt conveyor mounted on a boom with turntable permitting nearly half of a revolution. The outer end of the conveyor could be raised or lowered as desired, and the concrete was thus deposited where

[1] *Engineering News*, Jan. 15, 1903.

[2] *Ibid.*, Feb. 28, 1901.

needed in the work. To permit the mixer train to move along the track, the two ends of a cable were made fast to anchorages placed about a thousand feet apart, one in front of, and the other behind, the train. As this cable had about eight turns around a winding drum on the mixer car, the train could be propelled forward or backward at will.

A somewhat similar form has been used for **street work,** where the mixer and electric motor are mounted on a truck with a swinging conveyor for the delivery of concrete anywhere between the curbs. A pair of wheels in the rear serve to carry an inclined runway for wheelbarrows by which the materials are delivered to the mixer.

344. The data for the following items concerning the cost of mixing concrete for **culverts** on railroad work are taken from an article in *Engineering News*.[1]

"The plant is located on a hillside with the crusher bins above the loading floor or platform that extends over the top of the mixer, so that crushed stone can be drawn directly from the chutes of the bins and wheeled to the mixer. The sand is hauled up an incline in one-horse carts and dumped on the floor, and is also wheeled in barrows to the mixer." The capacity of the cubical mixer used was seven-eighths cubic yard. The cost of mixing and placing was as follows:

Items.	Cost per Day.	Cost per Cu. Yd.
One foreman assumed at $2.50 per day	$2.50	
Three men supplying mixer at $1.50 per day	4.50	
One engineman assumed at $2.00 per day	2.00	
Fuel and supplies assumed at	2.00	
Cost of mixing 40 cu. yds.	$11.00	$0.275
Two men loading wheelbarrows at $1.50	$3.00	
Four men wheeling wheelbarrows at $1.50	6.00	
Cost of wheeling 40 cu. yds. 100 feet	$9.00	0.225
Four men ramming at $1.50	$6.00	0.150
Four men wheeling in and bedding large stone in concrete at $1.50	6.00	0.150
Total cost mixing and placing	. . .	$0.800

[1] Location and Construction of the Ohio Residency, Pittsburg, Carnegie & Western R.R., *Engineering News*, May 21, 1903.

It is not explained why six men are required to load and wheel forty cubic yards one hundred feet in ten hours, but it may be that these men assisted in other operations.

Another contractor on the same work used a different form of mixer with much lower loading platform and handled the mixed concrete with skips and derrick. The cost is estimated as follows:

1 man feeding mixer	$1.50
1 engineman assumed at	2.50
1 derrick man assumed at	2.50
2 tagmen swinging boom and dumping	3.00
6 barrowmen supplying mixer	9.00
2 men tamping	3.00
Fuel, supplies, etc.	1.50
Cost of mixing and placing 50 cu. yds.	$23.00
Cost per cu. yd., 46 cents.	

Art. 44. Cost of Concrete

345. Quantities of Ingredients in a Cubic Yard.—As has already been indicated, the rational method of proportioning concrete is to use just sufficient mortar to fill the voids in the stone, or possibly a very small excess to allow for imperfect mixing; and in ordinary practice this rule should not be departed from unless it be for some special reason. When so proportioned, a cubic yard of concrete will contain approximately a cubic yard of stone, depending on the method of measurement. If we know the percentage of voids in the broken stone or gravel, and consequently the percentage of mortar which should be found in a cubic yard of the finished concrete, we may readily obtain the approximate cost per cubic yard of the latter for a given quality of mortar and given unit prices.

Thus, suppose we have stone in which the voids are such that the mortar will amount to forty per cent. of the finished concrete, and we wish to have the mortar composed of three volumes of loose sand to one volume packed natural cement, unit prices being as follows:

Cement, $1.25 per barrel of 300 pounds net, 3.75 cubic feet.

Sand, $1.00 per cubic yard.

Stone, $1.75 per cubic yard.

As in § 290, we find the ingredients in one cubic yard of mortar to cost $3.33. Since forty per cent. of the concrete is to be composed of mortar, the mortar in one cubic yard of concrete will cost forty per cent. of $3.33, or $1.33, and one yard of stone at $1.75 will make the total cost of the materials in the concrete $3.08 per cubic yard.

The **diagram** herewith may be used to get the approximate cost of the concrete after having obtained the cost of the mortar as before. Thus, if we enter the diagram with the cost of mortar $3.33, and follow it to the diagonal line marked forty per cent., we find this is on the ordinate $2.33, the cost of the ingredients in one cubic yard of concrete when the stone costs one dollar per cubic yard. Hence, $2.33 plus $0.75 equals $3.08, the approximate cost of the materials in a cubic yard of the concrete as desired.

346. The usual method, however, of stating proportions in concrete is to give the volumes of sand and stone to one volume of cement. Thus, one of cement, three of sand and six of stone would usually mean one volume of packed cement, three volumes of loose sand and six volumes of loose broken stone. To arrive at the cost of concrete when proportions are thus arbitrarily stated, involves a greater amount of work. From the tables already given (Art. 36), we can determine the amount of mortar which a given quantity of dry ingredients will make, and the consequent cost of the mortar per cubic yard. Then a knowledge of the voids in the broken stone will permit of a close estimate of the amount of concrete made, whence we can determine the cost of the latter.

For **example**, suppose it is desired to determine the cost of the materials in a cubic yard of natural cement concrete under the following conditions:

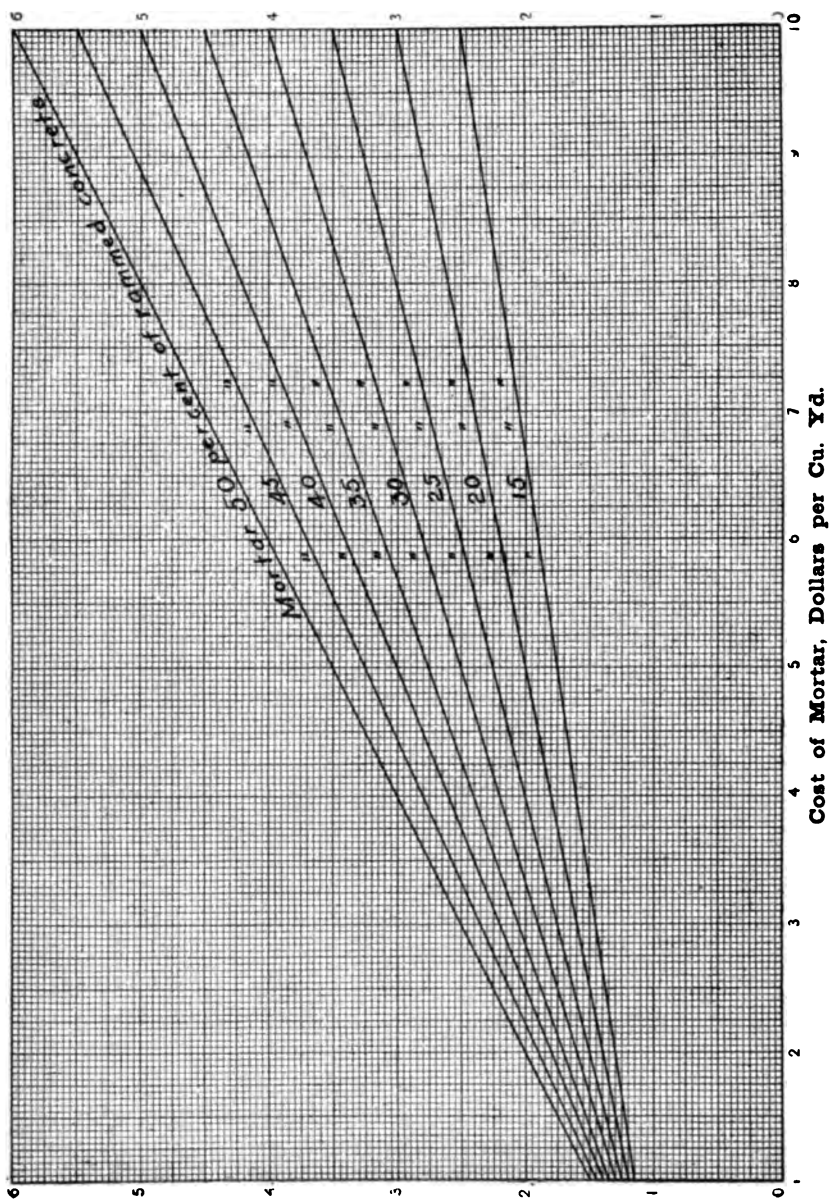
1 bbl. cement containing 280 pounds net, at $1.00 per bbl.
3 bbls. sand weighing 100 pounds per cu. ft., at $.75 per cu. yd.
6 bbls. loose broken stone, having 45 per cent. voids, at $1.25 per cu. yd.

1 bbl. cement	= 3.75 cu. ft.	= .139 cu. yd., cost	$1.000
3 bbls. sand	= 11.25 cu. ft.	= .417 cu. yd., cost	.313
6 bbls. stone	= 22.50 cu. ft.	= .833 cu. yd., cost	1.041
Total cost			$2.354

From Table 61, § 286, we find that it requires 2.03 barrels of cement to make one cubic yard of one-to-three mortar, when

CONCRETE MAKING

Cost of Concrete, Dollars per Cu. Yd.
Stone Assumed to Cost $1.00 per Cu. Yd.



proportions are stated as above; then one barrel of cement would make $\frac{1}{2.03} = .493$ cu. yd. As forty-five per cent. of the stone is voids, the amount of solid stone in six barrels would be $\frac{6 \times 3.75}{27} \times .55 = .458$ cu. yd. Then the mortar plus solid stone would be $.493 + .458 = .951$ cu. yd. It has been found by experiment that the amount of concrete will exceed the sum of the mortar and solid stone by from two to five per cent.; hence we may assume in this case that the amount of concrete made with the above materials would be $.95 + .03 = .98$ cu. yd., and $2.354 \div .98 = \$2.40$, the cost of materials in one cubic yard of finished concrete. To obtain the actual cost of concrete in place, the cost of mixing and deposition must be added (see Arts. 41 and 43). When the volume of mortar used is not greater than the voids in the loose stone, then the amount of rammed concrete made may be less than the volume of loose broken stone.

347. EXAMPLES OF ACTUAL COST OF CONCRETE. — The following data are given concerning the cost of concrete on several works where sufficient details have been published to be of value.

Defenses Staten Island.[1] Cubical box mixer; proportions by volume, 1 cement, 3 sand, 5 broken stone; 5,609 cu. yds. of concrete.

ITEMS.	COST PER CU. YD. CONCRETE IN PLACE.
Cement, Portland, at $1.98 per bbl.	$2.546
Broken trap rock	1.041
Sand drawn from beach	0.225
Receiving and storing materials	0.140
Mixing, placing and ramming	0.879
Forms, lumber and labor	0.477
Superintendence and miscellaneous	0.190
Total cost per cu. yd.	$5.507

It is stated that hand mixing for a portion of the concrete used in another emplacement cost fifty-six cents more per cubic yard than machine mixing.

[1] Major M. B. Adams in charge. *Report Chief of Engineers, U.S.A.*, 1900, p. 837.

348. *Defenses Tampa Bay, Florida.*[1] — Cockburn-Barrow mixer, with cableway for placing concrete. Shell concrete made up of 1 cement, 3½ sand and 5½ shell.

1.31 bbls. cement, at $2.42 per bbl.	$3.17	
.71 cu. yd. sand, at 21 cents per cu. yd.	.15	
1.08 cu. yd. shell, at 50 cents per cu. yd.	5.4	$3.86
Labor mixing	$0.28	
Labor placing and tamping	.33	
Labor on forms	.155	.765
Total cost per cubic yard		$4.625

The above does not appear to include costs of running machinery, fuel, repairs, and depreciation of plant.

At the same battery[2] in the following year the cost of broken stone and shell concrete was as follows:

.9 bbl. cement at $2.46 (including $0.59 per bbl. storage).	$2.214	
.28 cu. yd. shell, at $0.45 per cu. yd.	.128	
.47 " sand, at 0.12 " "	.056	
.80 " stone, at 2.95 " "	2.360	
Total materials		$4.758
Mixing and placing	$0.623	
Forms	.370	
Total		.993
Total cost per cubic yard		$5.751

349. *Defenses San Francisco, Cal.*[3] — Cubical mixer; materials drawn from bins into measuring cars, hoisted by elevator and dumped into hopper of mixer. Mixer given twelve to fourteen turns and concrete dumped into cars, pushed by hand out on trestles, and dumped in place. Average capacity plant, 280 cubic yards per day of eight hours. Itemized cost of 8,328 cubic yards of concrete in place was as follows:

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[1] Report Lieut. Robert P. Johnson, Corps of Engineers, U. S. A., *Report Chief of Engineers*, 1899, p. 906.

[2] Report Lieut. Frank C. Boggs, Corps of Engineers, U. S. A., *Report Chief of Engineers*, 1900, p. 931.

[3] Maj. Charles E. L. B. Davis, Corps of Engineers, in charge. *Report Chief of Engineers*, 1900, p. 980.

.758 bbl. Portland cement, at $3.03 per bbl	$2.298	
.887 cu. yd. rock, at $1.80 per cu. yd.	1.597	
.41 cu. yd. sand, at 0.73 per cu. yd.	.299	
Water	.016	
Cost of materials		$4.210
Concrete plant, erection per cu. yd. concrete	$0.269	
Concrete plant, running expenses per cu. yd.	.022	
Concrete plant, taking down	.020	
Cost for plant, exclusive of purchase price		.311
Forms — materials	$0.272	
Forms — labor in erecting	.346	
Forms — labor taking down	.079	
Cost forms		.697
Labor mixing, placing and ramming		.626
Total cost per cubic yard		$5.844

350. In the building of a concrete dam for the enlargement of the head of the Louisville and Portland Canal,[1] comparison of cost of **hand and machine mixing** is given by Asst. Engr. J. H. Casey.

1.63 bbls. natural cement, at $0.635 per bbl.	$1.034	
2 volumes sand, .47 cu. yd., at .87 per cu. yd.	.408	
5 volumes broken stone, .89, cu. yd. at $.84	.756	
Cost of testing cement	.081	
Forms, material for	.107	
Forms, labor making and setting up	.168	
Cost materials and forms		$2.554

Hand mixed concrete:

Cost of mixing	$1.917	
Cost of placing and tamping	.791	
Cost of mixing and placing		$2.708
Total cost hand mixed concrete per cu. yd. in place		$5.262

Machine mixed concrete:

Charging and running mixer	$0.864	
Placing and tamping	.585	
Cost mixing and placing		$1.449
Total cost machine mixed concrete per cu. yd. in place		$4.003
Difference in favor machine mixing		$1.26

[1] Capt. George A. Zinn, Corps of Engineers, U. S. A., in charge. *Report Chief of Engineers*, 1900, p. 3467.

Since the above concrete was placed in large masses, the costs of labor are considered high, and it is probable the work was done with exceptional care.

351. In the construction of the lock at the **Cascades Canal**[1] the concrete plant was so arranged that the materials did not have to be elevated, but much of the work of transportation was done by gravity. The mixing of about eighteen hundred yards by hand permits a comparison to be made with machine mixing by which method about seven thousand eight hundred yards were made. The costs were as follows:

Items.	Cost per Cu. Yd. of Concrete.			
	Hand Mixed and Placed by Derrick.		Machine Mixed and Placed by Chute.	
	Amounts.	Total.	Amounts.	Total.
.805 bbl. Portland cement at $4.08	$3.20		$3.20	
.456 cu. yd. sand at $1.04	.47		.47	
.579 cu. yd. gravel at $1.04	.60		.60	
.317 cu. yd. broken stone at $1.70	.54		.54	
Cost materials in concrete	. . .	$4.90	. . .	$4.90
Timbering	.15		.15	
Testing cement and general repairs	.22		.22	
Forms and tests	. . .	.37	. . .	.37
Mixing, labor	1.07		.39	
" repairs and fuel	.02		.04	
Total cost mixing	. . .	1.09	. . .	.43
Placing, labor	.60		.41	
" fuel, tramways, etc.	.19		.05	
Total cost placing	. . .	.79	. . .	.46
Total cost concrete per cu. yd.	. . .	$7.15	. . .	$6.16

352. In the construction of the retaining walls for the **Chicago Drainage Canal**,[2] a special plant was designed for the work on account of the large quantities of concrete required, and this, combined with the low cost of materials and the character of the work, resulted in a very low cost concrete. On

[1] Maj. Thomas H. Handbury, Corps of Engineers, U. S .A., in charge. Report Lieut. Edward Burr, *Report Chief of Engineers*, 1891, Vol. v. Abstracted, *Engineering News*, June 2, 1892.

[2] "Construction of Retaining Walls for the Sanitary District of Chicago," by Mr. James W. Beardsley, and discussion by Mr. Charles L. Harrison. Jour. W. Soc. Engrs., Dec., 1898.

Section 14 the stone was selected from the spoil banks along the canal and could usually be obtained within one hundred feet. This stone, which was delivered to the crusher by wheelbarrows, required some sledging to reduce it to crusher size. An Austin jaw crusher was mounted on a flat car with the Sooysmith mixer. "The cement, sand and stone were raised from their respective bins by means of belt conveyors running at the same rate of speed, but carrying buckets spaced proportional to the required ingredients." "The cost of a second hand plant used on this section was estimated at $9,600, including two crushers and two mixers at $1,500 for each machine. Common labor cost $1.50 per day; firemen, enginemen, and carpenters from $2.00 to $3.00 per day. The itemized cost is as follows:

Items.	Cost, Cents per Cu.Yd.
General, including superintendent, blacksmith, water boys, etc.	7.8
Quarrying, *i. e.*, delivering stone to crusher	30.3
Crushing	7.3
Transportation, delivering sand and cement to mixer by teams	14.2
Forms, exclusive of lumber	15.0
Mixing	12.1
Placing and tamping	10.8
Total	97.5
Cost of plant (no salvage allowance)	40.7
Cost of cement and sand	163.3
Total cost concrete per cubic yard	$3.015

The amount of concrete used on this section was 23,568 cu. yds.

353. On Section 15 of the same work the conditions were somewhat different. The stone had to be quarried within about a thousand feet of the crusher. The stone, after being broken to crusher size, was delivered on the tipping platform of the No. 7 Gates' crusher in cars drawn by a cable hoist. "The average output of the crusher for a day of ten hours was about 210 cubic yards." The materials were transported to the mixer in four and one-half yard dump cars drawn by a light locomotive. The mixer was of the spiral screw type and deposited the materials on a rubber belt conveyor. The mixer and operating machinery were mounted on a car which propelled itself by means of rope and winch. The plant for this section was new and estimated to cost $25,420, including $12,000 for one crusher.

The detailed cost is as follows:

Items.	Cost per Cu. Yd. of Concrete, Cents.
General, including superintendent, blacksmith, teams, etc.	8.2
Quarrying (exclusive of 8.3 cents for explosives)	19.2
Crushing	12.8
Transportation, delivering cement, sand and stone on a platform beside the mixer	8.1
Forms, exclusive of timber	14.2
Mixing, including shoveling materials from platform to mixer	25.0
Placing and tamping	11.6
Total	99.1
Cost of plant (no salvage allowance)	56.7
Powder for quarrying	8.3
Cement and sand	158.6
Total cost concrete per cu. yd.	$3.227

The amount of concrete used on this section was 44,811 cubic yards.

CHAPTER XV

THE TENSILE AND ADHESIVE STRENGTH OF CEMENT MORTARS AND THE EFFECT OF VARIATIONS IN TREATMENT

ART. 45. THE TENSILE STRENGTH OF MORTARS OF VARIOUS COMPOSITIONS AND AGES

354. THE PROPORTION OF SAND.—The rate of change in the strength of mortars as the proportion of sand is increased varies greatly for different cements. The fineness and chemical composition of the cement, and the quality of the sand, are the most important factors influencing this rate of change upon which the question of the relative economies of different mortars is so largely dependent.

Table 67 gives the results of tests with two brands of Portland cement mixed with from two to ten parts of river sand, the age of briquets being six months and two years. It is of interest to notice that the strengths of the mixtures are approximately in the inverse ratio of the number of parts of sand used. Thus the strength with six parts sand is approximately two-sixths of the strength with two parts, while with ten parts sand, the strength is nearly two-tenths of that with mortar containing two parts.

TABLE 67

Rate of Decrease in Strength with Addition of Sand

PORTLAND CEMENT; RIVER SAND, "POINT AUX PINS"

PARTS SAND TO 1 CEMENT BY WEIGHT.	TENSILE STRENGTH, LBS. PER SQ. IN.					PROPORTIONATE STRENGTH, TWO YEARS, IF 1 TO 2=100.
	6 MONTHS.		2 YEARS.			
	H	R	H	R	Mean.	
2	512	504	534	548	541	100
3	390	335	363	355	359	66
4.09	295	261	296	288	292	54
6	175	144	191	174	182	35
8	113	96	132	132	132	24
10	64	74	104	116	110	20

355. In Table 68 similar results are given for two samples of Portland cement and two kinds of sand, neat cement specimens being included in the comparison. The one-to-one mortars give a higher strength than neat cement, and even the mortar containing two parts of the limestone screenings is stronger than the neat specimens. From the one-to-one mortars the strengths decrease rapidly as more sand is added, until five parts sand are used, but the strengths then decrease less rapidly as larger additions of sand are made.

TABLE 68

Rate of Decrease in Strength with Addition of Sand

PORTLAND CEMENT, BRAND R; SAND, CRUSHED QUARTZ AND LIMESTONE SCREENINGS

Parts Sand to 1 Cement by Weight.	Tensile Strength, Pounds per Sq. In.		Proportionate Strength if Strength 1 to 1 Mortar = 100.	
	Sample Cement H H, Crushed Quartz Sand, 20–30. Age Briquets, 6¼ Months.	Sample Cement II, Limestone Screenings, 20–30. Age Briquets, 6 Months.	Crushed Quartz.	Limestone Screenings.
0	689	686	82	78
1	840	881	100	100
2	521	703	62	80
3	368	508	44	58
4	236	335	28	38
5	203	267	24	30
6	156	178	19	20
8	104	138	12	15
10	78	98	9	11

356. In Table 69 two samples of natural cement are treated in a similar manner, from one to eight parts river sand being used in the mortars. With Sample II the strength is diminished rapidly until five parts sand have been added, but with further additions of sand, the strength is decreased more slowly. Sample 18 S gives quite a different curve, as the one-to-two mortar is stronger, and the one-to-three mortar is but little weaker than the one-to-one. With four parts sand the mortar shows a marked falling off in strength, but further additions of sand diminish the strength more slowly.

357. INCREASE IN TENSILE STRENGTH WITH TIME. — In Table 70 are given the results obtained in tests of tensile strength

TABLE 69

Rate of Decrease in Strength with Addition of Sand. Natural Cement, Brand Gn; River Sand, "Point aux Pins"

Parts Sand to 1 Cement by Weight.	Age.	Tensile Strength, Pounds per Square Inch.			
		6 Months.		2 Years.	Proportionate Strength, Two Years if 1 to 2 = 100.
	Sample Cement	II.	18 S.	18 S.	
0	...	380	...	...	...
1	...	297	308	280	86
2	...	260	314	324	100
3	...	183	280	294	91
4	...	128	193	187	58
5	...	81	161	165	51
6	...	69	142	172	53
7	...	56	119	156	48
8	...	53	101	114	35

with twelve samples of Portland cement, illustrating the rates of increase in strength from seven days to three years. It is seen that rich mortars gain strength rapidly, neat and one-to-one mortars showing usually eighty to ninety per cent. of their ultimate strength in twenty-eight days. Mortars containing not more than four parts sand to one cement give practically their ultimate strength at six months. It is also of interest to notice that the variations in strength among the several samples are not very great. The lowest strength at the end of two to three years is seventy-five to eighty per cent. of the highest.

358. In the case of natural cements, results for ten brands of which are given in Table 71, only fifty to seventy per cent. of the ultimate strength is gained in the first twenty-eight days; with mortars containing three parts sand to one cement the average result at twenty-eight days is less than forty per cent. of the strength at two years. Most of the samples gain some strength after six months, but two samples fail at two years which had given a fair result at six months. The variations in strength among the several samples are very much greater than with Portland cements; even omitting the two samples that failed, the strength of the highest is two or three times the strength of the weakest sample at two years.

TABLE 70

Portland Cement, Twelve Samples. Strength of Mortar and Fineness

Cement.		Fineness: Per Cent. Passing.		Tensile Strength, in Pounds per Square Inch.																
				Neat Cement.					One Part Sand to One Cement by Weight.					Three of Sand to One Cement by Weight.					4 Sand to 1 Cemе't.	5 Sand to 1 Ceme't.
Brand.	Sample.	Sieve No. 100, Holes .0065 In. Square.	Sieve No. 120, Holes .0046 In. Square.	7 days.	28 days.	6 mos.	2 years.	3 years.	7 days.	28 days.	6 mos.	2 years.	3 years.	7 days.	28 days.	6 mos.	1 year.	2 years.	2 years.	2 years.
H	5 S	. .	. .	497	570	619	633	668	501	650	740	768	749	176	272	456	398	384	. .	. .
H	21 S	90.7	82.6	567	710	736	703	804	566	669	722	840	802	197	266	434	395	350	283	228
R	300 S	. .	. .	523	619	717	676	768	525	591	756	813	746	202	255	384	394	370	280	224
I	8 S	89.5	76.4	469	562	669	748	719	486	563	727	796	725	177	250	387	388	390	. .	215
P	2	. .	. .	516	626	721	638	741	467	653	752	814	728	148	251	381	388	365	268	. .
K	3	81.3	67.7	518	628	646	643	745	477	606	722	860	778	164	237	367	383	354	. .	. .
F	4	86.7	79.0	387	575	685	728	723	404	614	761	855	793	101	212	385	379	382	. .	. .
C	12 S	86.6	76.0	532	711	797	790	751	502	621	756	687	620	144	219	362	376	332	233	. .
N	18 S	83.0	70.4	403	479	574	637	604	399	546	650	649	719	133	185	311	351	318	. .	. .
J	17 S	89.0	79.1	574	743	737	767	745	503	665	743	764	722	181	261	392	350	343	249	. .
A	20 S	84.5	73.8	556	637	691	681	698	498	616	675	795	737	150	227	374	350	327	. .	198
G	1	92.0	80.0	542	616	732	730	762	469	560	661	704	672	175	240	338	333	311	. .	184
	Sum	. .	. .	6084	7476	8324	8374	8728	5798	7354	8665	9345	8791	1948	2874	4571	4485	4226	. .	. .
	Mean	. .	. .	507	623	694	698	727	484	613	722	779	733	162	240	381	374	352	. .	. .

TABLE 71

Comparative Tests on Ten Brands of Natural Cement

Reference.	Cement.		Tensile Strength, Pounds per Square Inch.																
	Brand.	Sample.	Neat Cement.				One Part Sand to One Cement.					Two Parts Sand to One Cement.				Three Parts Sand to One Cement.			
			1 day.	7 days.	28 days.	6 mos.	7 days.	28 days.	3 mos.	6 mos.	2 years.	7 days.	28 days.	6 mos.	2 years.	28 days.	3 mos.	6 mos.	2 years.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*
1	Bn	27*s*	46	130	293	376	103	247	324	298	358	72	148	202	195	85	102	122	117
2	In	28*s*	63	103	180	329	80	179	366	395	369	39	106	332	401	26	148	189	265
3	Jn	29*s*	93	174	208	510	125	237	457	445	177	69	132	330	106	64	128	213	99
4	Kn	30*s*	100	189	289	326	164	385	452	505	532	95	217	483	561	101	264	321	372
5	Gn	844	74	140	178	326	104	242	410	358	337	46	129	384	386	63	191	256	285
6	Hn	26*s*	117	203	344	468	198	342	..	346	271	..	223	..	157	113	207	200	130
7	Ln	31*s*	148	229	296	468	196	275	..	436	395	..	183	..	339	114	217	253	270
8	Mn	39*s*	162	189	263	473	164	247	..	544	631	..	158	..	515	93	157	259	340
9	Nn	40*s*	179	210	316	493	169	252	..	570	665	..	184	..	550	104	171	260	328
10	Dn	9*s*	54	258	226	335	341	413	..	386	411	..	279	..	322	175	240	204	327
Mean	of 10 results		104	182	259	410	164	282	..	428	415	..	176	..	353	94	182	228	253
"	of 4, 8 and 9		147	196	289	431	166	295	..	540	609	..	186	..	542	99	197	280	347
"	of 2, 5, 7 and 10		85	182	220	364	180	277	..	394	378	..	174	..	362	94	199	225	287
"	of 1, 3 and 6		85	169	282	451	142	275	..	363	265	..	168	..	153	87	146	178	115

In general, each result is the mean of five briquets.

359. Table 72 shows in some detail the rate of increase in strength of a sample of natural cement when the specimens are **maintained in air and in water.** This table has several points of interest. When hardened in water, the cement gained steadily in strength up to six months, when it began to fall off, and at two years this cement failed, as is shown in Table 71. The neat cement specimens hardened in air are very irregular, as usual. These specimens showed high strength at three months, suffered a marked falling off at six months and one year, but showed a remarkable strength, equal to neat Portland cement, at two years. The strength developed at one year by specimens of this sample containing two parts sand to one cement and hardened in air, is also equal to that shown by similar mortars of Portland cement.

TABLE 72

Rate of Increase in Strength in Water and Air

Age of Briquets.	Tensile Strength, Pounds per Square Inch.			
	Neat Cement.		Mortar Two Parts Sand by Weight to One Cement.	
	Water.	Air.	Water.	Air.
1 day	81	152	. . . . . .	. . . . . .
7 days	192	254	135	142
14 days	232	315	. . . . . .	. . . . . .
28 days	305	473	232	271
3 mos.	390	551	367	459
6 mos.	437	372	409	475
1 year	432	314	249	537
2 years	395	731	. . . . . .	. . . . . .

All cement, Brand Hn, Sample 26 S, which fails in water after two years, see Table 71.

Art. 46. Consistency of Mortar and Aëration of Cement

360. Effect of Consistency of Mortar on Tensile Strength. — The results in Table 73 are from briquets of Portland cement with two parts "Standard" crushed quartz. The consistency of the mortars varied from a "trifle dry," in which water rose to the surface only after continued tamping, to a wet mortar which would just hold its shape when placed in a heap on the slab. Half of the briquets were immersed, while the remainder were stored in the air of the laboratory. The air hardened specimens gave higher results in all cases than those hardened in water. The highest strength was given in general by the dryest mortar, but the differences in strength decrease as the age of the specimen increases.

TABLE 73

Effect of Consistency on the Strength of Portland Cement Mortar Hardened in Water and Air

Age of Briquets.	Tensile Strength, Pounds per Square Inch.									
	Consistency of Mortar.									
	Briquets Hardened in Fresh Water.					Briquets Hardened in Air of Laboratory.				
	a	*b*	*c*	*d*	*e*	*a*	*b*	*c*	*d*	*e*
7 days . . .	340	310	226	191	158	407	341	263	230	202
28 days . . .	383	378	314	291	249	506	463	345	393	302
3 months . .	515	535	514	429	411	665	593	638	597	451

Cement: Brand R, Sample 18 R, with two parts "Standard" sand.

Consistency: *a*, trifle dry; *b*, O.K.; *c*, moist; *d*, very moist; *e*, would just hold shape.

361. Tables 74 and 75 give similar results for Portland and natural cement mortars, respectively, all specimens having hardened in water for three months. The amount of water used in gaging had a wide range, giving mortars of all consistencies from very dry to very moist. The richness of the mortar was also varied, from neat cement to five parts sand. A comparison of the results in these two tables indicates that the highest strength is usually given by mortars a trifle dryer than that considered right for briquets; that an excess of water is less deleterious to rich mortars than to lean ones, and to Portland cement than to natural cement.

362. Conclusions.— Although all of these tests indicate the superiority of dry mortars, in considering the effect of consistency from a practical standpoint, one must not fail to consider the difference between the conditions existing in the actual use of mortars and in laboratory tests. When mortar is used in

TABLE 74

Variations in Consistency of Mortar

EFFECT ON STRENGTH OF PORTLAND MORTAR AT THREE MONTHS

PARTS SAND TO 1 CEMENT BY WEIGHT.	TENSILE STRENGTH, POUNDS PER SQUARE INCH, FOR CONSISTENCY NUMBER.								
	1	2	3	4	5	6	7	8	9
0	608	635	763	744	708	707	729	685	. . .
1	513	543	618	588	594	613	566	566	538
2	. . .	. . .	429	. . .	447	398	393	382	. . .
3	. . .	289	. . .	322	329	310	. . .	279	. . .
5	. . .	208	. . .	230	201	189	. . .	167	. . .

Consistency — Significance of numbers: Increasing per cent. water used for higher numbers.
- 1 — Very dry; little or no moisture appeared on surface of briquets.
- 5 — About proper consistency for briquets.
- 9 — Very moist; mortar would barely hold shape and shrank in molds in hardening.

TABLE 75

Variations in Consistency of Mortar

EFFECT ON STRENGTH OF NATURAL CEMENT MORTAR AT THREE MONTHS

PARTS SAND TO 1 CEMENT BY WEIGHT.	TENSILE STRENGTH, POUNDS PER SQUARE INCH FOR CONSISTENCY NUMBER.								
	1	2	3	4	5	6	7	8	9
0	. . .	. . .	372	373	. . .	305	. . .	268	263
1	. . .	. . .	312	314	. . .	286	281	241	207
2	. . .	239	255	283	277	258	242	204	176
3	. . .	. . .	217	208	206	183	. . .	139	. . .
5	. . .	. . .	150	155	125	101	. . .	74	. . .

Consistency — Significance of numbers:
- 1 — Very dry; little or no moisture appeared on surface briquets.
- 5 — About proper consistency for briquets.
- 9 — Very moist; mortar would barely hold shape and shrank in hardening.

masonry, the stones or bricks, even though they be dipped, or sprayed with a hose before setting, are very likely to press out or absorb considerable moisture from the mortar. To realize this one has only to raise a heavy stone just after it has been bedded; and the greater ease of setting either stone or brick, and obtaining a full mortar bed, with a rather wet mortar, is appreciated by all masons. In the laying of concrete, the difficulties of obtaining a compact mass with a dry mortar are also not to be overlooked, but this point is discussed elsewhere.

363. Effect of Aëration on the Tensile Strength of Cement. — Portland cements that are not perfect in composition and burning, and that therefore contain free lime, may sometimes be rendered sound by exposing them to air, and such exposure was at one time considered almost essential in Portland cement manufacture.

Fresh Portland cements that are slightly defective may have their properties quite radically changed by such treatment; their rate of setting becoming first more rapid, and then, by further aëration, slower, and their tendency to expand overcome or ameliorated. Portland cements that are perfectly sound suffer some loss in specific gravity by the absorption of carbonic acid and water from the atmosphere, but moderate aëration has no radical effect upon their strength, and Portlands deteriorate but very slowly by storage, provided the cement is kept dry and does not cake in the package.

Natural cements, however, usually suffer by aëration, and this is illustrated by tests on several samples of one brand given in Tables 76 and 77. Of the four samples in Table 76,

TABLE 76

Effect of Aëration on Four Samples of Same Brand Natural Cement

Number Weeks Cement Aërated.	Tensile Strength, Pounds per Square Inch.					
	Age of Briquets, 6 Months to 7 Months.				Age Briquets, 2 Years.	
	Sample QQ	SS	NN	OO	NN	OO
0	242	183	343	340	316	306
2	237	269	357	506	368	432
5	256	403	...	...	...	...
7	268	358	...	...	...	...
10	...	...	225	212	246	284
11	313	279	...	...	...	...
13	...	...	213	218	260	258

Cement: Brand Gn; Sand, two parts crushed quartz to one cement.

All briquets of one sample were made by one molder and same percentage water used.

NN and OO showed an improvement by two weeks' exposure to air, spread out in a thin layer, but longer exposure resulted in a serious loss of strength. Of the other two samples, SS was greatly improved by five weeks' aëration, but longer exposure was detrimental, while sample QQ showed a continuous improvement up to the limit of eleven weeks' exposure to air.

In Table 77 the effect of aëration on five samples of the same brand is shown. One of these samples was overburned and was rendered practically worthless by fourteen weeks' exposure to air. Nearly all of the samples in this table were seriously affected by six weeks' aëration.

TABLE 77

Natural Cement. Effect of Aëration

Cement.		Parts Sand to 1 Cement.	Age of Briquets.	Tensile Strength, Pounds per Square Inch, Cement Aërated.				a	b	Specific Gravity of Fresh Cement.
Brand.	Sample.			4 to 5 days.	11 to 12 days.	45 to 51 days.	99 days.			
Gn	84	2	6 mo.	414	321	208	216	80.5	54	3.01
"	83	"	"	463	392	211	235	85.9	41	3.11
"	82	"	"	445	350	217	266	85.6	34	3.09
"	U′	"	"	383	354	273	274	87.8	23	2.95
"	O′	"	"	263	293	277	52	89.7	97	3.14

a — Fineness expressed as per cent. passing holes .0046 inch square.
b — Time setting fresh cement, time to bear $\frac{1}{12}$ inch ¼ lb. wire.

Art. 47. Regaging Cement Mortar

364. The Effect of Thorough Gaging. — The value of thorough gaging is a point frequently overlooked in the preparation of mortars and concretes. Table 78 gives a few of the results obtained in experiments to determine the effect of thorough work in mixing. The tests are made with two brands of natural and one of Portland, with two parts sand to one cement by weight. The two minutes' mixing with hoe and box method gave a more thorough gaging than could have been accomplished in the same time with a trowel, and represented about the amount of work put on mortars for testing. We are not, therefore, comparing well mixed and poorly mixed mortars, but rather well gaged and better gaged. The effect of the additional work is shown in all cases; to double the time spent in gaging, increases the strength of the resulting mortar about five per cent., while to quadruple the time adds twenty-six per cent. to the strength.

TABLE 78

Effect of Thorough Gaging

Ref.	Cement.		Sand, Two Parts to One Cement.	Tensile Strength, Lbs. per Sq. In., for Mortar Gaged,		
	Kind.	Brand.	Kind of Sand.	2 Min.	4 Min.	8 Min.
1	Natural	Gn	Pt. aux Pins Pass #10 Sieve	352	356	482
2	"	"	Standard	418	459	572
3	"	An	Pt. aux Pins Pass #10 Sieve	368	376	421
4	Portland	R	Pt. aux Pins Pass #10 Sieve	525	554	616
Mean				416	436	523
Proportional				100	105	126

365. REGAGING. — When more mortar is mixed at one time than is required for immediate use, there is always a temptation to retemper the mass and use it, even though it may have been standing for some time. The practice is usually prohibited by specifications and strenuously opposed by engineers. The tests recorded in Tables 79 to 83 were made to determine the effect of regaging on the resulting strength of the mortar.

366. The results obtained with two brands of Portland cement are given in Table 79. The first result in each line of the table is the strength attained by the mortar when treated as usual. The severity of the treatment of the mortar as regards regaging is shown by the letters heading the columns and the corresponding foot notes. The first general statement to be made concerning the results in this table is that in no case is the effect of regaging Portland mortars containing sand shown to be seriously deleterious to the tensile strength. Neat cement mortar is not improved by regaging, and if allowed to stand more than one hour, and then made into briquets without any further addition of water, the strength is considerably decreased. If water is added and the mortar frequently regaged, however,

TABLE 79

Regaging Portland Cement Mortar

Ref.	Cement.		Sand.		Age of Briquets.	Tensile Strength. Pounds per Sq. In.										
	Brand.	Sample.	Kind.	Parts to 1 Cement.		*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
1	R	300S	P.P. pass No. 10	2	6 mos.	437	511	477	506	479	. .	. .	. .	. .	. .	. .
2	"	"	"	2	1 yr.	467	462	517	514	518	. .	. .	. .	. .	. .	. .
3	H	5S	"	2	3 mos.	559	. .	525	. .	. .	. .	556	537	599	. .	. .
4	"	"	"	2	1 yr.	605	. .	581	. .	. .	. .	559	576	612	. .	. .
5	R	EE	. . . . .	0	6 mos.	698	. .	684	407	. .	. .	. .	564	. .	593	542
7	"	"	. . . . .	0	"	710	. .	. .	. .	. .	698	. .	595	. .	572	544
7	"	"	. . . . .	0	2 yrs.	675	. .	704	. .	. .	. .	. .	. .	. .	603	573
8	"	"	. . . . .	0	"	747	. .	. .	. .	. .	688	. .	. .	. .	612	616
9	"	"	Standard	1	3 mos.	784	. .	. .	. .	. .	. .	. .	767	. .	.	. .
10	"	"	"	1	1 yr.	823	. .	. .	. .	. .	. .	. .	803	. .	. .	. .
11	"	"	"	4	3 mos.	218	. .	. .	. .	. .	. .	. .	278	. .	. .	. .
12	"	"	"	4	1 yr.	282	. .	. .	. .	. .	. .	. .	310	. .	. .	. .

Treatment: — *a* — Treated as usual.
b — Mortar allowed to stand 1 hour, and briquets molded without regaging.
c — Mortar allowed to stand 1 hour, regaged and briquets made.
d — Mortar allowed to stand 8 hours, regaged every hour.
e — Mortar allowed to stand 5 hours, regaged every hour.
f — Same as *c*, except that water was added in regaging to restore original consistency.
g — Mortar allowed to stand 8 hours, then regaged and briquets made, water added.
h — Same as *d*, except that water was added in regaging to restore original consistency.
i — Same as *e*, except that water was added in regaging to restore original consistency.
j — Mortar allowed to stand 5 hours, then regaged and briquets made: water added.
k — Mortar allowed to stand 6 hours, regaged every hour; water added to restore consistency.

even neat cement mortar does not suffer a great decrease in strength by three to six hours standing. Rich mortars, containing one part sand, are not seriously affected by standing three hours if regaged frequently. Poorer mortars, with two to four parts sand, show an actual increase in strength as the effect of such severe treatment as standing five hours, if retempered with more water once an hour. These two brands were slow setting Portlands, beginning to set in forty minutes to two hours. The increase in strength of the regaged mortars is doubtless due, at least in part, to the more thorough gaging which they received.

Table 80 gives similar results of briquets one year old made at another time with two parts river sand. The fact that during the delay between the making and use of the mortar it should be frequently retempered with water to make up for the loss by evaporation, is plainly shown.

TABLE 80

Regaging Portland Cement Mortar

Tensile Strength, Pounds per Square Inch, for Varying Treatment.							
a	*c*	*d*	*e*	*f*	*h*	*i*	*j*
579	565	569	570	568	...	...	...
554	579	...	...	...	627	624	560

Cement: Portland, Brand R, Sample 42 M. Sand: 2 parts "Point aux Pins" passing No. 10 sieve. Age of briquets, 1 year.

Treatment: — *a* — Molded as soon as gaged.
c — Mortar let stand 1 hour, regaged and briquets made.
d — Mortar let stand 3 hours, regaged each hour.
h — Mortar let stand 3 hours, regaged each hour and water added to restore original consistency.
e — Mortar let stand 5 hours, regaged each hour.
i — Mortar let stand 5 hours, regaged each hour and water added to restore original consistency.
f — Mortar let stand 5 hours, regaged and briquets made.
j — Mortar let stand 5 hours, regaged and briquets made; water added to restore original consistency.

367. Similar tests with natural cements are shown in Table 81, and it appears that cements of this class, especially if mixed neat, will not stand the same severe treatments without injury.

TABLE 81

Regaging Natural Cement Mortar

Ref.	Cement. Brand.	Cement. Sample.	Sand. Kind.	Sand. Parts to 1 Cement.	Age of Briquets.	Tensile Strength, Pounds per Sq. In., for Mortars Receiving Different Treatment. a	b	c	d	e	f	g	h	i
1	Gn	91M	P.P. pass No. 10	2	3 months	254	261	291	325	305	. . .	. . .	. . .	. . .
2	"	"	"	2	1 year	291	288	310	335	366	. . .	. . .	. . .	. . .
3	"	FF	—	0	6 months	405	. . .	. . .	. . .	. . .	290	247	248	252
4	"	"	—	0	2 years	415	. . .	. . .	. . .	. . .	286	280	318	320
5	An	D	—	0	6 months	343	. . .	. . .	. . .	. . .	342	287	257	253
6	Gn	FF	"Standard"	2	3 months	340	. . .	. . .	. . .	. . .	. . .	386	. . .	. . .
7	"	"	"	2	1 year	297	. . .	. . .	. . .	. . .	. . .	273	. . .	. . .
8	"	"	"	4	3 months	159	. . .	. . .	. . .	. . .	. . .	106	. . .	. . .
9	"	"	"	4	1 year	201	. . .	. . .	. . .	. . .	. . .	194	. . .	. . .

Treatment: — *a* — Molded as soon as gaged.

b — Mortar let stand 20 minutes after first gaging, then regaged and briquets molded.

c — Mortar let stand 40 minutes after first gaging, then regaged and briquets molded.

d — Mortar let stand 60 minutes after first gaging, then regaged and briquets molded.

e — Mortar let stand 60 minutes after first gaging, then regaged and let stand 30 minutes; then again regaged and briquets molded.

f — Mortar let stand 1 hour after first gaging, then regaged with enough water added to bring to about same consistency as before, and briquets molded.

g — Mortar let stand total time of 3 hours, being regaged every hour with enough water added to bring to first consistency.

h — Mortar let stand total time of 5 hours, being regaged every hour with enough water added to bring to first consistency.

i — Mortar let stand 3 hours, then regaged once with additional water and briquets molded.

All cements rather slow setting, Brand An very slow setting.

TABLE 82

Regaging Natural Cement Mortar

Ref.	Cement.		Sand.		Tensile Strength, Pounds per Square Inch, for Mortars Receiving Different Treatment.										
	Brand.	Sample.	Kind.	Parts to 1 Cement.	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*k*	*l*
1	Gn	54R	P.P. pass No. 10	2	359	381	336	404	364	...	...	...	...	...	...
2	"	"	"	2	386	...	...	...	...	394	345	435	412	...	...
3	An	13s	"	2	365	390	355	436	189	...	...	...	...	...	...
4	"	"	"	2	384	450	...	...	...	...	367	447	388	...	...
5	Gn	54R	"Standard"	2	455	...	395	421	...	...	...	...	...	431	359

Age of all briquets, 1 year.

Treatment: — *a* — Mortar molded as soon as gaged.

b — Mortar let stand 1 hour, regaged at intervals of ½ hour ; total number of gagings, 3.

c — Mortar let stand 2 hours, regaged and briquets made; total number of gagings, 2.

d — Mortar let stand 2 hours, regaged at intervals of ½ hour; total number of gagings, 5.

e — Mortar let stand 4 hours, regaged at intervals of ½ hour; total number of gagings, 9.

f — Same as *b*, except water added in regaging to restore consistency of mortar.

g — Same as *c*, except water added in regaging to restore consistency of mortar.

h — Same as *d*, except water added in regaging to restore consistency of mortar.

i — Same as *e*, except water added in regaging to restore consistency of mortar.

k — Mortar let stand 1 hour, regaged and briquets made.

l — Mortar let stand 4 hours, regaged at intervals of 1 hour; total number of gagings, 5.

Neat cement mortars of these two brands appeared more plastic when they were retempered with more water after standing one hour (column *f*), but if allowed to stand three hours (column *i*), they had then become quite hard set. Mortars containing two parts sand that had stood sixty to ninety minutes with intermediate retempering, showed a slight increase in tensile strength, but more severe treatment was deleterious.

In Table 82 the mortars all contain two parts sand to one of cement by weight. The only cases of any serious results of retempering are for mortars standing four hours and regaged, at intervals of one-half hour or one hour, with no water added to the original mortar. Briquets made from mortar that had been gaged every half hour, and was molded two hours after first mixed, showed a somewhat higher strength than briquets made of fresh mortar.

Table 83 shows that the behavior of regaged natural cement mortars, as shown in the preceding tables, is not an eccentricity of one or two brands. Mortars containing two parts sand do not appear to suffer in tensile strength by being allowed to stand two hours if regaged hourly.

TABLE 83

Effect of Regaging on Tensile Strength, Five Brands Natural Cement

Parts Sand to 1 Cement.	Age Briquets.	Time Elapsed between First Gaging and Molding.	Total Number Gagings.	Interval Between Successive Gagings.	Tensile Strength, Pounds per Square Inch. Brands. En	An	Dn	Kn	Hn
2	28 days	. . .	1	. . .	58	171	231	178	174
2	"	2 hours	3	1 hour	109	168	310	178	190
2	6 months	. . .	1	. . .	228	328	306	361	273
2	"	2 hours	3	1 hour	284	382	307	416	347
4	28 days	. . .	1	. . .	39	49	149	23	58
4	"	2 hours	3	1 hour	33	70	146	. . .	56
4	6 months	. . .	1	. . .	104	146	188	216	129
4	"	2 hours	3	1 hour	97	147	184	227	137

NOTES: —Sand, Point aux Pins, passing No. 10 sieve.
In general, each result mean of five briquets.
All briquets made by one molder and stored in one tank.
All mortars appeared about same consistency when molded.
No water added in regaging except Brand Kn, 1 to 2 mortar, standing two hours.

368. Conclusions. — The conclusions to be drawn from these tests appear to be as follows: The cohesive strength of mortars of neat cement is appreciably diminished if they are allowed to stand a considerable length of time after gaging before they are used. Sand mortars, especially of Portland cement, usually develop a higher tensile strength under moderate treatment of this kind; and if regaged frequently, with sufficient water added to keep them plastic, mortars of slow setting cements may be used several hours after made without serious detriment to the tensile strength. Portland cements withstand severe treatment better than natural cements.

The effect of regaging on the adhesive strength is shown in Table 117, § 405. These tests were quite severe and pointed to the conclusion that the adhesive strength is diminished by standing and regaging, rich mortars and natural cement mortars being most affected.

The effect of regaging on a given sample should be investigated before it is permitted to any great extent, or in the most careful work. Regaged mortars are said not to give good results in sea water, and it may be expected that quick setting cement will be injured by regaging.

ART. 48. MIXTURE OF CEMENT WITH LIME, ETC.

369. Mixture of Portland and Natural Cements. — For certain uses mortar is sometimes made from a mixture of Portland and natural cement, with the idea of retaining some of the properties of the Portland without involving the expense of using a clear Portland mortar. Several tests have been made to determine the rate of hardening and the ultimate strength of such mixtures.

The mortars used in the tests given in Table 84 contained two parts sand to one of cement, and the cement was composed of one-eighth, one-quarter and one-half Portland to seven-eighths, three-quarters, and one-half natural. Mortars made with Portland alone and with natural alone are included for comparison. It is seen that the mortars containing some Portland harden more rapidly than the natural cement mortar, so that the increased strength developed at short periods is more than proportional to the per cent. of Portland used. The results obtained at two and three years, however, indicate that mortars containing only a small proportion of Portland, as one-eighth or one-quarter, do not give a higher ultimate strength than is obtained with clear natural cement mortar.

TABLE 84

Tensile Strength of Mortars Made with Mixture of Portland and Natural

Reference.	Age Briquets.	Per Cent. { Portland / Natural	Tensile Strength, Pounds per Square Inch.				
			100 / 00	50 / 50	25 / 75	12.5 / 87.5	0 / 100
1	7 days	. . . . .	291	205	108	75	24
2	28 days	. . . . .	357	264	219	190	123
3	6 months	. . . . .	550	425	378	300	322
4	1 year	. . . . .	574	441	300	336	291
5	2 years	. . . . .	543	449	375	343	393
6	3 years	. . . . .	592	501	428	370	429

NOTES. — Portland cement, Brand R, Sample 42 M.
Natural cement, Brand Gn, Sample 54 R.
Sand, two parts of "Point aux Pins," pass No. 10 sieve, to one part cement by weight.
All briquets made by one molder and immersed in one tank.
Each result, mean of ten briquets.

370. In Table 85 four kinds or mixtures of cement are used, Portland, natural, an "Improved cement" or a cement

TABLE 85

Comparisons of Portland, Natural, and "Improved" Cements

Ref.	Parts Standard Sand to 1 Cement by Weight.	Age of Briquets when Broken.	Tensile Strength, Pounds per Square Inch.			
			Portland, Brand U.	"Improved," Brand Nn.	Portland, 20%, Natural, 80%.	Natural, Brand, Mn.
1	None	7 days	547	206	250	199
2	"	28 "	586	293	341	270
3	One	7 "	458	169	200	165
4	"	28 "	569	253	331	234
5	"	7 months	702	550	578	517
6	"	2 years	577	563	534	497
7	Two	2 "	522	510	573	529
8	Three	7 days	176	52	80	49
9	"	28 "	272	122	143	114
10	"	6½ months	389	301	282	255
11	"	2 years	371	346	356	342
12	Mean	2 years	490	473	488	456

sold as a mixed cement, and a sample made by mixing twenty per cent. of the Portland with eighty per cent. of the natural. The first point noticed is that the "Improved" cement does not exhibit the early hardening properties due to the Portland cement in its composition (if any), as strongly as the sample containing twenty per cent. Portland. In only two tests did the "Improved" cement give a higher strength than the clear natural. The results of the two-year tests are of interest as showing how nearly the same ultimate strength is shown by the four samples. The sample of natural cement is of exceptional quality.

371. Conclusions. — It appears from these tests on the effect of mixing Portland and natural cements that, in general, the full strength of both cements is developed in the mixture; that in the early stages of hardening, the mixture sometimes exhibits more nearly the properties of the Portland, gaining strength quite rapidly, but that the ultimate strength of mixtures containing small amounts of Portland are sometimes as low as mortars made with natural cement alone. It cannot be stated that all samples of Portland and natural cement will give as good results in combination as those obtained in the above tests, and any extended use of such mixtures should be based on full tests of mixtures of the brands that are to be used in combination.

372. Free Lime in Cement. — The presence of free lime in cement is known to be a serious defect. Table 86 gives the results obtained by adding ground quicklime to Portland cement in one-to-two mortars. It appears that eight per cent. quicklime reduces the strength at six months about twenty-five per cent., and smaller amounts of lime produce approximately proportional decrements. The seven-day results, both hot and cold, show greater proportional effects. The free lime occurring in cements as a result of defects of manufacture is likely to be much more dangerous in character than the lime used in these tests.

373. THE USE OF SLAKED LIME WITH CEMENT. — A small quantity of Portland cement is frequently added to lime mortar to hasten the hardening and improve the strength. The addition of a small amount of slaked lime to Portland cement mortar is also practiced. This not only cheapens the mortar

TABLE 86

Mixture of Ground Quicklime with Portland Cement

Briquets Stored in Water.	Age of Briquets.	Tensile Strength of Mortars in Pounds per Square Inch.				
		Lime as Per Cent. of Total Lime and Cement.				
		0	2	4	6	8
Hot 80° C.	3 days	269	223	207	194	159
Hot 80° C.	7 days	367	297	266	223	191
Ordinary tank . .	7 days	348	321	273	241	220
Ordinary tank . .	6 months	604	545	489	495	454

Notes.— Cement: Portland, Brand R, Sample 83 T.

Lime: Quicklime ground to pass No. 100 sieve (holes .0065 in. sq.).

Sand: Standard crushed quartz, 600 grams, to 300 grams of cement plus lime.

Per cent. of lime given replaced the same weight of cement; thus: for "4 per cent. lime" the mortar contained 288 grams cement, 12 grams lime and 600 grams sand.

All briquets made by one molder; each result, mean of five briquets.

but renders it much more plastic, or less "brash," in mason's parlance. It is very difficult to lay bricks in a full mortar bed with Portland cement mortar containing two or three parts sand to one cement, and to use a richer mortar is usually too expensive. The work is very much facilitated by mixing a little slaked lime paste or powder with the mortar.

374. The tensile strength of such mixtures is shown by the tests in Tables 87 to 89. In the mortars of Table 87 a sample of Portland cement is mixed with slaked lime in two forms, paste and powder. When the briquets are hardened in open air the addition of ten to twenty per cent. of CaO in the form of lime paste decreases the strength about twenty-five per cent.; seven per cent. of lime in the form of slaked, dry powder has, however, no deleterious effect, and even twenty-eight per cent. gives no serious decrease in strength. For water-hardened specimens the addition of twenty to thirty per cent. of lime in the form of paste appears to increase the strength twenty per cent. and no deleterious effect is shown by the addition of forty per cent. Also for water-hardened specimens, seven to twenty-eight per cent. of CaO in the form of slaked powder increases the strength nearly twenty per cent. It thus appears that the addition of lime gives better results in mortars that are to harden in water, and that for air-hardened mortars lime powder should be used in preference to lime paste. Similar tests of seven-day briquets showed the lime paste to retard the hardening of the mortar.

TABLE 87.

Slaked Lime in Portland Cement Mortars

Ref.	Lime in Form of	Proportions.			Tensile Strength, Pounds per Square Inch., Sample Stored in	
		Cement, Grams.	CaO in Lime Paste or Powder, Grams.	Sand, Grams.	Open Air.	Water Laboratory.
1	Paste	200	0	600	404	382
2	"	200	20	600	308	426
3	"	200	40	600	292	450
4	"	200	60	600	224	462
5	"	200	80	600	219	384
6	Powder	200	0	600	382	371
7	"	200	14.3	600	385	443
8	"	200	28.6	600	316	451
9	"	200	42.8	600	338	431
10	"	200	57.1	600	325	440

Cement: Portland, Brand R. Sand: Crushed Quartz, 20–30, or "Standard." Age of briquets, 6 months.

375. In Table 88 only lime paste is used, but both Portland and natural cement are tested, and the specimens are hardened in dry air and damp sand. In the first column of results are given the strengths attained by Portland cement mortar containing three parts sand to one of cement without lime. In the second column, ten per cent. CaO in form of paste is added to the cement. In the third, fourth and fifth columns, respectively, ten, twenty-five and fifty per cent. of the cement is replaced by CaO.

It appears that ten per cent. of the cement in a one-to-three Portland mortar may be replaced by lime made into paste without diminishing the strength, if the mortar hardens in damp sand. Even in dry air exposure, it is only at one year that the lime shows any deleterious effect. To replace twenty-five per cent. or more of the cement with lime, however, diminishes the strength of the mortar in a marked degree.

In the case of natural cement, replacing ten per cent. of the cement with lime is decidedly beneficial, and even twenty-five per cent. lime gives enhanced strength, except for specimens hardened in dry air.

Table 89 gives similar results for one-to-four mortars and different percentages of lime, the briquets being hardened in dry air and damp sand.

TABLE 88

Use of Lime Paste in Cement Mortars Containing Three Parts Sand

Reference.	Cement.		Briquets Stored.	Age Briquets.	Tensile Strength, Lbs. per Sq. In.					
					Cement, gm.	200	200	180	150	100
					Lime Paste, "	0	60	60	150	300
					CaO in Lime Paste, gm.	0	20	20	50	100
					Amt. CaO expressed as % of Cement plus Lime.	0	9	10	25	50
	Kind.	Brand.			Sand, gm.	600	600	600	600	600
1	Port.	X	Dry air	28 da.	. . .	201	242	238	168	57
2	"	"	Damp sand	"	. . .	294	330	309	238	95
3	"	"	Dry air	3 mo.	. . .	236	265	264	171	70
4	"	"	Damp sand	"	. . .	350	410	398	309	125
5	"	"	Dry air	1 yr.	. . .	384	377	317	215	98
6	"	"	Damp sand	"	. . .	430	445	442	332	171
7	Nat.	An	Dry air	3 mo.	. . .	310	338	359	251	69
8	"	"	Damp sand	"	. . .	267	344	327	318	93
9	"	"	Water	"	. . .	222	301	319	293	79

In all of the above tests the mortars containing much lime paste were not only more plastic, but somewhat wetter than the corresponding mortars of cement and sand alone, on account of the water contained in the paste.

376. The **conclusion** to be drawn from these tests appears to be that the addition of a small amount, ten to twenty per cent., of slaked lime to cement mortars containing as much as three parts sand, not only renders them more plastic, but actually increases the tensile strength, especially if the mortars are kept damp during the hardening. It also appears that for

TABLE 89

Use of Lime Paste in Cement Mortars Containing Four Parts Sand to One Cement

Composition of Mortar.					Tensile Strength of Mortar, Pounds per Square Inch.			
Cement.		Lime Paste, Grams.	Lime in Paste, Grams.	Sand, Grams.	Stored in Damp Sand.		Stored in Dry Air.	
Kind.	Grams.				Fresh Lime Paste.	Old Lime Paste.	Fresh Lime Paste.	Old Lime Paste.
Portland, Brand X, Sample 41 S	240	00	00	960	176	180	254	244
	240	80	27	960	212	200	280	250
	200	120	40	960	198	212	227	237
	180	180	60	960	204	194	232	184
Natural, Brand An, Sample L	240	00	00	960	150	133	127	142
	240	80	27	960	160	154	162	150
	200	120	40	960	166	173	131	170
	180	180	60	960	140	166	124	154

NOTE.—All briquets three months old when broken.

mortars exposed to the open air the lime should be in the form of slaked powder rather than paste. It may be added, that in all cases care should be taken that the lime is thoroughly slaked before use, and all lumps should be removed by straining or sifting. Further results on this subject are given in connection with the tests on adhesion of cement mortar to brick (Art. 5).

377. EFFECT OF PLASTER OF PARIS ON THE COHESIVE STRENGTH OF MORTARS.

The use of plaster of Paris, or calcium sulphate, in the manufacture of cement to regulate the time of setting, has already been mentioned. The amount of such additions at the factory are usually small, the German Cement Makers' Association limiting it to two per cent.

Tests on three brands of Portland cement, showing the effect of small additions of plaster Paris, are given in Table 90. All of these mortars hardened in water. It is not known whether any of the cements had received additions of plaster Paris before leaving the factory. It is probable that brands R and X had been so treated, since they are German cements, but it is not probable that the other brands of Portland had received any addition of plaster.

It appears that with these brands the addition of from one to three per cent. of plaster Paris hastens the hardening and increases the strength of the mortar at ages of six months to two years. Six per cent. plaster sensibly retards the hardening, but, in all cases except one, Brand S, neat, six months, the mortars containing six per cent. plaster, gave higher results on long time tests than did the corresponding mortars to which no plaster had been added.

TABLE 90

Plaster of Paris in Portland Cement Mortars, Hardening in Water

Reference.	Cement, Portland Brand:	Sand, Parts to One Cement.	Temperature Water in which Briquets Stored.	Age of Briquets When Broken.	Tensile Strength, Pounds per Sq In., with Per Cent. of Cement Replaced by Plaster of Paris.				
					0	1	2	3	6
1	S	0	60° to 65° Fahr.	7 da.	487	626	600	519	380
2	"	0	"	6 mos.	743	746	754	742	660
3	"	2	"	7 da.	323	388	360	289	182
4	"	2	"	6 mos.	492	530	547	607	663
5	"	2	"	1 yr.	487	515	610	588	647
6	"	2	"	2 yrs.	533	586	612	659	684
7	R	0	"	7 da.	562	608	726	709	432
8	"	0	"	6 mos.	745	751	799	804	795
9	"	2	"	7 da.	288	347	372	352	165
10	"	2	"	6 mos.	532	538	624	638	642
11	"	2	"	1 yr.	591	595	643	645	666
12	"	2	"	2 yrs.	590	623	680	673	666
13	X	0	"	7 da.	351	368	405	450	204
14	"	0	"	6 mos.	560	606	580	645	797
15	"	2	"	7 da.	227	258	261	282	96
16	"	2	"	6 mos.	494	546	591	574	563
17	"	2	"	1 yr.	572	580	586	583	652
18	"	2	"	2 yrs.	592	575	592	592	667
19	S	2	176° Fahr.	5 da.	296	307	362	391	422
20	R	2	140° "	5 da.	403	440	416	495	442
21	X	2	140° "	5 da.	361	334	390	452	474

NOTES. — Sand, Point aux Pins (river sand) passing No. 10 sieve, except for hot tests, where standard sand was used. Cement and plaster of Paris passed through No. 50 sieve before using. Plaster Paris had no apparent effect on consistency mortar at first, but after making first three briquets of batch of five, the mortar containing plaster Paris dried out somewhat.

Each result, mean of five briquets.

Similar tests of natural cement mortars hardening in water are given in Table 91. One of the brands is not much affected

TABLE 91

Plaster of Paris in Natural Cement Mortars, Hardening in Water

Ref.	Cement, Natural Brand.	Sand, Parts to One Cement.	Temperature Water Where Stored.	Age of Briquets When Broken.	Tensile Strength, Pounds per Square Inch, with Per Cent. of Cement Replaced by Plaster of Paris.				
					0	1	2	3	6
			Degrees F.						
1	An	0	60–65	7 da.	233	225	213	235	*a*
2	"	0	"	6 mo.	422	449	438	441	324
3	"	2	"	7 da.	111	109	97	141	*a*
4	"	2	"	6 mo.	418	416	435	409	133*c*
5	"	2	"	1 yr.	415	451	430	454	
6	"	2	"	2 yrs.	478	476	489	514	
7	Gn	0	"	7 da.	146	156	115*c*	*a*	*a*
8	"	0	"	6 mo.	383	398*b*	323	312*e*	234*f*
9	"	2	"	7 da.	62	80	94	*a*	*a*
10	"	2	"	6 mo.	374	312	355	86*f*	151*f*
11	"	2	"	1 yr.	448	395	408	131*f*	107*f*
12	"	2	"	2 yrs.	456	437	397	172*f*	*a*
13	An	2	140	5 da.	319	365	405	402	203
14	Gn	2	"	"	359	351	189	138	100

NOTE. — Sand, Point aux Pins (river sand) passing No. 10 sieve, except for hot tests, where standard sand was used.

a — Found badly swelled and nearly disintegrated after a few days in tank.

b — Surface cracks, 1 inch section swelled to 1 $\frac{1}{16}$ inches.

c — Surface cracks, 1 inch section swelled to 1 $\frac{1}{12}$ inches. Had nearly disintegrated after 2 days.

d — Surface cracks.

e — Badly cracked on surface.

f — Badly cracked on surface, and 1 inch section swelled to about 1 $\frac{1}{16}$ inches.

by additions of one to three per cent., but the other brand is practically ruined by the addition of more than one or two per cent., and both brands are rendered quite unsound by six per cent. plaster.

378. The briquets reported in the preceding tables were hardened in water, as usual. Table 92 gives some of the results obtained by adding plaster Paris to mortars that are hardened in dry air. The effects on the two samples of the same brand of Portland, one quick setting and one slow setting, are quite different. The strength of the quick setting sample is increased, two per cent. giving the best results, while that of the slow setting sample is diminished by the addition of plaster. Both brands of natural cement appear to be notably improved by the plaster, the best result being given by three per cent. Such an addition to one brand results in a remarkable increase in strength of 250 per cent.

TABLE 92

Plaster of Paris in Cement Mortars, Hardening in Dry Air. Effect on Different Samples, Portland and Natural

Ref.	Cement.			Age Briquets.	Tensile Strength Pounds per Square Inch, with Per Cent. of Cement Replaced by Plaster of Paris.				
	Kind.	Brand.	Sample.		0	1	2	3	6
1	Port.	R	26 R	6 mo.	443	443	560	529	403
2	"	R	23 R	"	559	483	419	436	337
3	Nat.	An	L	"	162	220	282	286	272
4	"	In	28 S	"	76	110	151	269	240

NOTES. — Sample 26 R, Portland, quick setting, bears $\frac{1}{12}$ inch wire in 18 minutes.

Sample 23 R, Portland, slow setting, bears $\frac{1}{12}$ inch wire in 244 minutes.

Sand, two parts Point aux Pins (river sand) to one cement.

All briquets stored in air of laboratory until broken.

Each result, mean of five briquets.

For the effect of plaster of Paris on the adhesive strength of mortar, see § 407.

379. Conclusions. — It is evident from the above tests that the addition of small amounts of plaster Paris affects different samples of cement in quite different ways, and it is necessary to bear this in mind in the application of general conclusions to special cases. The indications are that the addition to cement of from one to three per cent. of plaster of Paris or sulphate of lime generally hastens the hardening and will not usually result in decreased strength; that some natural cements, however, are sensibly injured by more than one per cent., especially if used neat. The presence of as much as six per cent. plaster of Paris retards the hardening (although hastening the initial set) and is quite apt to ruin either Portland or natural cements. The addition of plaster Paris usually gives better results in air hardened than in water hardened specimens.

ART. 49. MIXTURES OF CLAY AND OTHER MATERIALS WITH CEMENT

380. EFFECT OF CLAY ON CEMENT MORTAR AND CONCRETE. — Clay may occur in cement mortar or concrete due to the use of sand or aggregate that is not clean. As the plasticity of cement mortar is increased by the presence of clay, small amounts are sometimes added to produce this effect, and clay is also sometimes used to render mortar stiff enough to withstand immediate immersion in water. In the case of concrete, the presence of a certain percentage of clay renders it easier to compact the mass by tamping, though if too much clay is present, the mass becomes sticky.

A number of tests have been made to determine the behavior of such mixtures of clay and cement. In all of these tests the clay was first dried, pulverized and sifted, and then a weighed quantity equal to a given per cent. of the weight of the cement was added to the latter. In the writer's first tests of this kind small percentages of clay were used, less than ten per cent., but it was found that with lean mortars much larger percentages must be used to determine the point where clay began to be injurious.

381. Table 93 shows the effect of clay on the time of setting and soundness of neat cement. The effect of small percentages of clay on the time of setting of Portland cement is not very marked, but with natural cement even ten per cent. of clay retards the setting in a marked degree. As to the effect on soundness, Portland cement pats disintegrate with more than twenty-five per cent. of clay added, while the natural cement is affected if more than ten per cent. of clay is present.

382. Table 94 shows the tensile strength of neat cement mortars to which clay to the amount of 10 to 100 per cent. of the cement has been added. Some of the Portland briquets were immersed as soon as molded, while others were left the customary twenty-four hours in moist air before immersion.

It is seen that to mix clay with neat Portland cement results in a decided decrease in strength, the results obtained with twenty-five per cent. clay being only about sixty or seventy per cent. of the strength of the mortar without clay. With natural cement the presence of clay seriously retards the hardening and results in decreased strength, though it does not

TABLE 93

Effect of Pulverized Clay on the Time of Setting and Soundness of Cement

Reference.	Cement.			Clay.	Time to Bear 1/12 Inch Wire in Minutes, and the Condition of Pats after Five Months.				
					Clay as Per Cent. of Cement.				
	Kind.	Brand.	Sample.	Kind.	0	10	25	50	100
1	Portland	X	41S	Red	285	318	328	328	450
1	"	"	"	"	Good	Fair	Good	Bad *a*	Bad *a*
2	"	"	"	Blue	288	286	300	305	306
2	"	"	"	"	Good	Fair	Good	Bad	Bad *a*
3	Natural	Gn	KK	Red	69	123	195	345	445
3	"	"	"	"	Fair	Fair	Bad	Bad	Bad *a*
4	"	"	"	Blue	98	173	215	350	415
4	"	"	"	"	Poor	Poor	Bad	Bad	Bad *a*

Note. — Results marked *a*, pats cracked badly in air and were not immersed.

TABLE 94

Effect of Clay on Tensile Strength; Neat Cement Paste

Ref.	Cement.			Kind of Clay.	Time Elapsed Between Molding and Immersing, Hours.	Age Briquets.	Tensile Strength, Lbs. per Square Inch.				
							Clay Expressed as Per Cent. of Cement.				
	Kind.	Brand.	Sample.				0	10	25	50	100
1	Port.	X	41S	Red	24	8 mo.	658	535	474	336	253
2	"	"	"	"	0	"	600	587	476	318	255
3	Nat.	An	D	"	24	28 da.	389	280	138	60	22
4	"	An	D	"	24	3 mo.	376	365	323	219	176

have as deleterious an effect as it does with Portland. The mixing of clay with neat cement is of course very severe treatment.

In Table 95 the mortars contain equal parts cement and sand, and the clay is from 50 per cent. to 200 per cent. of the weight of cement. It appears from this table that clay in as large amounts as 50 per cent. of the cement is injurious to one-to-one mortars of either Portland or natural cement.

383. The mortars in Table 96 are all of Portland, and contain three parts sand to one cement. Smaller percentages of

TABLE 95

Effect of Large Amounts of Clay in Mortars Containing Equal Parts Cement and Sand

Reference.	Cement.			Kind of Clay.	Hours Elapsed between Molding and Immersing.	Age of Briquets.	Tensile Strength, Lbs. per Square Inch. Clay Expressed as Per Cent. of Cement.				
	Kind.	Brand.	Sample.				0	50	100	150	200
1	Port.	X	41 S	Red	24	3½ mos.	747	512	337	239	193
2	"	"	"	"	0	"	720	549	321	242	189
3	Nat.	Gn	KK	"	24	3 mos.	454	241	212	183	140
4	"	"	"	"	0	"	413	231	206	157	128
5	"	An	D	"	24	"	442	259	194	167	152
6	"	"	"	"	0	"	440	274	184	141	125
7	"	"	"	"	24	6 mos.	488	335	268	217	184

clay are used, namely, 10 to 40 per cent. The mortars hardening in water show a decided improvement due to the presence of clay, but the briquets hardening in the open air indicate that

TABLE 96

Effect of Clay in Portland Cement Mortar Containing Three Parts Sand to One Cement

Reference.	Briquets Stored.	Age of Briquets.	Tensile Strength, Lbs. per Square Inch. Clay Added as Per Cent. of Cement.			
			0	10	20	40
1	Tank, Laboratory	6 months.	385	435	480	533
2	" "	2 years.	375	412	478	593
3	Open Air	6 months.	381	403	394	418
4	" "	2 years.	660	624	631	570

NOTES. — Cement, Portland, Brand R, Sample 83 T.
Sand, three parts crushed quartz $\frac{20}{30}$ to one cement by weight.
Clay, red clay dried, pulverized, and passed through No. 100 sieve.
Clay added to mortar, amount cement and sand remaining constant.

at two years the mortar without clay is stronger. It may be noted in passing that these results, obtained at two years, with one-to-three mortars hardened in open air, are very high.

The effect of clay on mortars containing four parts sand to one cement is shown in Table 97. In this case the addition of clay equal to the weight of the cement almost invariably results in increasing the strength of the mortar. Briquets immersed as soon as made were especially benefited by the presence of clay, except in one case, the red clay did not appear to increase the ability of the natural cement Gn to withstand early immersion. The red clay appears to give better results than the blue with Portland, while the reverse is true with at least one brand of natural. Whether this difference is a chemical or physical one is not known; the red clay is a good puddling clay, while the blue clay is not, but appears to contain some very fine sand.

TABLE 97

Effect of Large Amounts of Clay in Cement Mortars Containing Four Parts Sand to One Cement

Reference.	Cement.			Kind of Clay.	Hours Elapsed between Molding and Immersing.	Age of Briquets.	Tensile Strength, Lbs. per Square Inch. Clay as Per Cent. of Cement.				
	Kind.	Brand.	Sample.				0	50	100	150	200
1	Port.	X	41 S	Red	24	3 mos.	271	348	305	239	193
2	"	"	"	Blue	24	"	227	304	250	179	145
3	"	"	"	Red	00	"	156*a*	320	324	200	192
4	"	"	"	Blue	00	"	149*a*	270	215	148	114
5	Nat.	Gn	KK	Red	24	3 mos.	138	155	146	164	133
6	"	"	"	Blue	24	"	118	167	200	167	134
7	"	"	"	Red	00	"	83	87	39	86	72
8	"	"	"	Blue	00	"	49	127	147	136	106
9	"	"	"	Red	24	2 yrs.	194	348	306	256	190
10	"	An	D	Red	24	3 mos.	138	218	174	174	190

NOTES.—Sand, crushed quartz $\frac{20}{30}$, ("Standard"), four parts to one cement by weight.
Clay, dried, pulverized and passed through sieve before using.
All briquets immersed in tank in laboratory as usual.
Each result, mean of five briquets.
Results marked "*a*," briquets disintegrated some on face from early immersion.

384. Table 98 gives the results of tests by other experimenters, showing the effect of clay on one-to-three mortars of Portland and natural cement.[1] The amount of clay used in these tests appears to be stated as percentage of the total ingredients instead of as a percentage of the cement as in the preceding tables. The mortars were mixed quite dry for these experiments. The Portland cement mortar seems to be improved by the addition of clay to the amount of twelve per cent. of the mortar. The hardening of natural cement mortar is somewhat slower with twelve per cent. clay than with three to six per cent., but at the age of twelve weeks the mortars containing clay were all stronger than that without clay.

TABLE 98

Effect of Clay on the Tensile Strength of One-to-Three Mortars

Cement.	Parts Sand to One Cement.	Age of Briquets When Broken.	Tensile Strength, Pounds per Square Inch. Clay Expressed as Per Cent. of Mortar.				
			0	3	6	9	12
Portland	3	2 weeks	202	267	280	318	333
"	3	4 weeks	362	301	334	381	353
"	3	12 weeks	451	506	521	522	547
Natural	2	1 week	68	117	101	90	65
"	2	4 weeks	152	199	219	170	146
"	2	12 weeks	170	214	252	230	211

Note. — Tests by Messrs. J. J. Richey and B. H. Prater.

385. Conclusions. — Always keeping in mind the limitations to be observed in drawing general conclusions from experiments having a limited range, it may be said that the indications are as follows: Neat cement and rich mortars are injured by the addition of clay, the rate of hardening and the ultimate strength being diminished. Lean mortars containing three to four parts sand to one cement are usually improved by the addition of clay to the amount of 40 to 100 per cent. of the cement, or 10 to 25 per cent. of the combined weight of cement and sand, and the ability of such mortars to withstand early immersion may be greatly enhanced by such additions. It is evident from the above tests that the expense which should be incurred in washing sand to remove a small percentage of clay is limited,

[1] Messrs. J. J. Richey and B. H. Prater, *Technograph*, 1902–3.

and for certain uses there is no question that mortar may be improved by the addition of clay.

(For the effect of clay on the compressive strength of concrete, see Art. 55.)

386. Powdered Limestone, Brick, etc. — Various foreign substances are sometimes used with cement, either in lieu of sand, or to make the mortar more plastic. Such foreign ingredients may also occur in mortar as impurities in the sand used. Powdered limestone, slaked lime, powdered brick and clay are some of the materials experimented with in this connection. A few tests of the effects of such mixtures on the setting time of ce-

TABLE 99

Foreign Substances in Cement Mortar

Reference.	Cement.			Parts Sand to One Part Cement.	Age of Briquets When Broken.	Tensile Strength, Pounds per Square Inch.					
						Composition of Mortar.					
	Kind.	Brand.	Sample.			*a*	*b*	*c*	*d*	*e*	*f*
1	Port.	R	JJ	None	3 months	705	...	674	583	615	667
2	"	"	"	3.75	5 days, H	152	217	164	175	240	198
3	"	"	"	3.75	3 months	259	367	297	284	311	304
4	"	"	"	3.75	1 year	309	365	367	333	438	438
5	Nat.	An	G	None	3 months	286	...	203	307	154	203
6	"	"	"	4	5 days, *h*	86	...	105	94	132	164
7	"	"	"	4	3 months	185	...	214	157	239	215
8	"	"	"	4	1 year	210	...	234	238	263	264

NOTES. — Sand, "Standard." Materials added to mortar were first pulverized and passed through No. 80 sieve, holes .007 inch square.

5-day results, H = immersed in hot water, 80° C.
5-day results, *h* = immersed in hot water, 60° C.

Composition of mortars: —

a — No foreign substance.

b — No foreign substance, but additional amount cement added, making mortar 1 to 3 instead of 1 to 3.75.

c — Kelleys Isd. Limestone, equal to 25 per cent. weight of cement added to mortar.

d — Slaked lime powder, equal to 25 per cent. weight of cement added to mortar.

e — Red clay, equal to 25 per cent. weight of cement added to mortar.

f — Red brick, equal to 25 per cent. weight of cement added to mortar.

ment indicated that the rate of setting of Portland cement was not appreciably affected by the addition of twenty-five per cent. of any of these substances, but the setting time of natural cement appeared to be sensibly hastened by such additions. None of these materials had any appreciable effect on the soundness of either Portland or natural.

Table 99 shows the effect on the tensile strength of mortar of adding twenty-five per cent. of each of the four substances mentioned. It appears that the strength of neat cement mortar, either Portland or natural, is usually diminished by the presence of such materials, but in almost every case mortars containing about four parts sand to one cement are improved by the addition of the substances in question to an amount equal to twenty-five per cent. of the cement. Pulverized clay and brick give the best results, the increased strength amounting to from twenty to forty per cent.

387. Sawdust. — Where a very light and porous mortar is desired for use in floors and similar purposes, the incorporation of sawdust in the mortar is suggested by a similar use in clay building materials. The results in Table 100 show that the use of sufficient sawdust to materially diminish the weight practically ruins the cohesion of the mortar, even ten per cent. of sawdust materially diminishing the strength.

TABLE 100

Sawdust in Cement Mortar

Reference.	Cement.		Parts Sand to One Cement.	Briquets Stored.	Age of Briquets When Broken.	Tensile Strength Pounds per Square Inch.					
						Sawdust as Per Cent. of Cement.					
	Kind.	Brand.				0	10	20	25	50	100
1	Port.	X	0	Tank	1 yr.	799	409	. . .	169	44	31
2	"	"	0	Dry air	"	674	492	. . .	193	28	*a*
3	"	"	2	Tank	"	502	. . .	. . .	. . .	32	32
4	"	"	2	Dry air	"	452	. . .	129	. . .	14	*a*
5	Nat.	An	0	Tank	"	433	253	. . .	104	38	*b*
6	"	"	2	Tank	"	313	. . .	108	. . .	58	20

NOTES. — Sand, crushed quartz, $\frac{20}{30}$. Sawdust from white pine, passed through sieve with one-quarter inch meshes.

a — Briquets broken in applying initial strain.

b — Briquets disintegrated in tank.

388. Use of Ground Terra Cotta as Sand. — A light weight mortar may also be made by using as sand or aggregate, materials of burned clay, such as brick or terra cotta. The tests in Table 101 were made to determine the value of ground terra cotta for use in place of sand, and it appears that this material gives excellent results. The strength given with one of the brands of natural cement is especially high.

TABLE 101

Use of Ground Terra Cotta as Sand in Cement Mortar

Reference.	Cement.		Age of Briquets.	Tensile Strength, Lbs. per Sq. In. Parts Ground Terra Cotta to One Cement, by Weight.				
	Kind.	Brand.		1	2	3	4	6
1	Portland	X	3 months	523	406	332	257	174
2	"	"	1 year	604	518	429	337	266
3	Natural	An	3 months	284	338	346	317	224
4	"	"	1 year	262	360	351	361	186
5	"	En	3 months	291	303	184	136	. . .
6	"	"	1 year	340	434	284	161	. . .

NOTES. — Terra Cotta tile, of medium burn, ground and passed through No. 20 sieve, and used in place of sand.

ART. 50. THE USE OF CEMENT MORTARS IN FREEZING WEATHER

389. It is frequently desirable to use cement in freezing weather, but to ensure good work under these circumstances it is necessary to take certain precautions. If mortar is frozen immediately after mixing, setting cannot take place until it has again thawed. In the practical use of cement it is always gaged with a larger quantity of water than is required for the chemical combination, and if this excess water is frozen after the setting is somewhat progressed, the consequent expansion may be sufficient to disrupt the partially set mortar. By warming the materials or by lowering the freezing point of the water by the addition of salt, glycerine, or some other substance having this effect, it is sought to prevent the mortar freezing until the work is protected by another layer of mortar, or otherwise, and thus to avoid the expansion. Salt is generally used much too sparingly to prevent freezing. The freezing point of water is lowered about one and a half degrees Fahr. for each per cent. of common salt added; thus a twenty per cent. solution would freeze at about two degrees Fahr.

390. The following tests are selected as showing typical results of a large number of experiments made under the author's direction to determine the effect of exposing cement mortars to frost, and to indicate what treatment will alleviate the deleterious effects of low temperature. In making tests with small specimens, it is difficult to approach the conditions existing in the actual use of mortars in freezing weather. A small mass of mortar exposed to the air on all sides sets more quickly than the interior of a large mass; and on the other hand, the effect of frost on a small specimen must be more severe and more quickly apparent. Many of the results are more or less contradictory, and the conclusions that have been drawn are such as appear to be indicated by the majority of the tests. The treatment of the briquets, and the conditions existing, are given in some detail, that the limits of applicability of such conclusions may be seen.

391. Exposure to Frost of Mortars Already Set. — In the tests recorded in Tables 102 to 104 the briquets were allowed to remain one or two days in the laboratory. It is evident that these results are of but limited practical importance, since it is seldom that mortars which are made in winter can be allowed to set in a warm place before exposure; they are given, however, for what they are worth. Tables 102 and 103 give the results obtained with Portland cement briquets exposed to a severe temperature twenty-four to forty-eight hours after made. The most important deduction, and the one most clearly indicated by these tables, is that Portland cement mortar made with fresh water may be subjected to very low temperatures twenty-four to forty-eight hours after molded, without seriously decreasing the tensile strength given at six months to two years. It also appears that solutions containing as much as fifteen per cent. salt are deleterious, and smaller percentages are not advantageous under these conditions.

Table 104, giving the results of **similar tests with natural cement** mortar, indicates that this brand gives good results if allowed to set in warm air before exposure to frost. Solutions

TABLE 102

Exposure of Portland Cement Mortars to Low Temperatures after Twenty-four Hours in Laboratory

Sand, Kind.	Date Made.	Age When Broken.	Tensile Strength, Pounds per Sq. In.						
			a	*b*	*c*	*d*	*e*	*f*	*g*
Standard . . .	1–15	6 mo.	772	960	816	. .	. .	524	507
Standard . . .	1–15	21 mo.	796	882	766	. .	. .	443	642
Pt. aux Pins, pass. sieve #10	1–18	6 mo.	651	630	. .	769	463	443	. .
Pt. aux Pins, pass. sieve #10	1–18	21 mo.	760	780	. .	711	543	447	. .

Notes. — Cement, Portland, Brand R. One part sand to one cement.

Briquets made in laboratory, temp., 64° to 66° Fahr.; materials about 65° Fahr.

Temperature, open air, Jan. 16 to Jan. 19, 4° to 15° Fahr.

Treatment of briquets: —

a — Fresh water, briquets stored in water in laboratory.
b — Fresh water, briquets stored in open air after 24 hours.
c — Fresh water, briquets alternated, two days in open air and then two days in air laboratory, for fifty-two days, then left in open air.
d — Water 5 per cent. salt; briquets stored in open air.
e — Water 15 per cent salt; briquets stored in open air.
f — Water 25 per cent. salt; briquets stored in open air.
g — Water 25 per cent. salt; briquets stored in water in lab.

TABLE 103

Exposure of Portland Cement Mortars to Low Temperatures, Twenty-four to Forty-eight Hours after Made

Sand, Kind.	Date Briquet Made.	Age When Broken.	Tensile Strength, Pounds per Sq. In.									
			a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*
Std. .	1–16	6 mo.	415	372	401	262	202	. .	. .	. .	. .	. .
Std. .	1–16	21 mo.	602	372	438	384	326	. .	. .	. .	. .	. .
P. P.	1–19	6 mo.	. .	. .	. .	. .	. .	381	394	360	371	233
P. P.	1–19	21 mo.	. .	. .	. .	. .	. .	638	430	418	375	344

Notes. — Cement, Portland, Brand R. Three parts sand to one cement.

Briquets made in laboratory. Temp.: Air and materials, 64° to 67° Fahr. Open air, Jan. 10 to 20, –15° to +18° Fahr.

Treatment of briquets: *a, b, c, d* and *e* mixed with water containing 0, 10, 15, 20 and 25 per cent. salt, respectively; *a* to *d*, inclusive, air laboratory 24 hours, water laboratory 16 hours, air laboratory 12 hours, then in open air.

f, g, h, i and *j*, mixed with water containing 0, 10, 15, 20 and 25 per cent. salt, respectively.

e to *j*, inclusive, put in open air after about 24 hours in air of laboratory.

TABLE 104

Exposure of Natural Cement Mortars to Low Temperatures, Twenty-four Hours after Made

Parts Sand to One Cement.	Date Made.	Age When Broken.	Tensile Strength, Pounds per Sq. In.					
			a	*b*	*c*	*d*	*e*	*f*
2	1-20	6 mo.	297	404	319	. . .	297	176
2	1-20	1 yr.	305	390	343	. . .	273	217
4	1-20	6 mo.	222	318	319	344	. . .	114
4	1-20	1 yr.	223	259	339	205	. . .	150

Notes. — Cement, Natural, Brand Gn. Sand, "Pt. aux. Pins" (river sand).

Temp. materials and air of laboratory where briquets were molded, 65° to 68° Fahr. Temp. open air Jan. 21 to 23, = − 1° to + 29°.

Treatment of briquets: *a*, briquets stored in water in laboratory. *b* to *f*, inclusive, briquets stored in open air after twenty-four hours in air of laboratory.

a and *b*, fresh water used for gaging mortar.

c, *d*, *e* and *f*, water used in gaging had 5, 10, 15 and 25 per cent. salt, respectively.

containing more than ten per cent. salt are deleterious for such treatment. Briquets of another brand of natural cement, a one-to-one mortar of which gave about 450 pounds tensile strength at one year, failed entirely when placed, one hour after made, in open air for three days, and then immersed in a tank in the laboratory. A 7.4 per cent. solution of salt used for gaging assisted very materially in preserving the mortar under the same severe treatment, although this amount of salt was not sufficient to lower the freezing point of the water below the temperature to which the briquets were subjected.

392. Effect of Salt in Mortars Hardened in Water and Air. — In the tests recorded in Table 105 the materials used were at a temperature of forty degrees Fahr., and the briquets were molded in an open warehouse where the temperature was usually below twenty-three degrees Fahr., though for a few of the tests the temperature of the air at time of molding was as high as twenty-seven degrees. The temperature of the mortar when briquets were finished was usually but little above thirty-two degrees Fahr. The briquets were left in a warehouse for three days, when part of them were immersed in cold water

TABLE 105

The Use of Portland Cement Mortar in Freezing Weather

Reference.	Cement.		Temperatures, Degrees Fahr.				Date Made.		Time Left Where Made.	Age when Broken.	Tensile Strength of Briquets, Pounds per Square Inch.													
					Mortar.						Stored in Canal, Cold Water.							Stored in Open Air.						
											Per Cent. Salt in Water Used in Gaging.							Per Cent. Salt in Water Used in Gaging.						
	Brand.	Sample.	Air Where Briquets Were Made.	Materials Used.	When Gaged.	When Briquets Finished.					0	3	5	10	15	20	25	0	3	5	10	15	20	25
	a	*b*	*c*	*d*	*e*	*f*	*g*		*h*	*i*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*	*t*	*u*	*v*	*w*	*x*
							mo.	da.	da.	mo.														
1	R	42M	21	40	. . .	. . .	3	17	3	6	358	428	376	459	448	483	459	. .	. .	. .	. .	. .	. .	. .
2	"	"	"	"	. . .	. . .	3	18	"	"	. .	. .	. .	. .	. .	. .	. .	521	473	479	481	489	431	406
3	"	"	"	"	. . .	. . .	3	17	"	18	499	514	487	473	534	541	523	. .	. .	. .	. .	. .	. .	. .
4	"	"	"	"	. . .	. . .	3	18	"	"	. .	. .	. .	. .	. .	. .	. .	856	820	835	804	738	747	715
5	R	EE	20–23	40	35–49	32–36	12	18	3	6	367	391	397	425	483	497	444	. .	. .	. .	. .	. .	. .	. .
6	"	"	12–16	"	39–47	32–37	12	19	"	"	. .	. .	. .	. .	. .	. .	. .	594	613	636	625	635	504	498
7	"	"	20–23	"	34–49	32–36	12	18	"	9½	461	439	477	501	487	527	453	. .	. .	. .	. .	. .	. .	. .
8	"	"	12–16	"	39–47	32–37	12	19	"	"	. .	. .	. .	. .	. .	. .	. .	590	585	611	568	535	498	416
9	R	GG	10–18	40	43–48	32–38	12	26	3	6½	413	386	461	467	523	491	502	. .	. .	. .	. .	. .	. .	. .
10	"	"	19–27	"	44–48	36–40	12	22	"	"	. .	. .	. .	. .	. .	. .	. .	589	633	713	572	587	486	445
11	"	"	10–18	"	43–48	32–38	12	26	"	9½	450	452	466	494	517	514	528	. .	. .	. .	. .	. .	. .	. .
12	"	"	19–27	"	44–48	36–40	12	22	"	"	. .	. .	. .	. .	. .	. .	. .	613	596	650	487	473	438	410
13	R	12R	16–19	40	43–48	34–38	12	29	1	6½	397	401	409	413	437	442	449	. .	. .	. .	. .	. .	. .	. .
14	"	"	4–9	"	42–47	32–36	12	30	"	"	. .	. .	. .	. .	. .	. .	. .	513	599	564	610	639	544	442
15	"	"	16–19	"	43–48	34–38	12	29	"	9½	468	436	443	468	482	456	468	. .	. .	. .	. .	. .	. .	. .
16	"	"	4–9	"	42–47	32–36	12	30	"	. .	. .	. .	. .	. .	. .	. .	. .	513	592	544	509	476	426	408
17	Means		. . .	. .	. .	. . .	. .	. .	. .	. .	427	431	440	462	489	494	478	599	614	629	582	572	509	492

Mortar: 2 parts "Point aux Pins" (river sand), passing No. 10 sieve, to 1 part cement, Portland Brand R. Each result, mean of five specimens. Canal and open air briquets made by different molders.

(under ice), and the remainder stored in open air on a shelf covered by a rough board roof, but with front left open to the weather. All mortars contained two parts river sand to one of cement by weight. The water used in gaging varied from fresh to a twenty-five per cent. solution.

The results indicate that Portland mortars made in low temperatures, to be immersed in cold water, are improved by fifteen to twenty per cent. salt in the water of gaging, but that more than five per cent. salt is deleterious for mortars exposed to the air only. The very high results given by the air-hardened specimens are worthy of notice.

A similar series of tests of natural cement gave results from which no definite general conclusions could be drawn. The effect of freezing and of the use of salt varied greatly for different samples. For any given sample the treatment, as regards the use of salt, giving good results in open air, was usually the reverse of that giving good results in cold water. The conclusions indicated for rich mortars were sometimes the reverse of those shown by lean mortars.

393. The results obtained with five brands of natural ce-

TABLE 106

Effect of Low Temperatures on Five Brands of Natural Cement

Reference.	Date Made.		Molder.	Parts Sand.	Temperature Air Where Made.	Per Cent. Salt in Water.	Where Stored.	Time in Water Just Before Breaking.	Mean Tensile Strength, Brand.				
									Gn.	An.	Kn.	Hn.	Jn.
	a		*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*
	Mo.	Da.			Deg.			Days					
1	2	20	N	1	9–11	18	Canal	. .	234	322	285	423	284
2	2	22	N	1	16–19	0	"	. .	201	327	326	302	219
3	2	20	S	1	9–11	18	Open air	0	344	416	412	321	292
4	2	22	S	1	16–19	0	"	0	367	305	480	360	311
5	2	20	S	1	9–11	18	"	7	274	306	413	244	304
6	2	22	S	1	16–19	0	"	7	292	338	426	311	304
7	2	21	N	2	7–14	19	Canal	. .	161	318	329	348	238
8	2	23	N	2	9–9	0	"	. .	160	217	355	258	186
9	2	21	S	2	9–14	19	Open air	0	288	289	382	282	319
10	2	23	S	2	9–9	0	"	0	338	275	422	423	367
11	2	21	S	2	9–14	19	"	3	268	271	340	240	295
12	2	23	S	2	9–9	0	"	7	317	333	414	345	356

NOTE.—All briquets broken when six and a half months old.

ment are given in Table 106. The briquets were made in a temperature of nine to nineteen degrees Fahr. Half of the briquets were made with fresh water, and half with water containing enough salt to lower its freezing point below that of the

TABLE 107

Portland Cement Mortar in Low Temperatures
Effect of Heating Materials

Reference.	Parts Sand to One Cement.	Temperature Degrees Fahr. Air Where Molded.	Per Cent. Salt in Water.	Where Stored.	Broken Dry or Wet.	Age of Briquets When Broken.	Tensile Strength, Pounds per Square Inch. Cold Materials, 40°.	Warm Materials, 110°.	Cold Materials, 40°.	Warm Materials, 110°.
						Mo.				
1	1	1–5	23	Canal	Wet	6	. . .	. . .	582	598
2	1	8–9	0	"	"	"	590	593	. . .	. . .
3	1	1–5	23	"	"	18½	. . .	. . .	711	734
4	1	8–9	0	"	"	"	770	737	. . .	. . .
5	2	14–16	14	"	"	6½	. . .	. . .	542	550
6	2	23–24	0	"	"	"	460	476	. . .	. . .
7	2	14–16	14	"	"	18½	. . .	. . .	549	597
8	2	23–24	0	"	"	"	467	541	. . .	. . .
Means	. . .	. . .	. .	. . . .	. .	. .	572	587	596	620
9	1	4–6	23	Open air	Dry	6½	. . .	. . .	469	450
10	1	9–10	0	"	"	"	711	724	. . .	. . .
11	1	4–6	23	"	Wet	"	. . .	. . .	487	470
12	1	9–10	0	"	"	"	628	614	. . .	. . .
13	2	15–18	14	"	Dry	"	. . .	. . .	507	542
14	2	24–25	0	"	"	"	673	657	. . .	. . .
15	2	15–18	14	"	Wet	"	. . .	. . .	422	453
16	2	24–25	0	"	"	"	543	495	. . .	. . .
Means	. . .	. . .	. .	. . . .	. .	. .	639	622	471	479
Grand	Means	. . .	. .	. . . .	. .	. .	605	605	534	549

NOTES.— Cement, Portland. Sand, "Point aux Pins."

When warm materials used, the temperature mortar after briquets finished, 63° to 71° Fahr.

When cold materials used, the temperature mortar after briquets finished, 32° to 39° Fahr.

When salt water used for mixing, water was 23 per cent. salt for 1 to 1 mortars and 14 per cent. salt for 1 to 2 mortars.

Briquets stored in canal were left in cold air three days before immersion.

Part of briquets stored in open air were immersed in tank in laboratory one week just before breaking, while others were broken dry as indicated.

In general, each result is mean of five briquets.

air where the briquets were made. The results are chiefly of interest as showing the strength that may be attained by natural cement mortars under these severe conditions.

Higher results are usually given by the air-hardened specimens than by those immersed in cold water, though this depends somewhat upon the brand. Salt is usually beneficial if the briquets are immersed, and detrimental for open air exposure.

394. Effect of Heating the Materials. — The tests in Table 107 were made to determine the effect of heating the materials when working in low temperatures, and thus delaying for a time the freezing of the mortars. The details of the tests are fully given in the table. The conclusion indicated is that the ingredients may be used cold or warm indifferently. A gain of only four per cent. is indicated for warm materials in mortars mixed with salt water and hardened in cold fresh water. In practical work, however, the use of warm materials may so delay the freezing as to permit thorough tamping before the mortar freezes. Table 108 gives similar results with one brand of natural cement, from which it appears that warm materials have a slight advantage for either cold water or cold air hardening.

TABLE 108

Natural Cement Mortars in Freezing Weather
Effect of Heating Materials

Reference.	Parts Sand to One Cement.	Temperature Air Where Briquets Molded.	Age of Briquets When Broken.	Tensile Strength, Pounds per Sq. In.			
				Stored in Canal.		Stored in Open Air.	
				Materials. 32° F.	Materials. 100° F.	Materials. 32° F.	Materials. 100° F.
		Deg. Fahr.					
1	3	15 to 16	6 mos.	140	151	311	372
2	3	15 to 19	9 "	175	203	. .	. .
3	2	22 to 24	9 "	167	204	355	361

Notes. — Cement, Brand Gn, Natural. All mortars made with fresh water.
Briquets made with warm materials were frozen in from 15 to 24 minutes after made.
Each result, mean of ten briquets.

395. Consistency of Mortars to Withstand Frost. — Since the injury due to frost is caused by the expansion of the water used in gaging, it would be expected that mortars mixed wet would suffer most. This conclusion is confirmed by the tests in Table 109. The superiority of dry mortars is especially shown in mortars that harden in the air. The treatment to which these briquets were subjected was very severe, yet the results are excellent.

TABLE 109

Consistency of Mortars as Affecting Ability to Withstand Low Temperatures

Age of Briquets When Broken.	Tensile Strength, Pounds per Square Inch.							
	Stored in Canal.				Stored in Open Air.			
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
6 mos.	414	414	372	501	601	571	521	674
9 mos.	474	468	431	527	727	622	525	568

Notes. — Cement, Portland, Brand R; sand, "Point aux Pins," passing holes .08 inch sq. Two parts sand to one cement by weight. Each result, mean of five briquets.

Temperature, air where briquets were molded, 13° to 14° Fahr.; materials used, 40° Fahr.

Temperature mortar when molding completed 32° to 36° Fahr.

Briquets made with fresh water had frozen after 30 minutes.

Treatment briquets: — *a* to *d*, stored in canal (under ice).
e to *h*, stored in open air, January, Northern Michigan.

Water used: — *a* and *e*, 10.4 per cent. fresh water.
b and *f*, 11.9 per cent. fresh water.
c and *g*, 13.3 per cent. fresh water.
d and *h*, 11.9 per cent. water containing 15 per cent. salt.

396. Fineness of Sand and Effect of Frost. — The briquets reported in Table 110 were made from mortar containing one and two parts limestone screenings to one cement, the screenings varying from coarse to fine. In general, the results follow the rule applicable to mortars used in ordinary temperatures, namely, that the coarse sands give the best results; but it appears that the briquets made with fresh water and exposed

TABLE 110

Effect of Degree of Fineness of Sand on Ability of Portland Cement Mortars to Withstand Low Temperatures

Ref.	Parts Limestone Screenings to One Cement by Weight.	Sample Portland Cement, Brand R.	Temperature Air Where Briquets Made, Deg. Fahr.	Per Cent. Salt in Water Used in Gaging.	Date Made.	Briquets Stored.	Tensile Strength, Pounds per Square Inch. Fineness of Limestone Screenings Retained between Sieves: 4 and 10.	20 and 40.	40 and 80.	Pass 10.	Briquets Broken Dry, or Immersed Some Hours Just Before Breaking.
					Mo. Da.						
1	1	JJ	15–18	0	2 15	Open air	494	826	855	695	Broken dry.
2	1	"	"	"	"	" "	367	572	604	524	Immersed 19 hrs.
3	1	"	12–13	14	2 19	" "	738	781	666	687	Broken dry.
4	1	"	"	"	"	" "	675	591	523	534	Immersed 48 hrs.
5	2	GG	16–18	0	2 15	" "	440	762	642	515	Broken dry.
6	2	"	"	"	"	" "	378	572	536	453	Immersed 19 hrs.
7	2	"	12–14	14	2 19	" "	721	697	550	532	Broken dry.
8	2	"	"	"	"	" "	533	483	343	413	Immersed 48 hrs.
9	1	"	13–20	0	2 14	Canal	686	634	583	687	Broken wet.
10	1	JJ	"	18	2 16	"	668	726	634	689	" "
11	2	GG	13–21	0	2 14	"	544	452	393	351	" "
12	2	"	10–12	18	2 16	"	685	659	516	624	" "

Notes. — Cement, Portland, Brand R. Sand, limestone screenings, sifted as indicated.
Materials used, 40° Fahr.
Briquets made with fresh water raised in molds.
Briquets left three days where made in warehouse before storage.
Age of briquets when broken, six months.

in open air reverse this rule, either the finest sand, $\frac{40}{80}$, or the $\frac{20}{40}$ giving the best result.

397. CONCLUSIONS. — The following conclusions concerning the use of cement mortars in freezing weather appear to be indicated by the foregoing tests:

1st, Mortars should not be mixed wet for use in low temperatures.

2d, Portland cement mortars made in cold weather usually develop a good tensile strength, especially when exposed to the open air.

3d, Portland cement mortars for open air exposure may be benefited by the use of from three to seven per cent. salt in the water used in gaging, and from ten to twenty per cent. salt in the gaging water may prove beneficial for mortars hardening in cold water.

4th, Warming the materials for Portland cement mortar appears to have but little effect on its frost resisting qualities.

5th, Coarse sand usually gives the best results in Portland mortars made in cold weather, but fresh water briquets exposed in open air appear to give better results with fine sand.

6th, Some natural cements give fairly good results in freezing weather, while others are practically destroyed by severe exposure. The effect of variations in treatment on different brands of natural cement is so varied that no general conclusions can be drawn from the above tests, but the indications are that salt water for gaging is beneficial if the mortar hardens in cold water, but detrimental for mortars exposed to the open air.

ART. 51. THE ADHESION OF CEMENTS

398. THE ADHESION BETWEEN PORTLAND AND NATURAL CEMENTS. — The question sometimes arises as to whether Portland cement will adhere to natural cement already set, and whether fresh natural and Portland cement mortars may be used together, as in the case of a Portland facing mortar used with natural cement concrete. Tests bearing on these points are given in Tables 111, 112 and 113.

In the tests in Table 111 fresh Portland cement mortar was applied to natural cement mortar that had set seven days. Natural cement briquets, made neat and with one to four parts sand, as seen in the headings of the columns of the table, were broken at the age of seven days. The fresh Portland mortar was applied to the half briquets on the same day that the latter were broken, by placing the half briquet in one end of the mold, and filling the other half of the mold with fresh Portland mortar of the composition shown in the second column.

TABLE 111

The Adhesion of Portland Cement to Hardened Natural Cement Mortar

Ref.	Parts Sand to One Part Portland Cement in Fresh Mortar.	Adhesion of Portland Mortar to Half Briquets of Hardened Natural Cement Containing Parts Sand.				
		0	1	2	3	4
1	0	246	255	197	194	161
2	1	185	210	186	152	120
3	2	63	75	60	84	85

NOTES. — Briquets of natural cement, containing parts sand indicated at top of columns, were broken at seven days. The half briquets were then placed in one end of briquet mold and the other end of mold was filled with fresh Portland mortar.

Fresh mortar made of Portland cement, Brand R.

Sand, " Point aux Pins," passing No. 10 sieve.

In general, each result is mean of ten briquets.

Nearly all briquets broke at juncture of Portland and natural mortars.

It is seen that the neat Portland gave the highest results in adhesion, the one-to-one mortar giving a comparatively low adhesive strength. It is also seen that the neat and one-to-one mortars adhered best to the richer natural cement briquets, but the one-to-two Portland gave the greatest adhesive strength with the poorer natural cement mortars. All of the tests gave very irregular results.

399. To make the briquets the results of which are recorded in Table 112, a plate was placed in the center of the mold, one-half of the mold was filled with fresh natural cement mortar, the plate was then withdrawn and the other half of the mold filled with fresh Portland mortar. Briquets in line 1 were made with Portland cement alone, while those in line 2 contained only natural cement, these briquets being made for purposes of comparison. The briquets containing both Portland

and natural were made neat and with from one to three parts sand. By noting the number of briquets that broke at the juncture between Portland and natural, it was found that, in general, the adhesion of rich Portland mortar to rich natural cement mortar is greater than the strength of the natural, but that with the poorer mortars the adhesion is less than the strength of the natural.

TABLE 112

Adhesion between Fresh Mortars of Portland and Natural Cement

Ref.	Parts Sand to One of Cement.		Adhesive or Cohesive Strength, Pounds per Square Inch.			
	In Portland Mortar.	In Natural Mortar.	28 days.	3 months.	6 months.	1 year.
1	2	......	278	372	410	464
2	......	2	164	243	268	308
3	0	0	318	358	323	380
4	1	1	252	326	376	383
5	0	1	229	331	356	357
6	2	1	226	196	339	298
7	2	2	128	235	265	285
8	1	2	145	213	259	271
9	1	3	103	160	185	206
10	2	3	95	176	206	197
11	3	3	63	162	197	193

Notes. — Portland Cement, Brand R.
Natural Cement, Brand An.
Sand, " Point aux Pins," passing No. 10 sieve.
Both mortars mixed fresh and filled in opposite ends of mold.

400. In Table 113 the natural cement mortar contained three parts sand to one of cement, while the richness of the Portland mortars varied from neat to four parts sand. Four combinations of different brands were used. Brand R, Portland, and brand An, natural, appear to give the best results together. It is also seen from this table that the adhesion of the rich Portland mortar is greater than the cohesive strength of the natural cement, but when the Portland mortar contains three or four parts sand to one cement, the adhesion is less than the strength of the natural cement mortar.

401. The Adhesion to Stone and Other Materials. — Since cement mortars are usually employed to bind other materials together, it follows that the adhesive strength is of the greatest importance. On account of the difficulty of making tests of adhesive strength, however, the data concerning it are very meager. Two methods have been employed by the author in making such tests. One method, used for brick, is to cement two bricks together in a cruciform shape. The other method consists in placing small blocks of the substance to be used in the center of a briquet mold, and filling the ends of the mold with the desired mortar.

TABLE 113

Adhesion between Fresh Mortars of Portland and Natural Cement

Reference.	Portland Cement Mortar. Brand Cement.	Natural Cement Mortar.		Age Briquets.	Adhesive Strength Pounds per Square Inch. Parts Sand to One Cement in Portland Mortar.				
		Brand Cement.	Parts Sand to One Cement.		0	1	2	3	4
1	R	An	3	3 mo.	162 N	173 N	177 N	162 J	127 J
2	R	Gn	3	"	147 N	175 N	167 N	156	151
3	A	En	3	"	156 N	157 N	143 N	136 N	134
4	G	Bn	3	"	88 N	106 N	115 N	94	91 J
5	R	An	3	1 yr.	214	206 N	206 N	201 N	183 J
6	R	Gn	3	"	167 N	165 N	180 N	175 N	169
7	A	En	3	"	157 N	158 N	173 N	166 N	160
8	G	Bn	3	"	108 J	127 J	126 J	130 J	114 J

NOTES: — In general, each result is mean of ten briquets.
Results marked N, briquets broke through the natural cement.
Results marked J, briquets broke at juncture of Portland and natural.

The small blocks were made one inch square and about one-fourth inch thick, two opposite edges of each piece being very slightly hollowed to fit, approximately, the side of the mold. These blocks being placed transversely in the center of the mold, and the ends of the latter filled with the mortar to be tested, formed two joints between the mortar and the block.

402. Table 114 shows the **adhesion** of a rich Portland cement mortar **to various materials.** The mortar adheres most strongly to brick, the adhesion exceeding the strength of the brick itself. A very high result is also obtained with terra cotta, and the adhesion to Kelleys Island limestone is high. The latter is a dolomitic limestone of the corniferous group, which is soft enough to be worked quite easily. The adhesion to Drummond Island limestone, which is a much harder stone belonging to the Niagara group, is considerably less, and the adhesion to the Potsdam sandstone is very low. A higher result than would be expected is obtained with ground plate glass, but the hammered bar iron gives the lowest result of any of the substances tried.

TABLE 114

Adhesion of Portland Cement Mortar to Various Materials

Reference.	Kind of Sand.	Parts Sand to One Cement.	Age of Specimens.	Cohesion of Mortar.	Adhesion, Pounds per Square Inch, to Materials.						
					a	*b*	*c*	*d*	*e*	*f*	*g*
1	Cr. Qtz. 20–30	1	28 days	742	91	78	211	100	241	223	290
2	" "	1	6 mos	775	103	122	201	252	284	310	305

Notes: — Cement, Portland, Brand R.
Adhesion Blocks, 1 in. × 1 in. × ½ in. inserted in center mold.
Materials: — *a* — Hammered bar iron.
b — Potsdam sandstone, cleavage surface.
c — Drummond Id. limestone, cleavage surface.
d — Ground plate glass.
e — Kelleys Id. limestone, sawn surface.
f — Soft terra cotta, filed surface.
g — Soft red building brick, sawn surface.

403. The Adhesion of Neat and Sand Mortars. — Table 115 shows the cohesive and adhesive strengths of different mortars, the adhesion blocks being all of the same material, Kelleys Island limestone. The Portland mortar giving the highest adhesive strength at six months is that containing one-half part sand to one part cement, though the greatest cohesive strength is given by the one-to-one mortar. With natural cement the one-to-one mortar gives the highest strength, both in adhesion and cohesion. The ratio of the adhesive strength to the cohesive strength is greater for natural than for Portland. It also appears that between twenty-eight days and six months the adhesive strength increases more than the cohesive strength.

404. Effect of Consistency on Adhesion. — Table 116 gives the results of tests to show the relative effects of the consistency of the mortar on the adhesive and cohesive strength. It

TABLE 115

Adhesion of Mortars Containing Different Amounts of Sand

Reference	Cement. Kind.	Cement. Brand.	Age of Specimens.	Cohesion or Adhesion.	Cohesive or Adhesive Strength, Lbs. per Square Inch, of Mortars with Sand, Parts by Weight. None.	One-Half Part Sand.	One Part.	Two Parts.
1	Port.	R	28 days	Cohesion	686	710	747	467
2	"	"	"	Adhesion	270	233	221	169
3	"	"	6 mos.	Cohesion	631	787	816	551
4	"	"	"	Adhesion	335	346	287	209
5	Nat.	An	28 days	Cohesion	183	198	218	186
6	"	"	"	Adhesion	94	104	116	66
7	"	"	6 mos.	Cohesion	263	334	383	376
8	"	"	"	Adhesion	228	222	233	171

NOTES: — Sand, crushed quartz, 20 to 30.
Adhesion blocks, 1 in. × 1 in. × ½ in., Kelleys Id. limestone, sawn surface, saturated before used.

is seen that the effect of consistency on the adhesive strength is less than on the cohesive strength, but that the best results in adhesion are given by a mortar that is considerably more moist than that which gives the highest strength in cohesion. The practical bearing of this point on the use of mortars is evident.

TABLE 116

Adhesion of Mortars. Varying Consistency

Reference.	Cement. Kind.	Cement. Brand.	Age of Specimens.	Cohesion or Adhesion.	Cohesive or Adhesive Strength, Lbs. per Square Inch, Mortar of Consistency: Trifle Dry.	Trifle Moist.	Quite Moist.	Very Moist.
1	Port.	R	28 days	Cohesion	541	502	443	372
2	"	"	"	Adhesion	148	160	145	136
3	"	"	6 mos.	Cohesion	697	660	616	539
4	"	"	"	Adhesion	191	209	228	192
5	Nat.	An	28 days	Cohesion	239	212	151	112
6	"	"	"	Adhesion	96	96	87	70
7	"	"	6 mos.	Cohesion	397	385	314	285
8	"	"	"	Adhesion	146	165	164	126

NOTES: — Sand, "Point aux Pins," pass No. 10 sieve, one part to one cement by weight.
Adhesion blocks, 1 in. × 1 in. × ½ in., Kelleys Id. limestone, surfaces filed smooth, saturated with water before used.

405. Effect of Regaging on Adhesive Strength. — The tests given in Table 117 were designed to show the effect of regaging on the adhesion of cement mortar to stone. A comparison is made between mortars used fresh and those that were allowed to stand three hours and gaged once an hour. There are but few tests from which to draw conclusions and the treatment is very severe, but it appears that while the regaging to which these mortars were subjected usually resulted in a slight increase in cohesive strength, the adhesive strength was considerably impaired. The decrease in adhesive strength was greater for natural cement than for Portland, and greater for rich than for poor mortars. The effect of regaging on the cohesive strength is treated in Art. 47.

TABLE 117

Effect of Regaging on Adhesive Strength

Cement.	Adhesion or Cohesion.	Adhesion or Cohesion, Lbs. per Sq. In.			
		One Part Sand to One Cement.		Three Parts Sand to One Cement.	
		Fresh.	Regaged.	Fresh.	Regaged.
Portland, Brand X	Adhesion	178	141	62	41
" " "	"	202	170	59	61
" " "	Cohesion	718	764	327	343
Natural, " An	Adhesion	142	90	17	...
" " "	"	180	120	31	28
" " "	Cohesion	352	361	235	227

Notes: — Sand, crushed quartz, $\frac{20}{30}$. Each result, mean of two to five specimens, broken at age of six months.

In adhesive tests, pieces Kelleys Id. limestone, 1 in. × 1 in. × ½ in., placed in center mold and two ends mold filled with mortar.

Results in columns headed "Fresh" from mortar treated as usual.

Results in columns headed "Regaged" mortar allowed to stand three hours before use, mortar being regaged each hour.

406. Character of Surface of Stone. — In the tests recorded in Table 118 all of the adhesion blocks were of Kelleys Island limestone, but part of them were finished with smooth filed surfaces, while the others were grooved with a coarse rasp. In the twenty-eight-day tests there is but little difference in the adhesion to the different surfaces, but at six months the adhesion to the smooth surfaces appears to be slightly greater, except in the case of one-to-two natural cement mortar.

TABLE 118

Adhesion of Mortars. Effect of Character of Surface of Stone

Cohesion or Adhesion and Character of Surface.	Age of Specimens.	Adhesion or Cohesion, Lbs. per Sq. In.			
		Portland Brand R.		Natural Brand D.	
		Parts Sand to One Cement.			
		1	2	1	2
Cohesion	28 days	539	377	343	289
Adhesion, smooth surface . .	"	151	85	138	113
" grooved surface .	"	152	115	129	98
Cohesion	6 mos.	714	503	387	304
Adhesion, smooth surface . .	"	238	176	141	68
" grooved surface .	"	223	154	115	96

407. The Effect of Plaster of Paris on the Adhesion of Mortar to Stone. — The results in Table 119 show the effect on the adhesive strength of adding small percentages of plaster of Paris to cement mortars of Portland and natural cement. The Portland cement used was a quick setting sample, neat cement pats of which began to set in eighteen minutes. The effect of plaster of Paris on the cohesive strength of mortars from these samples hardened in dry air, is shown in Table 92, § 378. It is seen that the addition of from one to three per cent. plaster

TABLE 119

Effect of Plaster of Paris on the Adhesive Strength of Cement Mortars

Ref.	Cement.			Parts P.P. Sand to One Cement.	Age of Specimens.	Adhesive Strength, Lbs. per Sq. In., of Mortars in which Per Cent. of Cement Replaced by Plaster of Paris.				
	Kind.	Brand.	Sample.			0	1	2	3	6
1	Port.	R	26 R	0	1 year	263	311	376	291	89
2	"	R	"	2	"	130	107	144	157	34
3	Nat.	An	L	0	"	88	97	87	133	*a*
4	"	An	"	2	"	64	74	89	82	93

Notes: — Adhesion pieces between two halves of briquet were of Kelleys Id. limestone, sawn surfaces, saturated with water before used.
Cement and plaster Paris passed through No. 50 sieve.
All briquets stored in tank in laboratory.
Each result, mean of four to ten briquets.
a Found badly cracked and separated from limestone prisms after three days.

has no deleterious effect on the adhesive strength of these samples at one year. Six per cent. plaster, however, ruins the Portland and the neat natural cement.

408. The Adhesion of Cement Mortar to Brick. — Tests of the adhesion of cement mortar to brick were made by cementing pairs of brick in a cruciform shape, with a one-fourth inch joint of mortar. The brick were placed together flatwise, with the bed down, so that in the case of stock brick, one stock mark, or depression in one side, was filled with mortar. The mortar was made more moist than was ordinarily used for briquets, but not so moist as would be used in brickwork. The top brick of each pair was slightly tapped to place with the handle of a pointing trowel, and the excess mortar cut away. About forty-eight hours after cemented, the pairs of brick were packed in damp sand in a large box prepared for the purpose, and the sand was kept in a moist condition by a thorough daily sprinkling. For pulling the bricks apart, a special clip was devised to equalize the pull on the two ends of each brick, and a simple lever machine was used to measure the force required.

409. Tensile tests were made of briquets from mortars similar to those used in the adhesive tests and stored in damp sand, and the results are used for comparison with the adhesive tests. The cohesive strength given by the briquets is not strictly comparable with the adhesive strength shown in the tests with brick, because of the great difference in the area of the breaking sections in the two cases. It has been well established in tensile tests of cohesion that briquets of large cross-section break at a lower strength than those of small section. It is quite possible also that even with the special clip devised, cross-strains were more likely to occur in the adhesive tests than in the briquet tests. An opportunity was furnished of comparing the tensile strength of neat natural cement mortar under the two conditions, for in one case six joints broke directly through the mortar, the adhesion being greater than the cohesion. It was found that the strength per square inch given by the briquets was at least six times that given by the large joint. This difference should be kept in mind in making comparisons in the tables between the cohesion and adhesion as given. It should also be noted that some of the highest results of adhesive strength represent in reality the strength of the brick rather than the adhesive strength of the mortar, as chips were pulled from the brick, leaving the mortar joint undisturbed. The brick were of a rather poor quality, but selected with a view to obtaining those of a uniform degree of burning.

TABLE 120

Adhesion of Cement Mortar to Brick. Variations in Richness of Mortar

Cement.	Age of Mortar.	Adhesion or Cohesion.	Tensile Strength, Pounds per Square Inch, of Mortars Containing Parts Sand to One Cement.				
			None.	½	1	2	3
Portland, X, 41 S	28 days	Cohesion	632	596	589	409	270
" " "	"	Adhesion	48	42	24	20	11
" " "	3 months	Cohesion	676	728	604	423	325
" " "	"	Adhesion	64	52	41	24	12
" " "	6 months	Cohesion	723	704	679	524	374
" " "	"	Adhesion	50	56	39	20	14
Natural, Gn, KK	3 months	Cohesion	180	240	317	279	181
" " "	"	Adhesion	46	52	42	28	15
" " "	6 months	Cohesion	276	444	388	331	236
" " "	"	Adhesion	44	52	50	38	18

Notes: — Bricks were cemented together in pairs in cruciform shape and kept in damp sand until time of test. Briquets for cohesion tests stored in same manner.

Each result in cohesion, mean of five briquets.

Each result in adhesion is in general mean of six results, three with common die cut brick and three with sand molded stock brick.

When adhesion exceeded 50 pounds per square inch, bricks were about as likely to break as the joint between brick and mortar.

410. Adhesion of Neat and Sand Mortars of Portland and Natural. — Some of the results of these tests are given in Table 120. The most noteworthy point developed is that for mortars containing more than one-half part of sand to one part cement, the adhesion of the natural cement is greater than that of the Portland with the same proportion of sand, although the Portland mortar was much the stronger in cohesion. The mortars giving the highest adhesive strength are those containing not more than one-half part sand to one part cement.

The addition of sand lowers the adhesive strength more rapidly than it does the cohesive strength. This point would be shown still more clearly if the true adhesive strength of the richest mortars was obtained, as we may be certain that the adhesion of these mortars would be shown to be considerably greater if the brick were strong enough to allow this strength to be developed. With natural cement mortars containing not more than two parts sand to one cement, the adhesion is one-sixth to one-ninth the cohesion, and with Portland mortars containing not more than one part sand, the adhesion is about one-fifteenth the cohesion. (But see § 409 in this connection.)

411. Effect of Lime Paste on Adhesive Strength of Cement Mortars. — A number of tests were made to determine the effect, on the adhesive and cohesive strength of mortars, of mixing lime paste with the cement. Tables 121 and 122 give the results of a few preliminary tests on this subject.

For the tests recorded in Table 121 the mortars were allowed to harden in dry air. From the cohesive tests it is seen that lime in form of paste to the amount of ten per cent. of

TABLE 121

Adhesion of Cement Mortar to Brick. Effect of Lime Paste in Mortar Hardened in Dry Air

CEMENT.	AGE OF MORTAR.	COHESION OR ADHESION.	TENSILE STRENGTH, POUNDS PER SQUARE INCH. Composition of Mortar.				
			A	*B*	*C*	*D*	*E*
Portland, X, 418	3 months	Cohesion	97	99	101	46	59
" " "	4 "	Adhesion	18	29	20	22	13
" " "	6 "	"	. .	24	20	19	11
Natural, Gn, LL	3 "	Cohesion	18	38	21	22	68
" " "	4 "	Adhesion	39	32	30	28	11
" " "	6 "	"	26	31	25	27	. .

NOTES: — Brick, sand molded stock.

All briquets and brick stored in dry air.

Composition of mortars:	*A*	*B*	*C*	*D*	*E*
Grams P. P. river sand,	480	480	480	480	480
Grams cement,	120	120	90	60	0
Grams lime paste,	0	40	30	60	120
Grams lime contained in lime paste,	0	14	10	20	41
Lime in paste expressed as per cent. of cement plus lime,	0	10	10	25	100

Consistency about same as mason's mortar.

the cement had little effect on one-to-four Portland mortars, but that a larger amount of lime was very deleterious for dry air exposure. The sample of natural cement used did not harden well in dry air, and the highest result is given by the lime mortar without cement. It appears that the adhesive strength of the Portland mortar was slightly increased by the addition of a small amount of lime paste, but the adhesive strength of natural was not greatly affected. The adhesive strength of the natural cement is, in general, higher than the Portland. The natural cement appeared to harden better in the joints than in the briquets, and we have, as a peculiar result, the adhesive strength exceeding the cohesion. This illustrates a statement already made, that to store briquets in dry air does not approach very nearly the ordinary conditions of use.

412. In Table 122 are given a few tests of mixtures of Port-

TABLE 122

Adhesion of Cement Mortar to Brick. Effect of Lime Paste in Portland Cement

Mortar Hardened in	Cohesion or Adhesion.	Tensile Strength, Pounds per Square Inch. Composition of Mortar.				
		A	*B*	*C*	*D*	*E*
Tank in Laboratory	Coh'n.	177	203	183	158	82
Dry air, "	"	167	180	167	150	81
Damp sand, "	"	173	198	171	154	88
Dry air, "	Adh'n.	15	36	40	33	26
Damp sand, "	"	16	33	35	32	27

NOTES: — Bricks cemented together in pairs in cruciform shape.
Age of all mortars when tested, three months.
Cement, Portland, Brand R, Sample 14 R. Sand, "Point aux Pins."
Lime paste slaked about six months before use.
Each result in cohesion, mean of five to ten briquets.
Each result in adhesion, mean of eight to sixteen pairs of bricks.
Half of pairs were hard burned brick and half soft burned.

Composition of mortars:	*A*	*B*	*C*	*D*	*E*
Grams P. P. (river) sand,	960	960	960	960	960
Grams cement,	240	240	200	180	120
Grams lime paste,	0	80	120	180	300
Grams lime contained in paste,	0	27	40	60	120
Lime as per cent. lime plus cement,	0	10	16.7	25	50

land cement and lime paste, the mortars being hardened in dry air and in damp sand. Cohesive tests are also given of briquets hardened in damp sand, water and dry air. It appears that the addition of ten per cent. of lime in the form of paste to mortars of this sample of Portland increases the tensile strength, the effect being least when the mortars harden in dry air. The substitution of lime for one-sixth of the cement in a one-to-four mortar has little effect on the tensile strength. Larger proportions of lime result in decreased strength, and if one-half of the cement is replaced by lime, the resulting strength is only about one-half that given by the cement mortar without lime. The results of the adhesive tests show that if half of the cement in the mortar is replaced by an equal weight of lime in the form of paste, the resulting strength is increased by nearly 100 per cent., and that if smaller amounts of lime are used, the adhesive strength is increased by about 150 per cent. over that given by the cement mortar without lime.

413. The results of a more complete set of tests on this subject are given in Table 123. The mortars used included one made with four parts sand to one of cement by weight; one in which about ten per cent. of lime by weight, which had previously been made into lime paste, was added to the mortar; a third in which lime, in the form of paste, was substituted for one-sixth of the weight of the cement used in the first mortar; a fourth, in which lime was substituted for one-fourth of the cement; and finally, a mortar composed of lime paste and sand only.

The adhesive strengths of the mortars are given in the table. The difference in the adhesion of Portland cement mortar to hard brick and to soft brick is not clearly brought out. Neither is the strength of air-hardened specimens much different from that of the mortars stored in damp sand. The use of lime paste with Portland cement in the amounts tried here more than doubles the adhesive strength of the mortar.

The first point to notice in the case of natural cement is that the adhesive strength of this mortar without lime is nearly double the adhesive strength of Portland mortar without lime. The adhesive strength of mortars hardened in damp sand is somewhat greater than the strength of similar mortars hardened in dry air. The addition of a small amount of lime paste

TABLE 123

Adhesion of Cement Mortar to Brick. Lime Paste with Cement

Reference.	Cement. Kind.	Cement. Grams.	Lime Paste, Gms.	Sand, Gms.	Stored in Damp Sand. Hard Brick. Fresh Lime Paste.	Stored in Damp Sand. Hard Brick. Old Lime Paste.	Stored in Damp Sand. Soft Brick. Fresh Lime Paste.	Stored in Damp Sand. Soft Brick. Old Lime Paste.	Stored in Dry Air. Hard Brick. Fresh Lime Paste.	Stored in Dry Air. Hard Brick. Old Lime Paste.	Stored in Dry Air. Soft Brick. Fresh Lime Paste.	Stored in Dry Air. Soft Brick. Old Lime Paste.	Means. Hard Brick.	Means. Soft Brick.	Means. Damp Sand.	Means. Dry Air.	Means. Fresh Paste.	Means. Old Paste.	Means. Mean of all the Results.
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*
1	Portland. Brand X. Sample 41S.	240	00	960	27.6	25.2	13.7	14.7	21.7	14.5	15.1	19.4	22.2	15.7	20.3	17.7	19.5	18.5	19.0
2	"	240	80	"	46.7	50.3	20.0	36.0	44.3	31.6	40.2	40.6	43.2	36.4	40.5	39.2	40.0	39.6	39.8
3	"	200	120	"	40.8	54.4	34.9	46.3	36.3	44.6	42.5	47.8	44.0	42.9	44.1	42.8	38.6	48.8	43.7
4	"	180	180	"	48.7	38.2	37.7	45.4	34.6	41.3	40.6	39.2	40.7	40.7	42.5	39.0	40.2	41.0	40.6
5	Natural, Brand An. Sample L.	240	00	960	37.7	40.2	39.2	34.3	30.3	35.9	29.9	39.8	36.0	35.8	37.9	34.0	34.3	37.6	35.9
6	"	240	80	"	47.6	43.7	41.4	42.6	48.9	38.3	26.2	40.3	44.6	37.6	43.8	38.4	41.0	41.2	41.1
7	"	200	120	"	40.4	44.6	33.9	38.1	44.3	38.7	30.5	38.6	42.0	35.3	39.3	38.0	37.3	40.0	38.7
8	"	180	180	"	39.6	48.5	34.4	35.7	36.9	28.8	32.5	31.6	39.0	33.6	39.5	32.5	35.8	36.2	36.0

NOTES: — All mortars three months old.
"Fresh" paste had been slaked three days to one week before used.
"Old" paste had been slaked five months before used.

increases the adhesive strength somewhat, and when as much as twenty-five per cent. of the cement is replaced by lime in the form of paste, the adhesive strength of the natural cement mortar is not usually diminished. The effect of lime paste, however, on the adhesive strength is not nearly so great as it is in the case of Portland mortars.

The following conclusions may be briefly stated: The ratio of adhesive to cohesive strength is much greater with natural cement than with Portland. If a high adhesive strength is desired, Portland cement should not be mixed with more than two parts sand unless lime paste is added to the mortar, as the use of lime paste materially increases the adhesive strength of lean mortars. Tests of cohesion of similar mortars containing lime paste are given in Art. 48.

414. The Adhesion of Cement to Rods of Steel and Iron. — The tests recorded in Tables 124 and 125 were made to determine the adhesion of cement mortar to iron rods, or the strength of a bolt anchorage secured with cement mortar, and the style of rod and kind of mortar which would give the best results. The bars were made in an ordinary concrete mold, ten inches by ten inches by four and one-half feet. The rods or bolts were placed in a row along the center of the box, being spaced about nine inches apart, and the mortar was rammed about them. After being allowed to set in a warm room for twenty-eight days, the rods were pulled by means of two hydraulic jacks, a special grip being used to grasp the free end of the rod, and an hydraulic weighing machine serving to measure the pull required to start it. The supports against which the hydraulic jacks were braced bore at points on the concrete bar about three or four inches from the center of the rod which was being tested.

415. The rods given in Table 124 were imbedded in mortar composed of one part of Portland cement to two parts limestone screenings. The rods were cut from bar iron and were perfectly plain, without nuts or fox wedges. The results indicate that the force required is proportional to the area of contact. Comparing the different styles and sizes of plain rods, no difference in favor of one style or size can be determined; the apparent higher resistance per square inch offered by one-inch rods would probably disappear in a large number of tests.

TABLE 124

Resistance to Pulling of Iron Rods of Various Forms Imbedded in Mortar

Ref.	Number of Rods.	Mortar, Bar No.	Description of Rod.	Perimeter of Rod, Inches.	Depth Imbedded, Inches.	Pounds Pull.	
						Per In. Depth Imbedded.	Per Sq. In. Area in Contact.
1	3	2, 6, 7	Plain, ½″ diameter	1.57	8 to 10	700	447
2	3	"	" 1″ "	3.14	"	1750	556
3	3	"	" 1¼″ "	3.93	"	2060	524
4	3	"	" ½″ square	2.00	"	1085	543
5	4	2, 5, 6, 7	" 1″ "	4.00	"	2250	562
6	3	2, 6, 7	" 1¼″ "	5.00	"	2170	434
7	3	4, 5	Twisted 1″ square, 1 turn in 8″ length	4.3[1]	9±	2595	608
8	3	"	Twisted 1″ square, 2 turns in 8″ length	4.3[1]	9±	2215	516
9	3	"	Twisted 1″ square, 3 turns in 8″ length	4.3[1]	9–9.5	2405	561

Notes: — Cement, Portland, Brand R.
Sand, limestone screenings passing ⅜ inch slits, two parts by weight to one cement.
Mortar one month old when tension was applied to rods.

The rods given in lines seven to nine were made by twisting a piece of one inch square bar iron. The twisted portion was eight inches in length. Comparing the plain one inch square bolts with the twisted bolts, it appears that the former offered a resistance of 2,245 pounds per inch depth while the latter gave 2,405 pounds, an increase of less than eight per cent.

416. In the tests recorded in Table 125, the ordinary river sand used in construction was employed. The mortar was made neat and with two and four parts sand to one of cement. The depth the rods were imbedded varied from two inches to ten inches. The one-to-two mortar gave nearly as good results as neat cement, but the one-to-four mortar gave much lower results. The resistance seems to vary directly as the area of contact without reference to the depth imbedded, except as

[1] In computing adhesion, or shear, or pounds pull per square inch of area in contact, perimeter considered circumference of a circle of diameter equal to the distance between opposite edges of rod after twisting. A core of mortar of this diameter, was torn from bar in pulling.

To perceive effect twisting, compare pounds pull per inch depth imbedded.

this enters in obtaining the said area. The results obtained in this table do not compare favorably with those obtained in Table 124, where limestone screenings were used.

TABLE 125

Resistance to Pulling of Iron Rods Imbedded in Mortar. Variations in Depth Imbedded and in Richness of Mortar

Parts Sand to One Cement.	Adhesion, Pounds per Square Inch of Surface in Contact for Different Depths Imbedded.										
	Depths Imbedded, In	1.9-2.2	3.2	4	4.5-4.8	5.8-6	7.8-8	8.8	9.6-10	No. Results.	Mean.
0	. . . . .	340	. .	346	. . .	313	. . .	228	340	5	313
2	. . . . .	272	294	270	262	255	247	.	275	15	264
4	. . . . .	74	. .	119	. . .	117	100	.	142	10	111

NOTES: — Cement, Portland, Brand R.
Sand, "Point aux Pins," river sand.
Mortar one month old when rods pulled.
Rods, round, 1 inch diameter.

417. Tables 126 and 127 are from similar tests made by Messrs. Peabody and Emerson.[1] The rods in Table 126 were of various shapes and included some having rivets through them. The ¼ inch by 1 inch bars gave lower adhesion per square inch than the square and round rods. When two rods are twisted together and imbedded in a small specimen, the tendency is to split the specimen. The bars containing rivets broke before the adhesion was overcome, although the depth imbedded was but six inches.

In Table 127 neat cement paste and concretes of several compositions are tried. These results are of interest as showing that concretes show as great adhesion to steel rods as do mortars. The very low result obtained with neat cement in this table is not explained and is in opposition to the results in Table 125.

[1] *Engineering News*, March 10, 1904.

TABLE 126

Adhesion of Mortar to Steel Rods of Various Shapes, Imbedded about Six Inches

No. of Tests.	Description of Rod.	Perimeter of Rod, Inches.	Pounds Pull.	
			Per Inch Depth Imbedded.	Per Square Inch Area in Contact.
4	Plain, ¼″ square.	1.0	360	369
3	Plain, ½″ square.	2.0	864	432
4	Plain, ½″ round.	1.57	804	512
4	Twisted, ½″ square.	. .	1250	. .
4	¼″ by 1 ″.	2.5	744	293
4	Two ¼″ rods twisted together.	Three specimens split. One rod broke at 8,000 lbs., or when adhesion was 1,250 lbs. per inch depth.		
4	¼″ by 1″ with ⅜″ rivets through.	One specimen split. Three rods broke at first rivet with 9,800 to 10,500 pounds, or when adhesion was 1,500 to 1,660 lbs. per inch depth.		

NOTES: — Tests by Messrs. George A. Peabody and Samuel W. Emerson.
Mortar composed of one part cement (Portland) to three parts sand.
Specimens approximately 6 inch cubes. One rod imbedded in each, 6 to 6½ inches.
Rods pulled forty and eighty days after mortar was made.

TABLE 127

Adhesion of Mortars and Concretes of Various Compositions to One Inch Square Steel Rods Imbedded about Ten Inches

No. of Tests.	Composition of Mortar or Concrete.				Pounds Pull.	
	Cement.	Sand.	Stone.	Gravel.	Per Inch Depth Imbedded.	Per Square Inch Area in Contact.
4	1	0	0	0	1112	278
4	1	3	0	0	1644	411
4	1	3	6	0	1912	478
4	1	3	0	6	2062	516
4	1	2	4	0	2348	587
4	1	2	0	4	2187	547

NOTE: — Tests by Messrs. George A. Peabody and Samuel W. Emerson.

CHAPTER XVI

THE COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY OF MORTAR AND CONCRETE

ART. 52. COMPRESSIVE STRENGTH OF MORTAR

418. The compressive strength of cement mortar is from five to ten times the tensile strength. As the result obtained in tests of either compression or tension depends upon the shape and size of the specimen, no definite value can be assigned to the ratio of compression to tension. Comparative tests have indicated in a general way that the cements giving the best results in tension show also the highest compressive strength; but with variations in treatment, different kinds and brands of cement do not give the same variations in the ratios of the two kinds of strength.

Mortar is not usually employed alone in large masses. It more frequently forms the binding medium between fragments of other substances, such as brick and stone. The dependence of the strength of masonry upon the strength of the mortar increases with the roughness of the stone or brick, and the thickness of the bed joints. In fine ashlar masonry this dependence is comparatively small, in brickwork it is important, and in concrete any increase in the strength of the mortar increases the strength of the concrete in nearly the same ratio.

Piers of brickwork may give a crushing resistance either greater or less than the strength of cubes made from mortar of the same composition as that used in building the piers. Thin beds of mortar between strong materials resist high compressive stresses, while in walls or piers built with weak blocks, the mortar is destroyed by the cracking of the blocks at a lower stress than the mortar would withstand in a cube pressed between steel plates. Since in brick and stone masonry the mortar forms but a small part of the structure, it is not economical to use a poor quality of mortar with good brick and stone.

419. Ratio of Compressive to Tensile Strength. — M. E. Candlot has made many experiments showing the effect of certain variations in the preparation of mortars upon the compressive and tensile strength. A few of the results of one series are presented in Table 128. The reduction from the metric system has been made, and a column added giving approximately the number of parts of sand to one of cement by weight, the accurate proportions appearing in the form of weight of cement to one cubic yard of sand. These results indicate that the ratio of the strength in compression to that in tension increases with the age of the mortar and also with its richness.

TABLE 128

Resistance of Cement Mortars to Tension and Compression, with Varying Proportions of Normal Sand

SPECIMENS HARDENED IN FRESH WATER

[From *Ciments et Chaux Hydrauliques*, par M. E. Candlot.]

Approx. Propor's, Pts. Sand, to 1 Cem. by Wt. if Sand Weighs 100 Lbs. per Cu. Ft.	Pounds Cement per Cubic Yard of Sand, Actual.	Resistance in Pounds per Square Inch in Tension and Compression.										Ratio Compression to Tension at Three Years.
		7 days.		28 days.		1 year.		2 years.		3 years.		
		T.	C.	T.	C.	T.	C.	T.	C.	T.	C.	
10.8	250	27	266	38	408	70	507	74	572	108	738	6.8
6.4	420	128	643	143	1164	212	1730	209	1630	219	1775	8.1
4.6	590	139	1040	234	1940	337	2980	284	2930	341	3080	9.0
3.5	760	233	1520	393	3080	435	4020	400	4400	462	4590	9.9
2.9	930	251	2110	462	3690	490	5580	490	5680	557	6060	10.9
2.5	1100	349	2630	551	5020	594	5820	557	6060	616	6480	10.5
2.0	1350	308	3360	550	5020	713	7750	805	7860	784	8710	11.1
1.6	1690	443	3310	561	5070	767	7670	907	8800	815	9180	11.3

From a study of the results of nearly three thousand tests made by Professor Tetmajer, the late Professor J. B. Johnson concluded that for mortars containing three parts sand to one cement the ratio of the compressive strength to the tensile strength is equal to $8.64 + 1.8 \log. A$, where A is the age of the mortar in months. It is shown above that the ratio increases with increasing proportions of sand.

420. Table 129 gives some results obtained at the Watertown Arsenal in tests of cement mortar cubes.[1] The mortars

[1] Prepared by Mr. George W. Rafter for the State Engineer of New York.

TABLE 129

Compressive Strength of Cement Mortar.—Portland and Natural

TESTS OF 12 INCH CUBES, TWENTY MONTHS OLD, MADE AT WATERTOWN ARSENAL FOR STATE ENGINEER OF NEW YORK

Method of Storage of Cubes.	Cement. Kind.	Cement. Brand.	Consistency of Mortar.	Crushing Strength, Lbs. per Square Inch, for Mortars Containing Parts Sand to One Cement by Volume: 1	2	3	4	Mean
Water 3 to 4 mo., then buried in sand.	Nat.	Buffalo	Dry	3479	2200	1154	. . .	2278
			Plastic	2795	1783	1000	. . .	1859
			Excess	2161	1698	776	. . .	1545
			Mean	2812	1894	977	. . .	1894
Covered with burlap; kept wet for several weeks, then exposed to weather. . .	Nat.	Buffalo	Dry	3347	2000 [1]	961	. . .	2103
			Plastic	2476	1294	692	. . .	1487
			Excess	2070	1358	738	. . .	1389
			Mean	2631	1551	797	. . .	1660
In cool cellar . .	Nat.	Buffalo	Dry	2844	2051	987	. . .	1961
			Plastic	2514	1256	883	. . .	1551
			Excess	2159	1386	678	. . .	1408
			Mean	2504	1564	849	. . .	1640
Fully exposed to weather . . .	Nat.	Buffalo	Dry	3272	1879	1054	. . .	2068
			Plastic	2667	1356	822	. . .	1615
			Excess	1996	1311	669	. . .	1825
			Mean	2645	1513	848	. . .	1669
Means			Dry	3236	2032 [2]	1039	. . .	2102
			Plastic	2613	1421	849	. . .	1628
			Excess	2097	1438	715	. . .	1417
Grand mean . .				2649	1630	868	. . .	1716
Water 3 to 4 mo., then buried in sand.	Port.	Empire	Dry	. . .	3897	2494	1782	. . .
			Plastic	. . .	3642	2168	1717	. . .
Covered with burlap; kept wet for several weeks, then exposed to weather. . .	Port.	Empire	Dry	. . .	3880	2492	1489	. . .
			Plastic	. . .	3672	2168	1726	. . .
In cool cellar . .	Port.	Empire	Dry	. . .	3397	2132	1614	. . .
			Plastic	. . .	3313	2164	1679	. . .
Fully exposed to weather . . .	Port.	Empire	Dry	. . .	4059	2450	1715	. . .
			Plastic	. . .	3589	2270	1465	. . .
Means			Dry	. . .	3808	2392	1650	. .
			Plastic	. . .	3554	2193	1647	. .

contained one, two and three volumes of sand to one of natural cement, and two to four parts sand to one volume of Portland.

[1] Result interpolated.

[2] 2,043 omitting interpolated result.

The proportions of water used were such as to give mortars of different consistency, "dry," like damp earth, "plastic," of the consistency usually employed by masons, and "excess," quaking like liver with slight tamping. The specimens were twelve inch cubes and four methods of storage were used, as indicated.

Comparing the results with similar tests of tensile strength, it appears that the strength in compression decreases more rapidly as sand is added than does the tensile strength. The same conclusion was drawn from Table 128.

The strength of the Portland mortar with four parts sand is about equal to the strength of the natural with two parts. The dry mortar gives the highest strength with natural cement, but with Portland the "dry" and "plastic" give about the same result.

Concerning the consistency, it has already been pointed out that the conditions of the actual employment of mortar are such as to favor, in general, the use of a wetter mixture than that which gives the best results in laboratory tests of mortars. As to storage, the specimens kept in water for three or four months after made, give the highest results with natural cement. There seems to be no choice between the other three methods of storage.

ART. 53. COMPRESSIVE STRENGTH OF CONCRETE WITH VARIOUS PROPORTIONS OF INGREDIENTS

421. With the increasing use of concrete in arch bridges, in foundation piers and in columns of buildings, and especially in connection with steel in beams, etc., the compressive strength of the material becomes of the greatest importance. Moreover, the composition of concrete may vary so much, the range of available aggregates is so wide, and the methods of manipulation are so diverse, that many tests must be studied before one can judge of the probable strength of a given mixture.

For any very extended work, it may be found economical to make a series of tests using the materials available, and combining them as nearly as possible in the manner proposed in actual construction. This practice has been followed in several important works, and the data thus accumulated have added much to our hitherto somewhat vague notions of the probable strength of different mixtures under varying conditions of use. It is possible here to abstract but a few of the more reliable and complete tests of this kind, selecting those which indicate the value of certain special kinds of aggregate or the effect of certain variations in manipulation.

422. In connection with the design of the Boston Elevated R. R., Mr. George A. Kimball, Chief Engineer, prepared a series of concrete cubes of mixtures usually employed in practice, and with the materials available for the work in hand, and these cubes were tested at the Watertown Arsenal in 1899. A portion of the results of these experiments are given in Table 130, where the details concerning character of the materials and the preparation of the specimens are shown. As each result in the table is the mean of at least twenty specimens, the irregularities frequently appearing in compressive tests have been largely eliminated, and the results are worthy of much confidence.

TABLE 130

Compressive Strength of Concrete

TESTS OF 12 INCH CONCRETE CUBES FOR BOSTON ELEVATED RAILROAD.

Composition of Concrete by Volume.			Crushing Strength, Pounds per Square Inch, at Age,			
Cement.	Sand.	Stone.	7 days.	1 month.	3 months.	6 months.
1	2	4	1525	2440	2944	3904
1	3	6	1232	2063	2432	2969
1	6	12	583	1042	1066	1313

NOTES: —

Materials: — Cement, mean results with four brands Portland, two American, two German.
Sand, coarse, clean, sharp, voids 33 per cent. loose.
Broken stone, conglomerate passing 2½ inch ring, voids 49½ per cent. loose.

Mixing: — Sand and cement turned twice, mortar and stone turned twice.

Storage: — Cubes removed from molds three or four days after made and buried in wet ground until about a week before testing.

Each result, mean of twenty or more tests.

Tests made at Watertown Arsenal, for George A. Kimball, Chief Engineer, Boston Elevated R.R. "Tests of Metals," 1899.

At the time of making these tests some cubes were crushed with a die having a smaller area than the face of the cube.

With a die 8 by 8¼ inches on one compression face, the area of the die being thus about .46 of the area of the cube face, the strength per square inch under the die was about twenty-five per cent. higher than when the entire face of the cube was pressed. This is in line with the behavior of all brittle substances under compression, as shown by Professor Bauschinger in testing sandstone specimens.

423. Tables 131 and 132 give a summary of a part of a very valuable series of tests of concrete cubes prepared by Mr. George W. Rafter and tested at the Watertown Arsenal for the State Engineer of New York.[1]

The results summarized in Table 131 are those obtained with four brands of Portland cement made in the State of New York, namely, Wayland, Genessee, Empire and Ironclad. Tests were also made with a sand-cement, and with one brand of natural, but these results are not included in the table. The aggregate was sandstone of the Portage group, broken by hand to pass a two inch ring.

The mortars used in making the cubes were of three degrees of consistency: (*a*) In the dryest blocks the mortar was only a little more moist than damp earth, and much ramming was required to flush water to the surface. (*b*) In another set the mortar was about the consistency of ordinary mason's mortar. (*c*) In the third set, the mortar was wet enough to quake like liver under moderate ramming.

424. The mortar was composed of one volume of loose cement to two, three or four volumes of loose sand. Other proportions were also employed, but in this table only those results are included in which the series of tests was complete as to variations in consistency and storage.

The voids in the stone were about forty-three per cent. when the measure was slightly shaken, and thirty-seven and a half per cent. when rammed without mortar. The amount of mortar used was made either thirty-three per cent. or forty per cent. of the volume of the loose stone.

Four methods of storage were used as follows: 1st, blocks immersed in water as soon as they were removed from the molds, and after three or four months they were buried in sand;

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[1] Report of State Engineer of New York, 1897.

TABLE 131

Compressive Strength of Concrete

MEAN RESULTS WITH FOUR BRANDS PORTLAND CEMENT, ILLUSTRATING EFFECTS OF PROPORTIONS, CONSISTENCY, AND METHODS OF STORAGE. TESTS OF CONCRETE CUBES, ABOUT TWENTY MONTHS OLD, MADE FOR STATE ENGINEER OF NEW YORK

PARTS SAND TO ONE CEMENT—VOL.		2		3		4		MEANS.		
VOL. MORTAR AS PER CENT. OF VOL. LOOSE AGGREGATE.		33	40	33	40	33	40	33 and 40		
STORAGE OF CUBES.	CONSISTENCY.	CRUSHING STRENGTH, POUNDS PER SQUARE INCH.						PROPORTIONAL.		
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
Water 3 to 4 mos., then buried in sand.	Moist Earth	3632	3785	2506	2482	1914	1989	2718	100	. .
	Mason's	3094	3516	2459	2354	1886	1928	2540	94	. .
	Quaking	3111	3116	2234	2318	2015	1794	2431	89	. .
	Mean	3279	3472	2400	2385	1938	1904	2563	. .	100
Covered with burlaps and kept wet for several weeks; then exposed to weather.	Moist Earth	2557	3176	2194	2126	1674	1728	2242	100	. .
	Mason's	2591	2909	1860	1930	1643	1678	2102	94	. .
	Quaking	2648	2912	1856	1925	1855	1548	2124	95	. .
	Mean	2599	2999	1970	1994	1724	1651	2156	. .	84
In cool cellar.	Moist Earth	3053	3006	2004	2012	1743	1612	2238	100	. .
	Mason's	2529	2846	1980	1829	1510	1679	2062	92	. .
	Quaking	2488	2554	1711	1965	1714	1625	2010	90	. .
	Mean	2690	2802	1898	1935	1656	1639	2102	. .	82
Fully exposed to weather.	Moist Earth	2515	3054	1910	2078	1614	1593	2127	100	. .
	Mason's	2606	2746	1983	1930	1554	1564	2064	97	. .
	Quaking	2459	2724	1793	1908	1682	1529	2016	95	. .
	Mean	2527	2841	1895	1972	1617	1562	2069	. .	81
Mean results, four methods of storage.	Grand Means	2774	3028	2041	2072	1734	1689	2223	. .	. .
	Ratios	$\frac{2774}{3028} = 91.6\%$		$\frac{2041}{2072} = 98.5\%$		$\frac{1734}{1689} = 102.6\%$		. . .	. .	. .
Mean results, four methods storage and two percentages of mortar.		STR.	PROP.	STR.	PROP.	STR.	PROP.			
	Moist Earth	3097	100	2164	100	1733	100	2331	100	. .
	Mason's	2854	92	2040	94	1680	97	2192	94	. .
	Quaking	2751	89	1964	91	1720	99	2145	92	. .

2d, blocks covered with burlap and wet frequently for several weeks, after which they were exposed to the weather; 3d, kept in a cool cellar from the time of fabrication until shipped for testing, and 4th, fully exposed to the weather throughout.

425. In Table 131 each result is the mean of four cubes, one of each brand. The mean results are so arranged as to show the effects of variations in the amount, the richness, and the consistency of the mortar, and of the different methods of storage.

Taking up first the question of **consistency,** it appears from column "*j*" that the use of plastic mortar, marked "mason's," gave from 92 to 97 per cent. of the strength given by the dry mortar of about the consistency of "moist earth;" and that the "quaking" concrete gave from 89 to 95 per cent. of the strength of that marked "moist earth." From the three lines at the bottom of the table it is seen that in the poor concrete, one-to-four mortar, the wettest mortar gave nearly as good results as the dryest, while in the rich concrete, one-to-two mortar, the strength of the wet was but 89 per cent. of the dry. The explanation of this may be found in the fact that in the poor concrete the mortar was "brash," and the concrete did not ram well with a dry mortar, while the rich mortar was "fuller" and more plastic, so that the excess of water was not needed to make a compact mass.

426. Turning to the question of the **amount of mortar,** it is plainly shown that the concrete containing forty per cent. is but little better than that containing thirty-three per cent. This is in line with what has been said elsewhere, that an excess of mortar, as well as a deficiency, may be an actual detriment to the strength of the concrete. In this case the thirty-three per cent. mortar was not quite sufficient to fill the voids in the stone, and forty per cent. was a very slight excess.

Some interesting conclusions are indicated by the results in the line marked "ratios," near the bottom of the table. The ratios of the strength of the concrete containing thirty-three per cent. mortar to the strength of that containing forty per cent. are 91.6 per cent., 98.5 per cent. and 102.6 per cent., respectively, for one-to-two, one-to-three, and one-to-four mortars. That is, with a rich mortar forty per cent. may be used to advantage, but if the mortar is of poor quality, the strength of the concrete is not increased by an excess of mortar.

Finally, as to the strength developed under different conditions of **storage,** column "*k*" shows that for these cements the highest strengths are attained by immersing the concrete in water. In comparison, the strength developed by the concrete covered with wet burlap is 84 per cent.; in cool cellar, 82 per cent.; and in the open air fully exposed to the weather, 81 per cent.

427. The results given in Table 132 are the mean crushing strengths obtained in the same series of tests as described above, so arranged as to bring out the effect of the **richness of the mortar**. Although several brands were tested, only the results obtained with a single brand of Portland, namely, Millen's "Wayland," are included here, since the series was not completed with other brands. From similar tests with concretes containing one-to-two and one-to-three mortars only, it was found that three other brands of Portland gave from 91 to 102 per cent. of the strength obtained with the Wayland, and a brand of sand-cement gave 66 per cent.

TABLE 132

Compressive Strength of Concrete. Effect of Richness of Mortar

MEAN RESULTS, FOUR METHODS OF STORAGE

Volume Mortar as Per Cent. of Volume of Aggregate.	Consistency of Concrete.	Mortar, Proportions Cement to Sand.				
		1-1	1-2	1-3	1-4	1-5
		Crushing Strength, Lbs. per Sq. In.				
33	Moist Earth	4267	2888	2056	1810	1537
	Mason's	4072	2777	2207	1600	1568
	Quaking	3764	2847	1723	1767	1441
40	Moist Earth	3966	3404	2179	1671	1559
	Mason's	4123	2960	2027	1750	1465
	Quaking	3256	3168	2016	1670	1400
	Mean	3908	3007	2035	1711	1495
	Proportional	100	77	52	44	38

NOTES: — One brand Portland cement.
Aggregate, Portage sandstone, broken to pass two-inch ring.
Age of cubes about twenty months.
Each result, mean of four cubes.

Each result in the table is the mean of four cubes, each stored in a different manner. Tests with four brands (Table 131) where the concretes were made with one-to-two, one-to-three and one-to-four mortars, indicated that the percentages of the mean strength developed in the several methods of storage were as follows: If stored in water, the cubes developed 115 per cent. of the mean result; covered with burlap kept wet, the cubes developed 97 per cent.; stored in a cool cellar, 95 per cent.; and fully exposed to weather, 93 per cent. of the mean strength.

The mean results given at the bottom of the table represent each a mean of twenty-four cubes made with two different amounts of mortar, three degrees of consistency, and four methods of storage. By applying the percentages given above the probable corresponding result for any set of conditions may be obtained. The last line of the table shows the proportions that the strength of the concretes made with poorer mortars, bear to the strength obtained with one-to-one mortar.

428. Table 133 gives the results of a series of tests made by J. W. Sussex at the University of Illinois.[1] The materials used were "Chicago AA Portland cement, sand containing a small

TABLE 133

Compressive Strength of Concrete. Relative Strength of Dry, Medium, and Wet Mixtures

Consistency.	Tamping.	Tensile Strength, Pounds per Square Inch, at Age of			Proportional Value at 3 Mos.
		7 days.	1 month.	3 months.	
Dry	Light	1200	1750	2500	82
Medium . . .	"	2290	2290	2150	71
Wet	"	1040	2230	3040	100
Dry	Hard	1340	1960	2600	86
Medium . . .	"	1330	2565	2580	85

NOTES: — Concrete composition:
Cement, Portland, one volume.
Sand, containing some fine gravel, three volumes.
Six volumes broken limestone passing one-inch mesh.
Specimens, six-inch cubes.
Results by J. W. Sussex, Univ. of Ill.

[1] *Technograph*, 1902–03.

percentage of fine gravel, and crushed limestone which would pass through a sieve with one-inch mesh." The proportions were three parts sand and six of broken stone to one volume of loose cement. The cubes were six inches on a side. The treatment during storage is not stated. The consistency of the concrete was as follows: "Dry," water 6.0 per cent., as moist as damp earth, no free water flushed to surface in ramming. "Medium," 7.8 per cent. water; water flushed to surface and concrete quaked only after being well rammed. "Wet," water 9.4 per cent., concrete quaked in handling and could be tamped but lightly.

Each result in the table is the mean of three cubes. The concrete was tamped in layers about one inch thick with a rammer weighing 11½ pounds and dropped six inches. Ten blows of the rammer constituted "light" tamping and twenty blows "hard" tamping. The results show that the "medium" concrete gains its strength more rapidly than the "wet," but that at one month the "wet" concrete has a higher strength than the dry, and that at three months the wet surpasses in strength both the dry and the medium.

ART. 54. CONCRETES WITH VARIOUS KINDS AND SIZES OF AGGREGATES

429. It has already been stated that the character of the aggregates is second only to the quality of the mortar in its effect on the strength of concrete. The materials available for aggregate in different localities are so varied that only a general idea of their relative values may be obtained from a limited number of tests.

The results given in Table 134 are from tests made at the Watertown Arsenal,[1] and show the compressive strengths of concretes made with **broken trap and gravel** of different sizes. The concretes are all very rich, and the strengths correspondingly high, although the oldest specimens have hardened less than three months. The results are somewhat irregular, and the conclusion to be drawn concerning the best size for the aggregate is not very clearly brought out. The one-inch trap gives uniformly good results, as do the mixtures of two or

[1] "Tests of Metals," 1898.

more sizes. The trap rock gives a higher result than the gravel, the mortar being sufficient to fill the voids in the trap, and in excess for the gravel.

TABLE 134

Compressive Strengths of Rich Concretes at Different Ages

TESTS OF TWELVE-INCH CUBES

CHARACTER OF AGGREGATE.	WT. PER CU. FT. OF CONCRETE WHEN ABOUT 1 MO. OLD, IN LBS.	COMPRESSIVE STRENGTH, POUNDS PER SQUARE INCH, AT AGE, DAYS,			
		7–8	19–23	29–34	61–76
Trap ½″	148.6	1391	2220	2800	5021
" ¾″	148.5	1900	2769	3200	. . .
" 1″	159.8	3390	4254	4917	5272
" 1½″	159.2	3189	4006	4562	2583
" 2½″	160.2	2400	4143	4140	4523
" ½″–1, 2½″–2	158.4	2800	3786	4349	4544[1]
" ½″–1, 1″–1, 2½″–1 .	159.8	2800	4156	4800	5542
Mean results, trap rock alone	. . .	2553	3619	4110	4581
Pebbles ⅜″	148.2	1298	2600	2992	3870
" 1½″	151.0	2276	3186	3817	4018
" ⅜″–1, 1½″–2 . . .	150.3	1994	3023	3800	3490
" ⅛″–1, ⅜″–1, 1½″–1	147.8	1486	2676	3000	3800
Mean, pebbles alone . . .	. . .	1764	2871	3402	3794

NOTES: — Tests made at Watertown Arsenal, "Tests of Metals," 1898.

All concretes composed of one cubic foot of Alpha Portland cement, weight 96½ to 106 lbs. per cu. ft., one cu. ft. of bank sand, weight 93½ to 104 lbs. per cu. ft., and 3 cu. ft. of aggregate, weighing from 93 to 105 lbs. per cu. ft.

The size of aggregate indicated gives the larger of the two screens used in separating it into different sizes; thus, "¾ inch" means passing ¾ inch mesh and retained on ½ inch mesh.

The compressive strength of twelve inch cubes of one-to-one mortar alone was 3,833 lbs. per sq. in. at seven days, and 4,800 lbs. per sq. in. at seventy-five days.

430. In 1896–97 Mr. A. W. Dow[2] prepared a number of twelve-inch cubes of concrete for the Engineer Commissioner

[1] Not fractured.

[2] Report Operations, Engineer Department, District of Columbia, 1897. Also Baker's "Masonry Construction," p. 112 r.

of the District of Columbia. These cubes are of interest as showing the strength of **natural cement concrete** as well as Portland, and the results are abstracted in Table 135.

TABLE 135

Compressive Strength of Concrete

TESTS OF TWELVE-INCH CUBES FOR THE ENGINEER COMMISSIONER OF THE DISTRICT OF COLUMBIA

REF.	COMPOSITION OF CONCRETES.						PER CENT. VOIDS IN AGGREGATE.	CRUSHING STRENGTH, LBS. PER SQUARE INCH AT ONE YEAR.	
	Cement.	Sand.	Broken Stone.		Gravel.			Portland.	Natural.
			Coarse.	Average.	Average.	Small.			
1	1	2	6	....	....	...	45.3	1850	829
2	1	2	...	6	....	...	45.3	3060	915
3	1	2	...	6[1]	....	...	39.5	2700	800
4	1	2	...	....	6	...	29.3	2820	763
5	1	2	...	3	....	3	35.5	2750	841
6	1	2	...	4	....	2	36.7	2840	915

NOTES: — Materials:

Cement, Portland, "Atlas" (American), 104 lbs. per cu. ft.; Natural, "Round Top," 70 lbs. per cu. ft.

Sand, 15 per cent. retained on No. 8 mesh, 75 per cent. between 8 and 40 mesh, 10 per cent. passing 40 mesh. Sand was used damp, and weighed in that condition 90 lbs. per cu. ft.

Stone, Bluestone, "Average," 93 per cent. between $\frac{1}{3}$ inch and 2 inches.
"Coarse," 80 per cent. between $1\frac{1}{2}$ inches and $2\frac{1}{2}$ inches.

Gravel, "Average," 90 per cent. between $\frac{1}{6}$ inch and $1\frac{1}{2}$ inches.
"Small," 90 per cent. between $\frac{1}{8}$ inch and $\frac{3}{4}$ inch.

Granolithic, 92 per cent. between $\frac{1}{10}$ inch and $\frac{1}{3}$ inch.

Mixing, thorough by experienced man.

Tamping, light, in 4 inch layers, just sufficient to bring mortar to surface.

Storage, cubes thoroughly wet twice a day.

Age of specimens when broken, one year.

The concretes all contained two parts sand and six parts aggregate to one cement, but the character of the aggregate varied as shown. The natural cement concrete gave from one-quarter to one-third the strength of the Portland concrete. The best result seems to be given by the average size broken stone, which was in reality a mixture of various sizes, ninety-

[1] Mixture of one part granolithic size to one of concrete stone.

three per cent. of it being retained on a one-third inch mesh and passing a two-inch mesh. The mortar was probably insufficient to fill the voids in the stone for the first three cubes in the table, and under these conditions the gravel, with its smaller percentage of voids, makes a good showing. This illustrates what we have already said, that the relative value of broken stone and gravel for aggregate depends upon the proportion of mortar used.

TABLE 136

Compressive Strength of Concrete. Portland Cement

TESTS OF SIX-INCH CUBES OF VARIOUS MIXTURES

Reference.	Parts by Volume to One Cement.			Crushing Strength, Pounds per Square Inch, at Age of,		
	Sand.	Gravel.	Broken Stone.	7 days.	30 days.	90 days.
1	0	0	0	3412	5318	6140
2	0	3[1]	0	1077	1908	2517
3	1	2	2½	1430	2215	2903
4	2	2	3	420	2117[2]	1324
5	2	3	4	640	1190	1290
6	2½	5	0	566	1385	1609
7	2½	0	5	739	2033	1783
8	2½	2½	2½	792	1482	2014
9	3	0	0	767	1345	1409
10	3	3	4	714	1028	1818
Means, Actual				1056	2003	2284
Means, Per Cent.				46	88	100

NOTE: — Results of Messrs. Ketchum and Honens.

431. The results in Table 136 were obtained by Messrs. R. B. Ketchum and F. W. Honens at the laboratory of the University of Illinois,[3] and illustrate the rate of gain in strength of several mixtures. The cement used was Saylor's Portland, fine and of good quality. The sand and gravel were composed principally of silica, with 10 to 30 per cent. of limestone. About 60 per cent. of the sand passed a "number thirty" sieve. The unscreened gravel had about 42 per cent. caught on a "number five" sieve and eighteen per cent. of it passed a "number

[1] Unscreened.
[2] Result irregular.
[3] *Technograph*, 1897-98.

thirty." Except in one mixture, however, the gravel and broken stone were screened, and only that portion passing a two-inch ring and retained on a "number five" sieve was used. The stone was a magnesian limestone.

The concrete was mixed dry, so that considerable tamping was required to bring water to the surface. The cubes were first kept under a damp cloth for one day, immersed six days, and then stored in air in a room until broken. In crushing, "the direction of the force applied was parallel to the tamped surface."

432. Each result in the table is the mean of six specimens. Comparing number 2 with number 9 indicates that the strength obtained with one part cement to three parts unscreened gravel is much higher than with mortar of one part cement to three parts sand. Comparing 9 and 10 indicates that seven parts gravel and stone may be mixed with one-to-three mortar and give higher strength than the mortar alone. A comparison of 6, 7, and 8 shows that in case there is sufficient mortar to fill the voids in the aggregate, angular fragments give a somewhat higher strength than rounded ones, but that a mixture of broken stone and gravel is better than either alone. One of the most important points brought out by the tests is that the strength at seven days is 46 per cent., and at thirty days is 88 per cent., of the strength attained at three months.

Art. 55. Cinder Concrete, etc.

433. For such purposes as floors for buildings, cinders are used in concrete to a considerable extent on account of their light weight. Cinder concrete weighs only from two-thirds to three-fourths as much as broken stone or gravel concrete. The strength, however, is correspondingly less, and whether for a given strength a floor may be made lighter by the use of cinders will depend upon the conditions of use and the character of the reinforcement.

Table 137 gives the results of the tests of eight-inch cylinders, fifteen inches high, made by Mr. George Hill.[1] In these cylinders, cinders, broken stone, and gravel were used as aggregates. The character of the materials is shown in the foot-note of the

[1] Trans. Am. Soc. C. E., Vol. xxxix, p. 632.

table. As the specimens were but one month old when tested, the results are low, but since in the construction of floor arches the centers are usually removed in less than one month, the strength developed in a short time has a special interest.

TABLE 137

Compressive Strength of Concrete about One Month Old

TESTS OF CYLINDERS, EIGHT INCHES DIAMETER, FIFTEEN INCHES HIGH

Aggregate.	Proportions by Volume.			Age,	Compressive Strength, Lbs. per Sq. In.	
	Cement.	Sand.	Aggregate.	Days.	American Portland Cement.	Slag Cement.
Cinders.	1	3	6	33	246	. . .
"	1	3	6	18	292	. . .
"	1	2	5	33	305	. . .
"	1	2	5	33	464	. . .
"	1	2	5	32	490	. . .
"	1	2.4	6	32	590	. . .
"	1	1.7	4.2	30	. . .	842
"	1	1.6	4	30	. . .	830
"	1	1.6	4	31	. . .	765
"	1	1.6	4	31	. . .	765
Stone.	1	3	6	30	398	. . .
"	1	2.4	4.1	30	503	. . .
"	1	2.4	4	33	. . .	645
"	1	2.4	4	30	. . .	730
Gravel.	1	3	6	30	917	618
"	1	2.4	4.8	30	. . .	650
"	1	2	7	25	880	. . .
"	1	1.6	6.5	31	. . .	730
Stone and gravel, graded	1	2	10	30	625	. . .

NOTES: —

Cement, American Portland, tensile strength 624 lbs. per sq. in., neat, seven days.

Slag cement, a little less than 400 lbs. per sq. in., neat, seven days.

Sand, clean, sharp, bank sand of mixed sizes, from moderately fine up to some pebbles size of bean.

Cinders, ordinary steam, dust to ¾ inch size.

Stone, broken trap, nearly uniform size passing 1½ inch ring.

Gravel, clean, washed, ½ in. to 1½ in.

Abstract of tests by Mr. George Hill, M. Am. Soc. C. E., Vol. xxxix, p. 632.

It is evident that cinder concrete should not be loaded very heavily within a month after made. The gravel gives a better result than broken stone.

434. In Table 138 are given the results of some tests of twelve-inch cubes of cinder concrete made at the Watertown Arsenal for the Eastern Expanded Metal Companies. Steam cinders were used, practically as they came from the furnace, only the larger clinkers being broken. Two proportions were used and the specimens were broken at one month and three months. It is seen that the one-one-three mixture is about twice as strong as the one-two-five with all brands. The variations between the several brands are also very great.

TABLE 138

Crushing Strength of Cinder Concrete. Portland Cement

TESTS OF TWELVE-INCH CUBES AT WATERTOWN ARSENAL

Brand of Cement.	Strength, Pounds per Square Inch.			
	Mixture A, 1-1-3.		Mixture B, 1-2-5.	
	Age of Specimens.		Age of Specimens.	
	1 month.	3 months.	1 month.	3 months.
A	2329	2834	940	1600
B	1602	2414	696	1223
C	1438	1890	744	880
D	1032	1393	471	685

NOTES: —

Concretes mixed rather dry, 10 to 12½ pounds of water per cubic foot of concrete.

Mixture "A," one part cement, one part sand, three parts cinders.

Mixture "B," one part cement, two parts sand, five parts cinders.

Weight of concrete, 104 to 116 pounds per cubic foot.

Tests for Eastern Expanded Metal Companies. Data from "Tests of Metals," 1898.

435. Table 139 gives the results of other tests in the same series, using a single brand of cement and five mixtures, the richest containing three parts cinders and one part sand to one volume cement, and the poorest six parts cinders and three parts sand to one cement. The weight per cubic foot of the several concretes is also given.

Tests of cinder concrete prisms made by the late Prof. J. B. Johnson at Washington University [1] indicated that the mixture

[1] "Materials of Construction," p. 628.

containing one part sand and three parts cinders to one volume cement gave the highest strength, or about twelve hundred pounds per square inch, at one month. The same mixture gave the highest values for the ratios of strength to cost, and of strength to weight per cubic foot.

TABLE 139

Crushing Strength of Cinder Concrete. Various Proportions with Germania Portland Cement

TESTS OF TWELVE-INCH CUBES AT WATERTOWN ARSENAL

Proportions in Concrete.			Weight per Cu. Ft. at 98 to 102 Days, Pounds.	Crushing Strength, Pounds per Square Inch, at Age,	
Cement.	Sand.	Cinders.		29 to 39 days.	98 to 102 days.
1	1	3	110.4	1466	2001
1	2	3	112.8	1008	1634
1	2	4	107.0	904	1325
1	2	5	105.3	769	1084
1	3	6	103.5	529	788

NOTE: — Tests for Eastern Expanded Metal Companies, "Tests of Metals," 1898.

436. Clay in Concrete. — The effect of clay on the tensile strength of mortars has already been shown (Art. 49). Aggregates available for concrete frequently contain a certain amount of clay, and the question arises whether such aggregate must be washed, or whether certain small percentages may be permitted in the concrete, using, perhaps, a trifle richer mortar. The results in Table 140 were made to determine the effect of clay on the crushing strength of concrete.[1]

The test specimens were six-inch cubes, and were broken when one week to twelve weeks old in an Olsen machine. The proportions were two parts sand and six parts gravel by weight to one of Portland cement, or two parts sand and four parts gravel by weight to one of natural cement. The clay is apparently expressed as the per cent. of total aggregates. It is seen that while six or twelve per cent. clay retards the hardening of both Portland and natural cement concrete, the strength of the Portland concrete after four weeks is increased by six per

[1] Tests by Messrs. J. J Richey and B. H. Prater, *Technograph*, 1902–03.

cent. clay, while at the same age the strength of the natural cement concrete is not greatly affected. The ramming of concrete is facilitated by the presence of a small amount of clay, but larger amounts may render the mass sticky and difficult to ram.

TABLE 140

Effect of Clay on Crushing Strength of Concrete

SIX-INCH CUBES

CEMENT.	PROPORTIONS BY WEIGHT, NO. PARTS TO ONE CEMENT.		AGE OF CUBES WHEN BROKEN.	CRUSHING STRENGTH, POUNDS PER SQ. IN.; CLAY AS PER CENT. OF CONCRETE.		
	Sand.	Gravel.		0	6	12
Port.	2	6	1 week	1030	1001	692
"	2	6	4 weeks	1398	1525	1287
"	2	6	12 "	2110	2760	1865
Nat.	2	4	1 week	208	131	81
"	2	4	4 weeks	428	364	283
"	2	4	12 "	786	722	480

ART. 56. THE MODULUS OF ELASTICITY OF CEMENT MORTAR AND CONCRETE

437. With the increasing use of concrete and steel in combination, the modulus of elasticity of cement mortar and concrete assumes a new importance, since the ratio of the stresses in the two materials depends upon the relative moduli of elasticity. Some of the earlier determinations of the modulus of mortar gave very high values. This may have been due to the use of richer mixtures, and the exercise of greater care in the manipulation, than are employed in actual construction, and also to the fact that the determinations were based upon the deformations resulting from the application of very limited loads.

It is now considered that the ratio of stress to strain is not constant, even for moderate loads, but that the modulus of elasticity decreases with increasing stress, and this fact is brought out in the following tables. The tests cited bring out a wide range of values for concretes and mortars made from a variety of sand and aggregate and of various compositions and ages.

438. Modulus of Elasticity of Natural and Portland Cement Mortars. — Table 141 gives the modulus of elasticity of mortars as determined by tests of twelve-inch cubes at the Watertown

TABLE 141

Modulus of Elasticity of Cement Mortar

TESTS OF TWELVE-INCH CUBES AT WATERTOWN ARSENAL FOR STATE ENGINEER OF NEW YORK

Cement.		Consistency of Mortar.	Proportions Cement to Sand in Mortar by Volume.										
			1-1			1-2			1-3			1-4	
			Modulus of Elasticity in Thousands, between Loads, in Pounds per Square Inch, of										
Kind.	Brand.		100-600	100-1000	1000-2000	100-600	100-1000	1000-2000	100-600	100-1000	1000-2000	100-600	100-1000
Natural	Buffalo	Dry	1667	1452	1380	1471	1364	1042	1042	804	...	...	...
"	"	Plastic	2500	1875	1020	1250	1250	...	1087	...	...	...	...
"	"	Excess	2273	1800	833	1250	1184	...	735	...	...	...	...
"	"	Mean	2147	1709	1081	1324	1266	...	955	...	...	...	...
Portland	Empire	Dry	...	...	...	3571	2500	1923	2500	1956	1250	3125	1875
"	"	Plastic	...	...	...	1923	1956	2083	...	...	...	2045	1250

NOTES: — Mortar cubes stored in water three months, then buried in sand about seventeen months.
For compressive strength of cubes, see Table 129.

Arsenal.[1] These specimens were a portion of those prepared by Mr. Rafter, the compressive strength being given in Table 129. As each value is the result of but one determination, the results are not as regular as might be desired. In general the strength and the modulus decrease together as the amount of water used in mixing is increased. The modulus also decreases with the strength as the proportion of sand increases.

439. Modulus of Concretes One Month to Six Months Old. — In the compressive tests of twelve-inch concrete cubes made for Mr. George A. Kimball and abstracted in Table 130, many of the specimens were also gaged for compression under load to determine the modulus of elasticity, and a part of the results are presented in Table 142.

TABLE 142

Modulus of Elasticity of Concrete

TESTS MADE ON TWELVE-INCH CUBES OF PORTLAND CEMENT CONCRETE AT WATERTOWN ARSENAL FOR BOSTON ELEVATED RAILROAD

Age of Cubes When Crushed.	Concrete 1-2-4.			Concrete 1-3-6.			Concrete 1-6-12.	
	Modulus of Elasticity in Thousands, between Loads, in Pounds per Square Inch, of							
	100-600	100-1000	1000-2000	100-600	100-1000	1000-2000	100-600	100-1000
7 days	2592*c*	2053*c*	1351*a*	1869*c*	1529*b*	. . .	. . . .	. . .
1 month	2662*c*	2444*c*	1462*c*	2438	2135	1219*a*	1376	. . .
3 months	3070	3170	2157	2976	2656	1805	1642	1363
6 months	3646	3567	2581	3608	3503	1868	1820	1522

NOTES: — Results marked "*a*" are means of five or more tests of one brand.
Results marked "*b*" are means of five or more tests on each of two brands.
Results marked "*c*" are means of five or more tests on each of three brands.
Results not marked are means of five or more tests on each of four brands, two American, two German.
For compressive strengths of similar cubes, see Table 130.

It is seen that the modulus increases with the age and richness of the specimens, and decreases as the load increases. For one-two-four concrete the modulus at one month, for loads between a hundred and a thousand pounds, is about two and

[1] "Tests of Metals," 1899.

one-half million, and for six months, three and a half million. The corresponding values for the one-three-six concrete are two million and three and one-half million. When the ultimate strength is approached, the modulus of elasticity decreases rapidly, and between loads of one thousand and two thousand pounds per square inch, the richest concrete gives only about one and one-half and two and one-half million at one month and six months, respectively.

440. Modulus of Concrete Dependent on Richness of Mortar. — The results in Table 143 are abstracted from the extensive tests made at the Watertown Arsenal for the State Engineer of New York. Although several brands were tested, the results in the table are from one brand only, namely, "Wayland" Portland. These cubes were all stored in the same manner, namely, in water three to four months, and then buried in damp sand until broken at the age of twenty months. The mean ultimate strengths of similar cubes stored according to four methods are given in Table 132.

Since in all of these mixtures the quantity of mortar was a given percentage, either thirty-three or forty, of the volume of aggregate, the effect of the richness of the mortar may be studied. While the proportional strengths of the concretes made with mortars containing from one to five parts sand are 100, 77, 52, 44, and 38, the corresponding proportional moduli of elasticity are 100, 92, 77, 60, and 55, the modulus decreasing less rapidly than the strength, with the addition of sand.

441. Gravel and Trap Aggregates. — Table 144 gives the results of the determinations of the modulus of elasticity of concrete specimens made and tested at the Watertown Arsenal,[1] the strength of which was given in Table 134. As these are all rich concretes, the moduli and the strengths are high. The values of the modulus for the gravel concretes are about 70 per cent. of those for the trap, but the strengths of the gravel concretes are in general about 80 per cent. of those obtained with concretes having trap aggregate. In a general way, however, the modulus and strength vary together.

442. Modulus of Cinder Concrete. — The modulus of elasticity of cinder concrete prepared for the Eastern Expanded

[1] "Tests of Metals," 1898.

TABLE 143

Modulus of Elasticity of Concrete. Wayland Portland Cement

TESTS OF TWELVE-INCH CUBES AT WATERTOWN ARSENAL, FOR STATE ENGINEER OF NEW YORK

Volume Mortar as Per Cent. of Volume Aggregate.	Proportion Cement to Sand in Mortar.	1-1			1-2			1-3		1-4		1-5		Means.
	Consistency of Concrete.	Modulus of Elasticity in Thousands, between Loads, in Pounds per Square Inch, of												
		100-600	100-1000	1000-2000	100-600	100-1000	1000-2000	100-600	100-1000	100-600	100-1000	100-600	100-1000	
33	Moist Earth	2273	2143	1136	2083	1956	1136	2500	2045	1667	1304	1471	1500	1773
	Mason's . .	1667	1731	1087	2778	2250	1429	2083	1667	1250	. . .	1562	1046	1686
	Quaking . .	1786	1800	1087	2083	1800	. . .	1471	1452	1667	1500	1250	. . .	1590
40	Moist Earth	2778	2250	1087	2083	1875	1111	2083	1800	1316	1184	1389	1154	1676
	Mason's . .	4167	2500	1219	2273	2143	1562	1786	1500	1471	1184	1250	. . .	1914
	Quaking . .	2273	2045	1111	2500	1956	. . .	1667	1364	1562	1286	1316	1046	1648
Means. . .		2491	2078	1120	2300	1997	1310	1932	1638	1489	1304	1373	1186	1714

TABLE 144

Modulus of Elasticity of Rich Concretes with Gravel and Trap as Aggregates

TESTS OF TWELVE-INCH CUBES AT WATERTOWN ARSENAL. 1–1–3, ALPHA CEMENT

Character of Aggregate.	Modulus of Elasticity in Thousands, between Loads of 100 and 1,000 Pounds per Square Inch, at Age, Days,			
	7–8	19–23	29–34	61–76
Trap ½″	1875	2500	3750	3750
" ¾″	3214	2368	5625	. . . . .
" 1″	4091	6429	5625	5625
" 1½″	4500	5625	5000	4091
" 2½″	3214	5625	4500	7500
" ½″–1, 2½″–2	5000	4500	7500	5625
" ½″–1, 1″–1, 2½″–1 . .	3461	4500	5625	7500
Mean Results, trap rock alone	3622	4507	5375	5682
Pebbles ⅜″	1800	3750	3461	3214
" 1½″	3750	4091	3750	3000
" ⅜″–1, 1½″–2 . . .	2812	3461	4091	4500
" ⅛″–1, ⅜″–1, 1½″–1 .	1800	3214	3461	3214
Mean Results, pebbles alone	2540	3629	3691	3482

NOTES: —

Tests at Watertown Arsenal, "Tests of Metals," 1898.

For crushing strength of these concretes, see Table 134.

The modulus of elasticity of twelve-inch mortar cubes, one volume cement to one volume sand, was, for loads between five hundred and one thousand pounds per square inch, 3,461,000 at seven days and 5,000,000 at seventy-five days.

Metal Companies is given in Table 145. The results are seen to be low, as is the crushing strength. The permanent set in five-inch gaged length for a load of six hundred pounds per square inch is also shown in the table.

TABLE 145

Modulus of Elasticity of Cinder Concrete

Tests of Twelve-inch Cubes, Three Months Old, at Watertown Arsenal

Portland Cement, Brand.	Volume Proportions in Concrete.			Compressive Strength.	Modulus of Elasticity in Thousands, between Loads per Square Inch of			Permanent Set in Five Inch Length after Load of 600 Pounds per Square Inch.
	Cement.	Sand.	Cinders.	Pounds per Square Inch.	100 and 600.	100 and 1000.	1000 and 2000.	
A	1	1	3	2780	2500	2500	1429	0.0000
B	1	1	3	2368	4167	3214	1190	0.0000
B	1	1	3	2580	2083	1875	1351	0.0001
C	1	1	3	1877	1667	1552	. . .	0.0001
D	1	1	3	1879	2273	1875	. . .	0.0001
Mean	1	1	3	2207	2542	2203	. . .	0.0001
A	1	2	5	1715	1471	1286	. . .	0.0002
A	1	2	5	1402	1087	957	. . .	0.0008
B	1	2	5	1263	1087	865	. . .	0.0024
B	1	2	5	1200	1190	849	. . .	0.0009
C	1	2	5	917	735	. . .	. . .	0.0057
C	1	2	5	871	658	. . .	. . .	0.0113
Mean	1	2	5	1228	1038	. . .	. . .	0.0035

Note: — Tests for Eastern Expanded Metal Companies. "Tests of Metals," 1898.

CHAPTER XVII

THE TRANSVERSE STRENGTH AND OTHER PROPERTIES OF MORTAR AND CONCRETE

ART. 57. TRANSVERSE STRENGTH

443. TENSILE, TRANSVERSE AND COMPRESSIVE STRENGTHS OF MORTAR COMPARED. — The tests given in Tables 146 and 147 were designed to compare the strengths of cement mortars in tension, bending and compression, and to show the relative effect on the three kinds of strength of certain variations in manipulation.

The tensile specimens were briquets of the ordinary form, made in brass molds. The transverse and compressive specimens were made in wooden molds, the bars for transverse tests being two by two by eight inches and molded horizontally, while the specimens for compressive tests were two-inch cubes. Specimens of the three forms were made from the same batch of mortar to obviate, as far as possible, variations due to difference in gaging. Two cubes, two briquets and one bar were usually made from one gaging of mortar.

The briquets were broken in the usual manner on a Riehlé cement testing machine. The bars were broken on a home-made lever machine. Two fixed knife edges were placed five and one-third inches apart, and the breaking stress was applied through a third knife edge at mid-span. The lengths of the lever arms of the testing machine were in the ratio of one to twenty-five, and water was allowed to run gently into a vessel at the end of the longer arm. The span of five and one-third inches was chosen because at this length the modulus of rupture, for a two inch square specimen, has the same numerical value as the center load applied.

The cubes were crushed in a crude machine, improvised for the purpose, consisting of two iron plates, two hydraulic jacks, with hydraulic weighing gage and proper framework. The upper plate was fastened to the base of the framework by means of two bolts which worked freely in the lower plate, and the latter was connected to the weighing gage at the top of the framework by two bolts which worked freely in the upper plate. An hydraulic jack was placed under either end of a yoke, at the middle of which was supported the weighing gage. While the tensile and transverse tests are doubtless good, the compressive tests are lacking in accuracy because of the crude method of crushing.

444. Table 146 shows the comparative tensile, transverse and compressive strengths of two samples of cement, one of Portland and one of natural, with different proportions of sand. It is seen that the modulus of rupture, or stress on the extreme fiber in transverse tests, computed by the ordinary formula, is considerably greater than the strength obtained in direct tensile tests. The ratio of the transverse to the tensile strength varies from 1.25 to 1.90 for Portland and from 0.95 to 2.19 for natural.

These tests indicate that the ratio of the compressive strength to the tensile strength diminishes with the addition of sand, but the reverse has been found to be true in other series of tests where the facilities for making compressive tests were better. The result obtained here may be attributed to the fact that richer mixtures gave cubes with smoother and more regular faces, and thus less subject to eccentric loading. The compressive strength increases between three months and one year much more than the tensile and transverse strengths. Tests on ten brands of Portland and ten brands of natural showed that in general the brands giving the highest strength in tension gave also the highest strength in transverse and compressive tests.

445. A few results to show the effect of **consistency** of the mortar on the three kinds of strength are given in Table 147. With Portland cement the highest strength in transverse and compressive tests is given by a wetter mortar than that giving the highest strength in tension, but with natural cement the compressive strength is lowered more than the tensile strength by an excess of water. All of the specimens were one year old when broken.

446. TRANSVERSE TESTS OF CONCRETE BARS. — The effect on the strength of concrete of variations in manipulation and treatment is most satisfactorily investigated by tests of large

TABLE 146

Comparative Tensile, Transverse, and Compressive Tests. Varying Proportions of Sand

Ref.	Cement.	Age of Specimens.	Mean Strength, Pounds per Square Inch, for Varying Richness of Mortars, Parts Sand to One of Cement by Weight. Neat Cement.			One Part Sand.			Two Parts Sand.			Three Parts Sand.			Five Parts Sand.		
			Tens.	Trans.	Compr.	Tens.	Trans.	Compr.	Tens.	Trans.	Compr.	Tens.	Trans.	Compr.	Tens.	Trans.	Compr.
1	P	7 da.	588	1115	3453	484	607	2672	294	407	1420	182	247	695	. .	. . .	. . .
2	P	28 da.	698	1237	4617	630	915	3343	. .	. . .	. . .	277	397	1088	. .	. . .	. . .
3	P	3 mo.	733	1340	4447	705	1121	3250	491	764	1950	338	541	1245	187	286	520
4	P	1 yr.	. .	. . .	. . .	728	1185	5825	. .	. . .	. . .	379	582	1725	252	369	725
5	N	7 da.	136	237	940	90	145	505	64	78	340	. .	. . .	. . .	. .	. . .	. . .
6	N	28 da.	214	470	1834	. .	. . .	. . .	128	212	730	110	103	412	. .	. . .	. . .
7	N	3 mo.	285	515	2410	408	639	1813	319	465	1165	247	321	675	140	170	377
8	N	1 yr.	. .	. .	. . .	. .	. . .	. . .	313	472	1227	. .	. . .	. . .	143	224	415

NOTE: —Cement P. = Portland, Brand R ; N = Natural, Brand An; Sand, crushed quartz, passing No. 20, retained on No. 30 sieve.

sized specimens either in compression or bending. In the preparation of such large specimens the conditions of actual construction may be closely reproduced, and the results, although likely to be quite irregular, as the strength of concrete in structures is not uniform throughout, are nevertheless very valuable On account of the expense connected with such tests, the number of specimens is usually so limited that the natural irregularities in strength mask the true conclusions.

TABLE 147

Comparative Tensile, Transverse and Compressive Tests. Effect of Varying Consistency of Mortar

Ref.	Cement.	Water as Per Cent. of Dry Ingredients.	Mean Strength, Pounds per Square Inch.			Transverse and Compressive Strength as Per Cent. of Tensile.	
			Tensile.	Trans.	Comp.	Trans.	Comp.
1	P	9	516	837	1731	162	335
2	P	12	533	987	2173	185	408
3	P	15	467	850	2498	180	533
4	P	18	461	966	2823	209	612
5	P	21	430	1022	2487	239	578
6	N	12	272	447	2270	164	835
7	N	14	325	516	2141	158	659
8	N	16	319	519	1481	163	464
9	N	20	304	509	1512	167	497
10	N	24	315	462	1317	147	418

Notes: — Cement, P = Portland, Brand R; N = Natural, Brand In; Sand, "Point aux Pins," pass No. 10 sieve. Age of specimens, one year. Two parts sand to one cement by weight.

In Tables 148 to 156 are given some of the results obtained in testing over two hundred concrete bars at St. Marys Falls Canal. The molds for making the concrete bars were ten inches square by four and one-half feet long inside. The concrete was rammed into the mold with a light wooden rammer. The bars were, in general, covered with moist earth soon after completed, to await the time of breaking. To break them they were supported on knife edges placed four feet apart, and the load was applied at mid-span through an iron bolt laid across the bar. In the earlier tests a direct load was imposed by means of a platform which was gradually loaded with one-man stone, but in the later tests the load was applied by means of hydraulic jacks, an hydraulic gage being used to measure the force. In many cases the half bars were again broken at a later date with a twenty-inch span, as shown in the tables.

447. Variations in Richness of Mortar. — In Table 148 several concretes made with mortars having different proportions of sand are compared, and the results of briquet tests on similar mortars are also given. Although the briquets were not broken at the same age as the bars, the tests on the latter at the different ages show that they were not gaining strength rapidly, and the results may therefore be compared without serious error.

TABLE 148

Transverse Tests of Concrete. Variations in Richness of Mortar

No. Bars.	Date Made.	Cement.	Parts Sand to One Cement by Weight.	Strength of Mortar Briquets in Tension at Age of 3 Yrs. and 1 Mo.	Modulus of Rupture.					
					Four Foot Span.			Twenty Inch Span.		
					No. Tests.	Age.	Mean.	No. Tests.	Age.	Mean.
	Mo. Da.					Yr. Mo.			Yr. Mo.	
76-77	11-2	Port.	0	717	2	1 7	593	4	2 9	600
78-79	"	"	1	790	2	"	689	4	"	698
80-81	"	"	2	595	2	"	538	4	"	577
82-83	"	"	3	432	2	"	489	3	"	415
84-85	11-3	"	4	335	2	"	379	4	"	385
86-87	"	"	5	252	2	"	284	4	"	316
88-89	"	"	6	218	2	"	262	4	"	279
90-91	11-4	Nat.	1	483	2	"	420	4	"	450
92-93	"	"	2	396	2	"	332	4	"	387
94-95	"	"	3	330	2	"	240	4	"	224
96-97	"	"	4	237	2	"	186	4	"	205

NOTES: —

Portland, Brand R, Sample 82 M.

Natural, Brand Gn, Sample 83 T.

Sand, from "Point aux Pins" (river sand).

Stone, Potsdam sandstone, retained on ⅜ inch square mesh, and no pieces larger than 3 inches in one dimension.

Amount mortar used in each case equal to voids in stone measured loose, except in case 1-2 natural, when mortar exceeded voids by seven per cent.

The fracture showed concrete very compact in nearly all cases.

The results obtained with natural cement show that the tensile strength of the mortar in pounds per square inch was greater than the modulus of rupture obtained for the concrete.

This is also the case with rich mortars of Portland cement, but for Portland mortars containing more than three parts sand to one of cement the concrete gives the higher result. The strength of the concrete with one-to-four mortar is fifty-five per cent. of the strength with one-to-one mortar for Portland, and forty-five per cent. for natural. The decrease in strength due to larger proportions of sand in the mortar is usually greater than the decrease in cost.

TABLE 149

Transverse Tests of Concrete. Variations in Quantity of Mortar

No. Bar.	Date Made.	Am't Mortar Used as Per Cent. of Loose Stone.	Am't Rammed Concrete Made as Per Cent. of Loose Stone.	Modulus of Rupture.					
				Four Foot Span.			Twenty Inch Span.		
				No. Tests.	Age.	Mean.	No. Tests.	Age.	Mean.
	Mo. Da.							Yr. Mo.	
42	7 3	31	88	1	1 yr.	247	2	1 10	363
37–40	7 1	38	92	2	"	284	3	"	447
38–41	7 1	47	104	2	"	350	4	"	596
39–43	7 1,3	60	112	2	"	346	4	"	589

NOTES: —

Cement, Portland Brand R, Sample 64 T.

Sand, "Point aux Pins," three parts by weight dry to one cement.

Stone, Drummond Island limestone, passing 1 inch slits and retained on ⅜ inch slits.

448. Variations in Amount of Mortar Used. — Bars 37 to 43, Table 149, were all made with the same kind and quality of stone and the same quality of mortar, three parts sand to one cement by weight, but the amount of mortar varied; thus, in bars 41 and 38 sufficient mortar was used to fill the voids in the stone, while the bars above were deficient in mortar, and those below contained an excess. It is seen that the highest result is given by the bars in which the mortar was just sufficient to fill the voids in the stone, though the bars containing an excess of mortar gave practically the same result, while a deficiency of mortar resulted in decreased strength.

449. Variations in the Amount of Sand for Fixed Quantities of Cement and Stone. — In Table 150, bars 68 to 75 were all made with the same kind and quantity of cement and stone, but the amount of sand, and consequently the quantity and quality of the mortar, varied. The highest strength is given by the concrete in which the weight of the sand was three times the weight of the cement; this quantity of sand gave sufficient mortar to fill the voids in the stone. The richer mortars, though stronger, were deficient in quantity, while four parts sand made an excess of mortar having a lower strength.

TABLE 150

Transverse Tests of Concrete. Variations in Quantity of Sand for Fixed Quantities of Cement and Stone

No. Bar.	Cement, Pounds.	Dry Sand, Pounds.	Parts Sand to One Cement.	Amount of Mortar Made as Per Cent. of Compacted Stone.	Amount Rammed Concrete as Per Cent. Compacted Stone.	Modulus of Rupture. Four Foot Span. No. Tests.	Age.	Mean.	Twenty Inch Span. No. Tests.	Age.	Mean.	Remarks.
							Yr. Mo.			Yr. Mo.		
74–75	65	65	1	16	95	2	1 8	209	4	2 10	295	*a*
72–73	65	130	2	24	101	2	" "	335	4	" "	303	*b*
70–71	65	195	3	32	104	2	" "	324	4	" "	354	*c*
68–69	65	260	4	42	110	2	" "	322	4	" "	321	*d*

NOTES: —

Cement, Portland, Brand R, Sample 768.

Sand, " Point aux Pins."

Stone, Potsdam sandstone, screened with $\frac{3}{4}$ inch mesh, and all pieces larger than 3 inches in one dimension rejected.

Appearance of fracture: *a*, very porous; *b*, many voids; *c*, some voids; *d*, few voids.

450. Consistency of Concrete. — The bars, the results of which are given in Table 151, were made to show the effect of the consistency of the concrete on the strength obtained. It is seen that the highest strength is given when the consistency is such that a little moisture is shown when ramming is completed; the decrease in strength from an excess of water is much less than that caused by a corresponding deficiency. The results of briquet tests on similar mortar are also given in the table, and it appears that the highest result is given by the mortar containing the least water, which shows the familiar fact that the mortar for concrete should be more moist than that which gives the best results in briquet tests.

451. Value of Thorough Mixing. — Bars 182 to 189, Table 152, were made to show the effect of thorough mixing of the

TABLE 151

Transverse Tests of Concrete. Variations in Consistency

Bar.	Cement, Kind.	Proportions. Cement, Lbs.	Proportions. Sand, Lbs.	Water, Cu. Ft.	Amount Rammed Concrete Made, Cubic Feet.	Modulus of Rupture. 4 Foot Span, 13 Months. No. Tests.	Modulus of Rupture. 4 Foot Span, 13 Months. Mean.	Modulus of Rupture. 20 In. Span, 2 Years. No. Tests.	Modulus of Rupture. 20 In. Span, 2 Years. Mean.	Consistency.	Tensile Strength.
138–139	Port.	120	237	0.61	7.31	2	354	2	289	*a*	509
136–137	"	120	237	0.83	7.12	2	450	3	482	*b*	404
140–141	"	120	237	1.03	7.00	2	450	4	442	*c*	415
142–143	"	120	240	1.16	7.12	2	385	4	417	*d*	400
146–147	Nat.	115	230	0.83	7.64	2	180	4	156	*a*	267
144–145	"	115	230	1.03	7.31	2	223	4	282	*b*	187
148–149	"	115	230	1.16	7.12	2	234	4	256	*c*	145
150–151	"	115	230	1.35	7.12	2	202	4	177	*d*	127
152–153	"	115	230	1.51	7.12	2	155	3	170	*e*	116

NOTES: — Portland cement, Brand R, Sample M.
Natural cement, Brand Gn, Sample 88 T.
Sand, "Point aux Pins" (river sand).
Stone, Potsdam sandstone, 7 cubic feet to each batch.
Results in last column give tensile strength at one year of briquets made from similar mortar.

Consistency: — *a*, very dry; no moisture shown on ramming.
b, slight moisture appeared at surface after continued ramming.
c, quaked somewhat.
d, quaked and water rose to surface in ramming.
e, too wet to ram.

TABLE 152

Transverse Tests of Concrete Bars. Value of Thorough Mixing

No. Bar.	Mixing of Concrete.	Modulus of Rupture. Four Foot Span. No. Tests.	Four Foot Span. Age.	Four Foot Span. Mean.	Twenty Inch Span. No. Tests.	Twenty Inch Span. Age.	Twenty Inch Span. Mean.
182–186	Turned once and back	2	1 yr.	290	4	21½ mo.	373
183–187	" twice " "	2	"	294	4	"	353
184–188	" 3 times " "	2	"	308	4	"	444
185–189	" 4 " " "	2	"	328	4	"	474

NOTES: — Cement, Portland, Brand X, 200 lbs.
Sand, "Point aux Pins," 600 lbs.
Stone, Potsdam sandstone, 15 cubic feet.

concrete. Comparing the concrete turned once or twice, and back, with that turned three or four times, and back, it is seen that the mean strength of twelve tests with the former is 328 pounds per square inch, while the mean strength of the same number of tests with the more thoroughly mixed concrete is 388 pounds per square inch, an increase of eighteen per cent.

TABLE 153

Transverse Tests of Concrete. Variation in Size of Aggregate

No. Bar.	Cement Sample.	Stone.			Amount Compact Stone Used, Cubic Feet.	Amount Rammed Concrete Made, Cubic Feet.	Modulus of Rupture. Lbs. per Sq. In.	
		Kind.	Sizes.	Per Cent. Voids in Compact.			One Bar, 4 Ft. Span, Age 1 Yr.	Half Bar, 20 In. Span, Age, 21 Mo.
202	XR6	*a*	V	45	3.75	3.75	259	367
199	"	*a*	$\frac{1}{3}$ V, $\frac{2}{3}$ F	43	3.75	3.75	259	347
201	"	*a*	M	44	3.75	3.75	216	269
200	"	*a*	$\frac{1}{3}$ each, V, F, & M	40	3.75	3.75	245	292
198	"	*a*	$\frac{1}{4}$ each, K, V, F, & M	36	3.75	3.75	288	390
196	XM3	*d*	V	32	3.75	. . .	216	311
195	"	*d*	F	33	3.75	3.86	186	302
197	"	*d*	M	34	3.75	3.75	131	208
194	"	*d*	$\frac{1}{3}$ each, V, F, & M	30	. . .	. . .	207	302

NOTES: —

All mortar, three parts sand to one part Portland cement by weight.
Quantity of mortar about one-third volume of compact stone.
Stone: — a = Potsdam sandstone; d = gravel.
Size: — $K = \frac{1}{10}$ inch to $\frac{1}{4}$ inch.
$V = \frac{1}{4}$ " $\frac{1}{2}$ "
$F = \frac{1}{2}$ " 1 "
$M = 1$ " 2 "

452. Variations in Size of Stone and Volume of Voids. — The bars given in Table 153 were all made with mortar composed of three parts sand to one of Portland cement by weight. The stone for these bars was sorted into different sizes, and these were recombined in the proportions indicated in the table. The sizes are denoted as follows: that passing one-half inch mesh and retained on one-quarter inch mesh, is called V; one-half inch to one inch is called F; one inch to two inches, M; two inches to three inches, C; and coarse sand, one-tenth inch to one-quarter inch, is called K.

The first five bars were made with broken sandstone, and it is seen that the coarsest stone, size one inch to two inches, gave the lowest result. The size V, one-quarter inch to one-half inch, although containing no smaller percentage of voids, gave a much higher strength. The highest result was given by the bar made with a mixture of four sizes, the voids in this mixture being only thirty-six per cent.

The bars containing gravel as aggregate indicate that the strength decreases as the size of stone and volume of voids increase, but a mixture of three sizes gives nearly as good a result as the fine gravel alone. Comparing the results with similar sizes of the two kinds of aggregate, it appears that the broken sandstone gives somewhat better results than gravel, notwithstanding that the proportion of voids in the former exceeds that in the latter.

453. Sandstone and Bowlder Stone Compared. — The results given in Table 154 are from a series of tests made for the Michigan Lake Superior Power Company by Mr. H. von Schon, Chief Engineer,[1] and show the strength of concretes made with two kinds of aggregate available at Sault Ste. Marie. Two samples of Portland cement, one made from marl and one from limestone, a slag cement, and a natural cement, are used in these tests.

The two samples of Portland cement give nearly the same result, the slag less than half the strength, and the natural quite weak. The ratio of the strength obtained with crushed bowlders to that made with sandstone is about 1.6 with Portland, and the superiority of the former is shown with all cements.

454. Various Kinds of Aggregate. — Table 155 gives the results obtained at St. Marys Falls Canal in using various kinds of stone. In bars 25 to 30, three kinds of stone are compared. The superiority of the Kelleys Island Limestone "shavings" from the stone planers is evident. The shape of the pieces may have had a considerable influence on this result, the planer shavings being flat, or lenticular in form. Bar 34 was made with a hard limestone from Drummond Island, 33 with gravel, and 31 and 32 with gravel and stone mixed in equal propor-

[1] Tests reported by H. von Schon in Trans. A. S. C. E., Vol. xlii, p. 135.

TABLE 154

Transverse Strength of Concrete with Crushed Sandstone and Bowlders

Aggregate.	Mixture No.	Modulus of Rupture, Pounds per Square Inch.			
		Portland. (Marl.)	Portland. (Rock.)	Slag.	Natural.
Sandstone	1	328	312	122	43
"	2	283	265	161	34
"	3	220	178	118	40
"	4	178	173	74	. . .
"	5	106	186	131	35
Mean, Sandstone		223	223	121	38
Bowlder Stone .	1	407	397	145	36
" "	2	377	395	167	67
" "	3	332	374	176	55
" "	4	327	351	146	52
" "	5	333	325	123	60
Mean, Bowlder Stone		355	368	151	54
Ratio of Moduli { Bowlder Stone / Sandstone } . .		1.59	1.65	1.25	1.42

NOTES: — Cross breaking tests of 6 in. by 6 in. by 24 in. bars made for Michigan, Lake Superior Power Co.

Materials: — Cement, representative brands of each of four classes.
Sand, river sand, " Point aux Pins," mostly quartz, 96½ lbs. per cubic foot. Voids, 41.7 per cent. Fineness, 96 per cent. passing No. 20 sieve, 39 per cent. passing No. 40 sieve.
Stone, Sandstone, broken Potsdam 1 to 1½ inch size.
Bowlder stone, broken gneiss and granite bowlders, 1 to 1½ inch size.

Proportion in mortar, 1 part cement to 2.4 parts sand by volume.

Mixing: — Consistency, plastic; cement and sand mixed dry, then wet and mixed; mortar added to wet aggregate and concrete mixed by hand.

Storage: — Bars stored in shed, protected from rain, fully exposed to air. Age of specimens when broken, sixty days.

Mixture: — 1. Mortar 15 per cent. in excess of quantity required to fill voids.
2. Mortar 10 per cent. in excess of quantity required to fill voids.
3. Mortar 5 per cent. in excess of quantity required to fill voids.
4. Mortar just sufficient to fill voids in stone.
5. Mortar 15 per cent. in excess of amount required to fill voids in stone, but this 15 per cent. excess made with lime instead of cement.

TABLE 155

Transverse Tests of Concrete. Value of Different Kinds and Sizes of Aggregate

Bar.	Cement.		Aggregate.	Proportions.			Modulus of Rupture.					
							Four Foot Span.			Twenty Inch Span.		
	Kind.	Sample.		Cement, Lbs.	Sand, Lbs.	Stone, Loose. Cu. Ft.	No. Tests.	Age.	Mean.	No. Tests.	Age.	Mean.
25	Nat.	Gn55T	*a*	50	119	2.79	1	1 yr.	124	. . .	. . . .	. . .
26	"	"	*b*	"	"	"	1	"	150	. . .	. . . .	. . .
27	"	"	*c*	"	"	"	1	"	242	. . .	. . . .	. . .
28	"	"	*a*	"	144	"	1	"	94	. . .	. . . .	. . .
29	"	"	*b*	"	"	"	1	"	96	. . .	. . . .	. . .
30	"	"	*c*	"	"	"	1	"	204	. . .	. . . .	. . .
34	Port.	R63T	*b*	"	151	3.66	1	"	185	1	22 mo.	345
33	"	"	*d*	"	"	"	1	"	192	2	"	358
32	"	"	½*b*, ½*d*	"	"	"	1	"	239	2	"	408
31	"	"	½*a*, ½*d*	"	"	"	1	"	219	2	"	403
154–157	"	R87R	*e*	120	240	7.00	4	11 mo.	302	8	22–24 mo.	397
158–159	"	"	*c*	120	240	7.00	2	"	413	4	2 yr.	604

Aggregate: — *a* = Potsdam sandstone; size, ¾ inch to 1 inch.
b = Drummond Island limestone; size ⅜ inch to 3 inches.
c = Kelleys Island limestone; shavings from stone planers; size, ¼ inch to 3 inches.
d = Gravel.
e = Broken brick.

tions The gravel and hard limestone gave about the same result, but it is seen that the mixture gave a higher strength. Bars 154 to 159 were made to test the value of broken brick for use in concrete. It is seen that the strength obtained with brick is considerably lower than that obtained with the soft limestone. Had a poorer mortar been used, the brick would doubtless have given a better comparative result, since with the one-to-two mortar, the brick are not strong enough in themselves to utilize the full adhesive strength of the mortar.

TABLE 156

Transverse Tests of Concrete. Use of Screenings with Broken Stone

No. Bar.	Stone.		Sand and Stone to 80 Lbs. Cement.		Voids in Loose Stone, Cu. Ft.	Volume Mortar, Cu. Ft.	Modulus of Rupture.			
							Four Foot Span. Age, 11 Mos.		Twenty Inch Span. Age, 2 Yrs.	
	Character.	Per Cent. Voids in Loose.	Sand, Dry, Lbs.	Stone, Loose, Cu. Ft.			No. Tests.	Mean.	No. Tests.	Mean.
114–115	*a*	49	240	7.0	3.43	3.05	2	233	4	237
124–125	*b*	48.4	243	7.0	3.39	3.05	2	196	4	210
112–113	*c*	44	240	7.0	3.08	. . .	2	194	3	236
116–117	*d*	44	138	7.8	3.43	2.16	2	227	3	311
118–119	*e*	40.5	243	7.0	2.83	3.10	2	201	4	219
120–121	*f*	38.8	243	7.0	2.72	3.05	2	122	4	164
122	*g*	. . .	243	7.0	. . .	3.05	1	130	2	141

Notes: —

Cement: Natural, Brand Gn, Sample 92 T, 80 lbs.

Stone: — *a* = Drummond Island limestone, screened.

b = 10 parts screenings to 100 parts stone.

c = 17 parts screenings to 100 parts stone.

d = 17 parts screenings to 100 parts stone. Screenings replacing equal amount sand.

e = 50 parts screenings to 100 parts stone.

f = 100 parts screenings to 100 parts stone.

g = Screenings only, no broken stone.

455. Use of Screenings with Broken Stone. — Table 156 gives the results of a number of tests made to show the effect of mixing screenings with the broken stone. A smaller amount of mortar is required to fill the voids in a given volume of stone and screenings mixed than is required for the same volume of stone. It is seen that, with natural cement, when the same volume of mortar is used in the two cases, the presence of screenings to the amount of one-third of the total aggregate does not make a material change in the strength of the resulting concrete, but when the screenings are allowed to take the place of a part of the sand in the mortar, as in bars 116 and 117, a much stronger concrete results. Natural cement mixed with sand and screenings alone, bar 122, does not make a strong concrete, but Portland cement with screenings without sand was found to give excellent results.

456. Deposition in Running Water. — A few tests were made to show the effect of depositing concrete in rapidly running water. The molds were placed in the stream and weighted down in twelve inches of water. The concrete for two bars was deposited as soon as mixed, that for two other bars was allowed to stand in the air three hours before deposition, until it should have acquired an initial set, and two bars were made after the mortar had been allowed to stand five hours and twenty minutes before deposition; by this time the mortar had set quite hard. No attempt was made to ram the concrete, which was deposited by lowering it carefully into the water with shovels, the molds being filled as rapidly as possible. A very large amount of the cement was washed out by the current in all cases. After a few months the bars were removed from the stream and covered with earth as usual. The tests at eleven months did not appear to show any advantage in allowing the mortar to stand some time before deposition, but the tests at two years showed a distinct advantage in this treatment.

457. Use of Concrete in Freezing Weather. — Table 157 gives the results obtained with Portland cement concrete made in the open air during cold weather. The conditions as to temperatures and the character of the materials are fully given in the table. The experiments are too limited to permit of drawing definite conclusions, but the following points are indicated by the results obtained. The use of warm water, 100° to 156° Fahr., in freezing weather appears to give somewhat better results than cold water. Salt should not be used unless the temperature is below the freezing point, but in very cold weather the use of enough salt in the water to lower its freezing point below the temperature of the air seems to hasten the harden-

TABLE 157

Transverse Tests of Concrete Bars. Use of Concrete in Low Temperatures

Date Made.	Proportions in Concrete.				Temperatures. Deg. Fahr.		Per Cent. Salt in Water.	No. Tests.	Age.	Modulus Rupture.		Remarks.
	Cement, Lbs.	Sand, Lbs.	Stone Loose, Cu. Ft.	Water, Cu. Ft.	Air When Moulded.	Water Used.				4 ft. Span.	20 in. Span.	
Mo. Da. Yr.									Mos.			
2 12 94	135	270	7.32	0.90	9	40	. . .	1 1	16 30	202	188	*a* *a*
" " "	"	"	"	"	8	100	. . .	1 2	16 30	245	224	*b* *b*
" " "	"	"	"	0.84	12	156	. . .	1 2	16 30	227	242	*c* *c*
2 13 94	"	"	"	0.84	3	40	. . .	1 1	16 30	223	318	*d* *d*
" " "	"	"	"	. . .	12	44	12.5	1 2	16 30	273	419	*e* *e*
" " "	"	"	"	. . .	9	40	18.75	1 2	16 30	351	333	*e* *e*
11 12 94	120	240	7.00	0.80	27	. . .	. . .	2 4	10 20	332	351	. . .
" " "	"	"	"	"	27	. . .	10	2 1	10 20	326	417	. . .
12 6 94	"	"	"	0.74	27	34	. . .	2 3	9 20	433	559	. . .
" " "	"	"	"	0.68	35	35	10	2 4	9 22	386	517	. . .
12 13 94	"	"	"	"	33	37	. . .	2 3	9 22	447	570	. . .
" " "	"	"	"	"	34	40	10	2 3	9 22	385	429	. . .
1 5 95	"	"	"	0.74	14	32	. . .	2 1	8 21	(82)	487	*f*
" " "	"	"	"	0.68	18	40	14	2 4	8 21	311	460	. . .
3 9 95	60	120	3.5	0.33	12	. . .	. . .	1 2	19 26	206	238	. . .
" " "	"	"	"	"	15	. . .	5	1 2	19 26	301	380	. . .
" " "	"	"	"	"	20	. . .	12	1 2	19 26	376	451	. . .
" " "	"	"	"	"	27	165	12	1 2	19 26	288	458	. . .

Remarks: —

a, Concrete frozen after 10 to 20 min.; *b*, frozen in 45 min.; *c*, began to freeze in 15 min.; *d*, frozen hard following morning after molding; *e*, concrete still soft 9 A.M. morning after molding; *f*, bar defective.

Notes: — Cement, Portland, Br. R. Sand, "Point aux Pins." Stone, Potsdam sandstone.

ing as well as to increase the ultimate strength. (For tests of mortars in freezing weather, see Art. 50.)

Art. 58. Resistance to Shear and Abrasion

458. Shearing Strength. — The shearing strength of mortars and concretes is of importance not only because of its intimate relation to the compressive strength, but because of the shearing stresses to which these materials are subjected in structures reinforced with steel. But few tests of shearing strength have been made, however, partly because of the lack of appreciation of their value, and partly because it is difficult to subject a specimen to a purely shearing stress. It is frequently stated that the shearing strength is somewhat in excess of the tensile strength, perhaps as much as twenty per cent.

Table 158 gives the results of a series of tests made by Prof. Bauschinger in 1878.[1] The values in shear are very closely twenty per cent. in excess of the tensile strengths of similar mortars tested at the same time.

TABLE 158

Shearing Strength of Portland Cement Mortar Cubes Hardened in Air

Cement.	Number Parts Sand to One Cement.	Shearing Strength, Pounds per Square Inch. Age of Mortar.				Tensile Strength of Similar Mortars at Eight Weeks.
		1 week.	2 weeks.	4 weeks.	8 weeks.	
Quick setting Portland, mean results of four brands.	None	225	270	257	259	210
	3	108	128	154	196	169
	5	67	94	112	168	139
Slow setting Portland, mean results of four brands.	None	301	323	341	377	256
	3	124	164	199	237	181
	5	78	122	138	199	169

Note: — Cement, each result mean of four brands. Sand, medium grain, clean. Mortars hardened in dry air.
Tests by Professor Bauschinger, 1878.

459. A distinction should be drawn between the resistance offered by a thin mortar bed to the sliding of one stone or brick on another and to shear of the mortar itself. The former re-

[1] Quoted by Mr. Emil Knichling in a Report on Cement Mortars.

sistance involves the adhesion of the mortar to the surface of the brick or stone, and the values for this resistance are usually much less than the shearing strength, and not greatly in excess of the adhesive strength. The one is of importance in the determination of the stability of masonry dams, retaining walls, etc., but the latter is the resistance in question in the design of monolithic concrete structures.

460. Resistance to Abrasion. — The resistance of cement mortar to abrasion depends on the quality of the sand as well as the cement. The abraiding surface wears away the cement or pulls the particles of sand out of their beds in the cement matrix. If the adhesion to the sand grains is strong, the sand particles receive the wear and withstand it until nearly worn away. With hard sand particles, therefore, the resistance to abrasion should increase as the proportion of sand increases, until the volume of the cement matrix becomes relatively too small to thoroughly bind the sand grains together. This limit is reached, however, when the mortar contains not more than two parts sand. With soft sand grains, the neat cement will usually give the highest resistance to abrasion, at least in the case of Portland. It has been found that specimens hardened in the air are brittle and wear more rapidly than those hardened in water.

461. Table 159 gives the results of several tests made to determine the relative wearing qualities of different mortars for such uses as sidewalk construction. The specimens were two-inch cubes, hardened in water and dried for a few hours just before grinding. An emery plate, set horizontally, was used in most of the tests. The results in any given line of the table are comparable, but, owing to changes in the grinding plate and in the methods used, the results in different lines are not all intercomparable. It is seen that when soft sand is used, such as limestone screenings, the greatest resistance to abrasion is offered by the neat cement mortar, and the resistance decreases constantly as the amount of sand is increased. When hard sand, such as the siliceous river sand, from Point aux Pins ("P.P." in the table) is employed, the greatest resistance is offered by mortars containing about equal parts of sand and cement. A comparison of lines 5 and 10 indicates that rich natural cement mortars lose about twice as much as similar mortars of Portland, but natural cement mortars containing

TABLE 159
Abrasive Tests of Cement Mortars

Ref.	Cement.			Sand used in Mortar, Kind and Fineness.	Grinding.				Age of Specimen.	No. of Specimens of each Proportion.	Loss of Weight of Specimen in Grams per Sq. In. of Surface Subjected to Abrasion. Parts Sand to One Cement by Weight.									
	Portland or Natural.	Brand.	Sample.		Kind of Plate.	Crushed Quartz used on plate, Total Amt. Grams.	No. Rev. Plate.	Pressure per Sq. In. on Specimen, Lbs.			0	½	1	1¼	1½	1¾	2	2¼	2½	3
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*	*t*
1	P.	R	PP.	P.P. pass No. 10	C. Iron	60	180	8	21 da.	2	5.2	3.4	2.8	3.2	3.7	4.2	4.7	4.1	5.3	5.9
2	"	Z	43S	" "	Emery	none	60	4	"	2	1.4	1.3	0.9	0.9	1.0	3.6	9.1	14.5	20.0	35.6
3	"	X	41S	Limest. Scr. pass No. 4 Si.	"	"	60	4	"	2	1.7	2.4	2.8	2.9	3.7	4.2	4.9	4.4	4.9	5.6
4	"	X	41S	Limest. Scr. pass No. 10 Si.	"	"	60	4	"	2	2.6	4.4	5.2	6.0	5.9	6.0	6.5	7.1	7.1	7.6
5	"	R	PP.	P.P. pass 10	"	20	60	8	3 mo.	2	1.8	0.8	0.9	1.1	1.3	1.2	1.7	1.6	2.2	3.5
6	"	Z	43S	" "	"	none	60	8	"	4	0.7	0.4	0.4	0.4	0.4	0.9	2.5	2.8	2.7	21.0
7	"	X	41S	Limestone Scr. pass 4	"	20	60	8	"	4	1.5	2.7	3.8	4.3	5.6	5.7	5.7	6.0	6.6	8.2
8	"	X	41S	Limestone Scr. pass 10	"	20	60	8	"	4	2.2	4.5	6.0	7.2	8.0	. .	8.4	8.6	7.6	7.6
9	N.	An	. .	P.P. pass 10	"	none	30	4	21 da.	1	5.7	5.4	8.2	10.5	11.1	19.1	23.5	29.0	33.1	42.6
10	"	An	. .	" "	"	20	60	8	3 mo.	4	3.6	1.9	1.4	1.7	2.4	3.1	3.0	4.0	8.0	12.4

more than two parts by weight of sand do not give relatively as good results.

ART. 59. THE EXPANSION AND CONTRACTION OF CEMENT MORTAR, AND THE RESISTANCE OF CONCRETE TO FIRE

462. Change in Volume during Setting. — Cement mixtures shrink somewhat when hardened in air, while specimens stored in water expand a trifle during hardening. Although several experiments have been made on this subject the specimens used have been so small that the results obtained by various authorities do not agree, and the effect of variations in the character of the mixtures has not been thoroughly investigated. The importance of the question is found in the necessity of providing expansion joints in long walls or sheets, and in the effect of such changes in volume in producing initial stresses in concrete or steel where these materials are used in combination.

Certain general conclusions are well established and may be stated as follows: 1st. The shrinkage of mortar and concrete hardening in air is considerably greater than the expansion of similar specimens hardening in water; 2d. The amount of change in volume increases with the proportion of cement used in the mixture; 3d. The change in volume is continuous up to one year, but about one half of the change occurs in the first week, and it is very slow after 3 to 6 months.

The following values of the change in linear dimensions are derived from the results of several experimenters, and show in a general way what changes are to be expected at the end of three months.[1] Variations in the character of the cement and the consistency of the mortar will affect the result.

COMPOSITION: PARTS SAND TO ONE PORTLAND CEMENT.	SHRINKAGE OF MORTARS HARDENED IN AIR.	EXPANSION OF MORTARS HARDENED IN WATER.
	CHANGE IN LINEAR DIMENSIONS, ONE UNIT IN	
Neat cement	300 to 800	500 to 2000
One part sand	600 to 1200	1200 to 3000
Three parts sand . . .	700 to 1200	3000 to 5000

[1] For more detailed results the reader is referred to the following authorities: — Dr. Tomëi, Trans. A. S. C. E., Vol. xxx, p. 16. Mr. John Grant, Proc. Inst. C. E., Vol. lxii, p. 108. Prof. Bauschinger, Trans. A. S. C. E. Vol. xv, p. 722.

463. The Coefficient of Expansion of Cement and Concrete. — Concerning the coefficient of expansion of cement mortars of various compositions, we know but little. The result obtained by M. Bonniceau, giving the coefficient of neat Portland cement as about .000006 per degree Fahr., is frequently quoted. This is very nearly the value for iron and steel, and has formed a theoretical basis for combining these materials. In the case of cement mortars and concretes, however, it is highly probable that the coefficient follows quite closely the behavior of the sand and stone used in the mixture, and is much less dependent upon the coefficient of the cement. This was indicated by the results of M. Bonniceau who obtained a value of about .000008 for concrete.

464. A number of experiments to determine the coefficient of expansion of cement concretes were carried out under the direction of Prof. Wm. D. Pence by students of Purdue University.[1] As a mean of seven tests with one-two-four concrete of Bedford oölitic and Kankakee limestones combined with Portland cements of two well-known brands, the mean result for the coefficient was .0000055, the lowest result being .0000052, and the highest result .0000057. The coefficient of a bar cut from the Kankakee limestone was .0000056, the same result as obtained from the mean of three tests of concrete containing broken stone of this variety.

The average result of four tests of gravel concrete composed of one part Portland cement, two parts sand and four parts screened gravel, or one part Portland cement to five parts unscreened gravel, gave .0000054 as the coefficient of expansion.

These values differ from the coefficient of steel enough to indicate that in positions where the range in temperature is great, the resulting stresses in the concrete and steel may be considerable, and worthy of attention.

465. THE FIRE-RESISTING QUALITIES OF CONCRETE. — The value of concrete as a material to be used in the construction of the walls and floors of buildings, is largely dependent on its fire-resisting qualities. That its use for such purposes is rapidly extending, is some evidence that these qualities are

[1] Paper read before the Western Society of Engineers, *Engineering News*, Nov. 21, 1901.

as satisfactory as in other classes of materials devoted to the same use.

Under favorable circumstances, a fire in a building filled with combustible materials may reach a temperature of 2,000° to 2,300° Fahr. If a small specimen of cement mortar or concrete is subjected to a temperature approaching this intensity, the cement loses its water of crystallization and becomes friable. If cooled suddenly in water, the specimen cracks and disintegrates. If cooled gradually, the outer edge of the specimen crumbles away. From such tests on small specimens some very erroneous conclusions have been drawn as to the value of concrete as a fire-resisting material. Such conclusions have done much to prejudice the public mind against concrete, and to retard its introduction in buildings designed to be fireproof.

466. Conductivity. — The great value of concrete as a fire resistant is due to its low conductivity of heat, and while the surface of a mass of concrete exposed to an intense flame for some time is ruined, and may be flaked off by the application of a strong stream of water from a fire hose, the depth to which the heat penetrates is very limited. Steel is said to lose ten per cent. of its strength at about 600° Fahr. and fifty per cent. at about 750° Fahr. The importance of protecting the steel framework of a building, not only from warping and complete destruction due to flames, but from loss of strength from overheating, is therefore evident.

Among engineers and architects it is recognized that the term "fireproof construction" is only relative, although the lay mind is apt to give a definite and literal meaning to the term. It is well known that fireproofing tile, whether hard or porous, will fall to pieces if subjected to a temperature above that employed in its manufacture. The practical question then is, what type of construction will withstand long continued intense flame, and subsequent quenching with water, with the least injury to the strength of the structure. The results of fire tests that have been conducted in several places, and notably those made by the Department of Buildings of New York City, have shown that floor arches properly constructed of concrete-steel are equal to any style of floor with which they come in competition.

The low conductivity of concrete is shown by the fact, stated by Mr. Howard Constable in connection with the discussion of fire tests of concrete floor arches,[1] "that in some thirty-five cases where the temperature ranged from 1,500 to 2,400 degrees, the time of exposure being from one to six hours, the temperature of the upper flanges of six-inch to ten-inch beams might be approximately placed at not much above 200 degrees." He also says "in one case, where the beam was protected by three inches of concrete, the fire was maintained for five hours, and the temperature went as high as 2,300 degrees, and there was no practical or permanent set produced in the beams."

467. Behavior in Conflagrations. — As to the behavior of concrete-steel arches in an actual fire, a board of experts was appointed by the insurance companies to investigate the causes and extent of damage to the fireproof buildings in the Pittsburg, Pa., fire of May 3, 1897. This board stated in their report that they believed that in important structures of this class "the fireproofing should be in itself strong and able to resist severe shocks, and should if possible, be able to prevent the expansion of the steel work"; and continued, "There seems to be but one material that is now known that could be utilized to accomplish these results, and that is first-class concrete. The fire-resisting qualities of properly made concrete have been amply proven to be equal, if not better than fire clay tile, as shown by the tests carried on by the Building Department of the City of New York."

468. In a report on the Baltimore fire, Captain Sewall,[2] Corps of Engineers, U. S. A., says concrete "undergoes more or less molecular change in fire; subject to some spalling. Molecular change very slow. Calcined material does not spall off badly, except at exposed square corners. Efficiency on the whole is high. Preferable to commercial hollow tiles for both floor arches or slabs and column and girder coverings. In form of reinforced concrete columns, beams, girders and floor slabs, at least as desirable as steel work protected with the best commercial hollow tiles. Stone concrete spalls worse than any

[1] Trans. A. S. C. E., Vol. xxxix, p. 149.

[2] Report to the Chief of Engineers, U. S. A., by Capt. John Stephen Sewall, Corps of Engineers. Published in *Engineering News*, March 24, 1904.

other kind, because the pieces of stone contain air and moisture cavities, and the contents of these rupture the stone when hot. Gravel is stone that has had most of these cavities eliminated by splitting through them, during long ages of exposure to the weather. It is therefore better for fire-resisting concrete than stone. Broken bricks, broken slag, ashes and clinker all make good fire-resisting concrete. Cinders containing much partly burned coal are unsafe, because these particles actually burn out and weaken the concrete. Locomotive cinders kill the cement, besides being combustible. On the whole, cinder concrete is safe only when subjected to the most rigid and intelligent supervision; when made properly, of proper materials, however, it is doubtful whether even brickwork is much superior to it in fire-resisting qualities, and nothing is superior to it in lightness, other things being equal."

469. Aggregate for Fireproof Work. — Since air is a poor conductor of heat, the more porous concretes are the better protectors against fire. On this account, as well as because of its lightness, cinder concrete is preferred for fireproofing. Care should be taken that cinders to be used in fireproofing concrete do not contain any appreciable amount of unburned coal; in concrete to be used next to steel members the cinders should also be practically free from iron rust. (See § 473.)

The strength of cinder concrete is much inferior to that made with the ordinary aggregates, and there should be no difficulty in making a porous concrete with the latter. In fact, in many other classes of construction it has been seen that great precautions must be taken to avoid porosity. By the use of insufficient mortar to fill the voids in the stone, voids may be left in the concrete, though at the expense of diminishing somewhat the strength of the mixture. In adopting such an expedient one should not lose sight of the fact that in order to preserve the imbedded steel from corrosion, it must be fully covered with the mortar.

470. Broken bricks are excellent for fireproofing concrete. The bricks themselves are fire resistant, porous and light, while the adhesion of cement mortar to bricks is so great that unless a very weak mortar is used, the strength of the concrete is limited only by the strength of the brick employed.

Sandstones, especially those with siliceous cementing material, are also well adapted for this purpose. Limestone, on account of the low temperature at which it is broken up, is not good, though as to just how far a limestone concrete would be disintegrated by the heat of an ordinary building fire has not, so far as the author knows, been fully investigated. It is known, however, that limestone masonry is calcined to a certain depth in a conflagration.

Granite in large pieces is cracked by only a moderate degree of heat, and spalls badly. Just how much danger there might be of a similar action in concrete aggregates of this material is not known, nor whether small pebbles or fine gravel would have this property in the same degree, though it is believed they would not, and this view has been confirmed by observations of the Baltimore ruins.

Before adopting a given aggregate for fireproof work, one should satisfy himself by actual test as to the suitability of the materials available, but such tests should be conducted upon concretes containing the proposed aggregates, rather than upon fragments of the materials not incorporated with mortar.

Art. 60. The Preservation of Iron and Steel by Mortar and Concrete

471. The rusting of steel members in modern buildings and other engineering structures is one of the most serious menaces to their permanence. The introduction of concrete-steel construction has given rise to some discussion, especially among those unfamiliar with the properties of concrete, as to the effect of the concrete upon the steel.

472. Action of Corrosion. — The rusting of iron takes place only in the presence of moisture, air and carbon dioxide. In perfectly dry air, or in perfectly pure water, iron does not rust. Under the proper conditions, however, the iron, water and carbonic acid combine to form ferrous carbonate, which at once combines with oxygen from the air to form ferric oxide, the carbonic acid being liberated to act on a fresh portion of the metal. It is seen that only a very small amount of the carbon dioxide is necessary. If, however, the carbon dioxide or other acid filling the same rôle, is neutralized by the presence of an alkaline substance, the foregoing reactions cannot take place. As cement is strongly alkaline, it thus furnishes an almost perfect protection against rusting.

473. Tests of Effect of Concrete on Corrosion of Metal. — To determine the cause of occasional rusting of steel surrounded by cinder concrete, and consequently the proper methods of applying cement mortar or concrete to steel, Prof. Chas. L. Norton, engineer in charge of the Insurance Engineering Experiment Station at Boston, made tests on several hundred briquets in which steel was imbedded in mortars and concretes of various compositions.[1] The briquets were subjected to air, steam and carbon dioxide, others to air and steam, to air and carbon dioxide and to the ordinarily dry air of a room. At the end of three weeks it was found that neat Portland cement had furnished a perfect protection in all cases. The corrosion of the steel in other specimens was always at a point where a void existed in the concrete, or where a badly rusted cinder had lain. In every case where the concrete or mortar had been mixed wet, and the surface of the steel had been thus coated with a thin layer of grout, no rust spots occurred.

In the first tests made by Professor Norton the specimens were thoroughly cleaned before being imbedded in the concrete, but later tests indicated that in specimens that had begun to corrode before treatment, the rusting was arrested by the coating of cement mortar or concrete. After from one to three months in tanks holding steam and carbon dioxide, specimens which had been in all stages of corrosion before being imbedded in the concrete had not suffered any sensible change in weight or size except when the concrete had been poorly applied.

474. The results of these experiments showed that the steel need not necessarily be freed from rust before being imbedded in the concrete; that the concrete to be applied next the steel should be mixed wet, or that the steel should be first coated with grout by dipping or brushing; and it appeared that the rusting sometimes found in cinder concrete is due to the rust in the cinders rather than to the sulphur, and that if proper precautions are taken, cinder concrete is nearly as effective as stone concrete in preventing corrosion. Prof. Norton says, "In the matter of paints for steel there is a wide difference of opinion. I cannot believe that any of the paints of which I have

[1] Report III of Insurance Engineering Exp. Station, Boston, Mass.

any knowledge can compare with a wash or painting with cement."

475. Sulphur in Cinders. — The conclusions drawn by Booth, Garrett and Blair from a series of tests made for the Roebling Construction Co., were that cinders from anthracite pea coal contained about two-tenths per cent. of sulphur which they considered sufficient to cause corrosion of unprotected iron-work, more or less rapidly, depending on the presence or absence of moisture; but they further concluded that a "full" concrete (one in which the voids in the cinders were entirely filled by mortar of cement and sand) would fully protect the steel.

In a paper read before the Associated Expanded Metal Companies, Prof. S. B. Newberry has this to say concerning cinder concrete: [1] "The fear has sometimes been expressed that cinder concrete would prove injurious to iron, on account of the sulphur contained in the cinders. The amount of this sulphur is, however, extremely small. Not finding any definite figures on this point, I determined the sulphur contained in an average sample of cinders from Pittsburg coal. The coal in its raw state contains rather a high percentage of sulphur, about fifteen per cent. The cinders proved to contain only 0.6 per cent. sulphur. This amount is quite insignificant, and even if all oxidized to sulphuric acid, it would at once be taken up and neutralized in concrete by the cement present, and could by no possibility attack the iron."

476. Precautions. — While so far as the corrosion of steel is concerned, the above experiments by Prof. Norton show that the rusting is corrected by the concrete, yet it is quite possible that the adhesion of cement to steel may be impaired by a coating of rust. The cleaning of the steel may be accomplished by first brushing with wire brushes to remove all scales, followed by treatment with hot dilute sulphuric acid, and finally applying an alkaline wash such as hot milk of lime to neutralize all traces of the acid. Oxalic acid may be used in place of the sulphuric, and the application of the milk of lime dispensed with, since the acid oxidizes. The crystals of oxalic acid as purchased commercially should be mixed with about seven parts hot water and the solution applied with a brush or sponge. When the

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[1] *Engineering News*, Apr. 24, 1902.

adhesion of the mortar or concrete to the steel is of any importance, as it is in all concrete-steel construction where the stresses are divided between the steel and concrete, any of the ordinary oil paints will not only be quite unnecessary, but may be a very serious detriment to the construction.

The experiments quoted indicate the importance of having the steel covered with an unbroken coating of cement or cement mortar. To insure this the steel must either be coated with a layer, preferably of neat Portland, by dipping or brushing, or the mortar placed next the steel must be wet enough to insure intimate contact throughout. It may be added also, that the addition of a small amount of thoroughly slaked lime to Portland cement mortar or concrete will not only render the material more alkaline, but will make the mortar more plastic, and thus insure a better coating of the steel. Such small additions have no deleterious effect on the mortar.

477. Practical instances of the preservation of iron by concrete are not wanting. The writer has stored in water, briquets with small iron plates imbedded in Portland cement mortar, and at the end of six months the plates were found moist, but entirely free from corrosion except where they projected beyond the mortar. A concrete-steel water main built on the Monier system at Grenoble, France, was taken out and examined after fifteen years service in damp ground. The metal imbedded in the mortar showed no signs of corrosion, and the mortar could only be detached from it by hammering.

Mr. W. G. Triest [1] relates that in breaking up cast-iron, concrete-filled pillars, a wrench was found that had been buried in the concrete for twenty-two years. The wrench had maintained its metallic surface in the concrete, while a part of it that had been imbedded in coal ashes had corroded badly.

Similar instances showing the action of concrete on steel and iron might be multiplied, but it is sufficient to state that the preservation of iron or steel properly imbedded in Portland cement mortar or concrete is now seldom questioned, and the use of cement paint, in place of the ordinary oil paints, as a steel preservative, has been adopted in many places.

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[1] Trans. A. S. C. E., April, 1894.

ART. 61. POROSITY AND PERMEABILITY; EFFLORESCENCE; POINTING; USE IN SEA WATER

478. The porosity and permeability of mortars have been thoroughly investigated by M. Paul Alexandre, who has published his results in "*Recherches Experimentales Sur Les Mortiers Hydrauliques.*"[1] The results and conclusion in the following notes on the subject are largely a resumé of the systematic investigation made by M. Alexandre.

The two qualities, porosity and permeability, should not be confused, nor should it be thought that a porous mortar is always very permeable, or that a permeable mortar must of necessity be very porous. Porosity is measured by the amount of water which will be absorbed by a specimen after drying, while permeability is measured by the amount of water which will pass through a specimen in a given time under certain defined conditions of thickness, water pressure and area of face.

479. Porosity. — The porosity of mortars is due to, and in fact is measured by, the volume of the voids contained. These voids may be divided into three classes, according to the causes to which they may be attributed, as follows: 1st, apparent voids, due to the mortar not being properly compacted; 2d, latent voids, due to the imprisonment of air in the mortar when made; and 3d, voids resulting from the evaporation, during hardening, of a portion of the water used in gaging.

480. Apparent voids may occur as the result of using insufficient cement to fill the voids in the sand, or, in the case of concretes, insufficient mortar to fill the voids in the aggregate. They may also be due to improper manipulation as to tamping, or improper mixing, giving an excess of matrix in one place and a deficiency in another. It was found by experiment that mortars made with coarse sand had the largest volume of apparent voids.

It has been shown elsewhere that if dry sand be moistened and agitated, the bulk of the sand is increased. This is caused partially by the imprisonment of air bubbles in the mass, and if a measure of sand so treated is filled with water, the bubbles will rise to the surface on jarring the vessel. Latent voids in mortar are due to a similar action, and hardened mortars con-

[1] *Extrait des Annales des Ponts et Chaussées*, September, 1890.

taining such voids refuse to absorb water to replace the air bubbles, at least for a long time.

481. A portion of the water used in mixing mortar enters into chemical combination with the cement, another portion is absorbed by the sand grains, and a third portion goes to moisten the sand. The quantity absorbed by the grains depends upon the character of the sand, and the amount required to moisten the sand depends upon the superficial area of the grains in a given volume, being greatest for fine sands and least for coarse ones. At least one fourth of the water ordinarily used in mixing neat cement is given off later, if the hardened mortar is allowed to remain in dry air. The water required to moisten the sand, and at least a part of that absorbed by the sand grains, also dries out, leaving voids of the third class mentioned.

The apparent voids may be reduced to a very small percentage by care in the proportions and preparation of the mortar. The latent voids may amount to six or seven per cent. of the total volume. The evaporation of water may leave from six to eighteen per cent. of voids in the mass.

482. The **conclusions** drawn from M. Alexandre's experiments are briefly as follows: The porosity varies between wide limits according to the fineness of the sand and the richness of the mortar. It may be as low as thirteen per cent. and may exceed thirty-one per cent.

With sand of the same degree of fineness, the porosity diminishes as the proportion of cement in the mortar increases.

With the same quantity of cement per volume of sand, the porosity increases with the fineness of the sand. This is especially marked in rich mortars, where the increase in porosity may reach 50 to 100 per cent., while in lean mortars the use of a fine sand may not increase the percentage of voids more than 20 per cent.

The least porous mortars are those rich in cement and made with coarse sand. Mortars made with fine sand are relatively very porous, even when made rich with cement.

Mortars gaged dry are more porous than those of ordinary consistency, and mortars gaged wet are also likely to be more porous, unless the manipulation is such as to allow the excess water to rise to the surface of the mortar.

483. Permeability — The degree of permeability of mortars is a more important property than the porosity, since not only does it affect the suitability of the mortar for certain uses, but the life of the structure may depend upon the difficulty with which water may percolate the mass.

The permeability of mortar decreases as the proportion of cement is augmented, and in the case of concretes the permeability diminishes as the percentage of mortar increases, at least to the point where the latter is in excess of the voids in the stone.

From experiments made at the Thayer School of Civil Engineering, Messrs. J. B. McIntyre and A. L. True found that a five-inch layer of concrete containing from 30 to 45 per cent. of one-to-one Portland cement mortar, and some of the specimens containing 40 to 45 per cent. of one-to-two mortar, were impermeable with pressures of 20 to 80 pounds per square inch, maintained for two hours.

484. Mortars made with fine sand are much less permeable than those made with coarse sand. This difference is so marked that a less permeable mortar is made with one barrel of cement per cubic yard of fine sand, passing a sieve having, say, fifty meshes per inch, than with two barrels of cement per cubic yard of very coarse sand in which the grains are, say, one-tenth inch in diameter. Mortars made with sands composed of a mixture of grains of various sizes are neither very porous nor easily permeated.

Mortars mixed very dry or very wet have greater permeability than those of the ordinary consistency, and in the case of concretes, it would probably be found that a deficiency of water would result in a much more permeable mass than the use of what might be considered an excess.

All of the above conclusions indicate that a mortar may be quite porous, and yet so long as the voids are very minute, the percolation of water through it will be slow. This is especially shown by the fact that mortars of coarse sand, not porous, are more permeable than the porous mortars of fine sand.

485. When water is permitted to percolate continuously through a mass of mortar, the interstices gradually become filled, and the permeability decreases in marked degree. M. Alexandre found that a volume of water which passed a certain mass of mortar in twenty minutes at the beginning of the experiment, required five hours to percolate the mass at the end of a month. M. R. Feret has obtained similar results in making extensive experiments[1] on the subject of permeability, and considers that fine particles of cement or lime are carried along by the water, forming efflorescence at the surface and tending to stop the flow.

486. The Preparation of Water-Proof Mortar and Concrete. — To enumerate briefly the precautions necessary to attain water-tightness in mortars and concretes, it may be said that different brands of cement present different characteristics in this regard. Fine grinding is a prime requisite, and sand cement or silica cement, containing as it does very fine grains of sand intimately mixed with cement particles of extreme fineness, is admirably adapted to such uses.

The sand should, if possible, be composed of a mixture of grains of various sizes, because such a mixture gives a mortar not only little permeable, but one that is not porous, and that has, besides, a good strength. The amount of cement in the mortar should be in excess of the voids in the sand, not less, in general, than three barrels of cement per cubic yard of sand.

In concrete the volume of mortar should exceed the volume of voids in the aggregate, and to obtain this result without too great expense, the aggregate should be so selected as to have a minimum of voids. Gravel concrete properly proportioned may be made water-tight somewhat more easily than broken-stone concrete, but a mixture of gravel and broken stone will give good results not only in this regard, but in the matter of strength as well.

487. To make a compact mortar for use where the facilities for tamping are ordinarily good, the consistency should be neither very wet nor very dry. When the mortar is struck with the back of a shovel, moisture should glisten on the surface, but in a pile the mortar should appear but little moister than fresh earth. This is the consistency which, with a moderate amount of tamping, gives the least volume of mortar with given quantities of dry materials. In places difficult of access,

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[1] *"La Capacité des Mortier Hydrauliques," Annales des Ponts et Chaussées*, July. 1892.

or in the preparation of concrete, better results will be obtained with a mortar somewhat wetter than the above, since large voids will be less likely to occur in the more plastic mass. In fact, unless the supervision is very close, it is advisable to use a rather wet mixture in preparing concrete where water-tightness is desired.

488. Washes. — The application of certain washes to the surfaces of walls intended to be water-proof, and the introduction of foreign materials into the mortar or concrete to make it less permeable, have been practiced to some extent. Alternate coatings of soap and alum solutions are applied with a brush, not only to concrete, but to brick and stone masonry surfaces. These penetrate the pores of the masonry, forming insoluble compounds which prevent percolation. Washes of grout, composed of cement, or of cement and slaked lime, are used for a similar purpose.

"**Sylvester's Process** for Repelling Moisture from External Walls" consists in applying first a solution of three quarters of a pound of soap to one gallon of water, followed, after twenty-four hours, by the application of a solution containing two ounces of alum per gallon of water. Both solutions are applied with a brush, the soap solution boiling hot, and the alum solution at 60° to 70° Fahr. The applications are alternated, with twenty-four hours intervening each time. Experiments at the Croton Reservoir[1] indicated that four coats of each wash were required to render brickwork impervious to a head of forty feet of water and the cost of the four double applications was about ten cents a square foot.

In Reservoir Number Two of the Pennsylvania Water Co., two washes of each solution were used on the walls at a cost for materials and labor of twenty-three cents per hundred square feet, and the results were said to be good.

A modified recipe for such a wash in which but one solution is made is given as follows:[2] A stock solution is prepared of one pound lye, five pounds powdered alum, dissolved in two quarts water. One pint of the stock is used to a pail of water in which ten pounds Portland cement has been well mixed.

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[1] Trans. A. S. C. E., Vol. i, p. 203.

[2] J. H. G. Wolf, *Engineering News*, June 30, 1904.

489. In a few cases the use of alum and soap solutions in the body of the mortar has been tried with apparently successful results. Mr. Edward Cunningham,[1] in making experiments on water-proof concrete vessels, used powdered alum equal to one per cent. of the combined weight of the sand and cement, mixing this with the dry ingredients. To the water used in mixing, one per cent. of yellow soap was added. The results were said to be very satisfactory. In the above proportions, however, the amount of alum is made to depend upon the amount of cement and sand used, while the soap added depends upon the amount of water, whereas the soap should bear a definite ratio to the alum.

In experiments with mortar composed of one part cement to two and one-half parts of bituminous ash, Prof. W. K. Hatt[2] found that the alum and soap mixed with the mortar at the time of gaging increased the strength and hardness of the ash mortar about fifty per cent., and diminished the absorption by the same percentage. One half of the water used for gaging was a five per cent. solution of ground alum, the other half being a seven per cent. solution of soap. The alum solution was used first and the gaging completed with the soap solution.

Mr. W. C. Hawley[3] employed a stock solution of two pounds caustic potash, five pounds powdered alum, and ten quarts water, and used in the finishing coat three quarts of this solution in each batch of mortar containing two bags of cement. The mortar was mixed with two volumes of sand to one of cement and covered forty-eight square feet to a depth of about one-half inch. The extra cost for materials and preparing solution was only about nine and a half cents per hundred square feet. With less than two parts sand to one cement, it was found the finishing mortar checked in setting. It was also found that any organic matter in the sand was softened by the potash, and an excess of potash caused checking, although an excess of alum had no deleterious effect.

490. Use of Lime, etc. — The introduction of slaked lime in mortars designed to be water-proof is suggested by the fact

[1] Trans. A. S. C. E., Vol. li, p. 128.
[2] Trans. A. S. C. E., Vol. li, p. 129.
[3] Journal New England Water-Works Association, 1904.

that the permeability of mortar diminishes if water is allowed to percolate it for some time, the theory being that fine particles of cement and lime are dislodged by the passage of the water to form a deposit at or near the surface, and check the flow. This suggestion, however, needs experimental confirmation, since it seems quite possible that the introduction of a substance containing such a large proportion of water as does slaked lime, may increase the percentage of voids in the mortar, if not the permeability.

The use of pulverized clay and pozzolanic materials for a similar purpose has been suggested. It has already been shown that moderate doses of clay have no deleterious effect on the strength of mortars for ordinary exposures. The action of the pozzolanic substances has been found by Dr. Michaëlis and M. Feret to be not mechanical alone, but chemical, and the effect on the strength of the resulting mortar depends upon the exposure to which it is subjected, such admixtures being deleterious for mortars hardened in air.

491. Efflorescence.—The white deposit sometimes formed at the surface of brick and masonry walls is usually due to the filtration of water through the mortar, dissolving out salts of potash, soda, etc., and depositing these salts on the surface by evaporation or by the formation of sodic carbonate. The absorption of water from the atmosphere may also account for this deposit in some degree, especially near the sea. The same term is applied to a more harmful deposit, sulphate of calcium, which may be supplied by the filtrating water or may come from the cement, either from the addition of gypsum or from the fuel used in burning. The crystallization of this salt in the pores of the masonry at the surface may cause disintegration.

On the other hand efflorescence may be quite harmless, as when it is formed by washing out from the mortar an excess of hydrate of lime. A portion of the latter may then be changed to carbonate of lime near the surface of the wall and actually stop up the pores or voids, and prevent further filtration.

492. The discoloration of brickwork and fine masonry by efflorescence is sometimes serious. To ameliorate these conditions, the use of water-proof mortars, and careful pointing of the work, are precautions to be recommended. General Gillmore, in "Limes, Hydraulic Cements and Mortars," suggests the use of about ten pounds of animal fat to one hundred pounds of lime and three hundred pounds of cement; the object of the fat being to saponify the alkaline substance, the lime in form of paste serving only as a vehicle for the fat. A more practical method, however, would seem to be the application of soap and alum washes on the surface, or the use of soap and alum in the preparation of the mortar to be used near the face of the wall, and especially for pointing. The remedy to be adopted, however, will depend upon the cause of the efflorescence.

493. Pointing Mortar. — Pointing serves the double purpose of making the joint practically water-tight at the edges, and giving a finish to the face of the wall. If the edge of the joint is not well filled, moisture collects there either from the face or from seepage through the wall. Subsequent freezing or the crystallization of certain salts may spall the stones or loosen them from their bed.

In laying cut-stone masonry, the joints should be raked out for about two inches back from the face to be pointed. Pointing mortar should be prepared from fine sand and the best Portland cement. The proportion of sand should not exceed two parts by weight to one cement, and in the highest class work, equal parts of cement and sand are sometimes used. No advantage is gained, however, by using a mortar richer in cement than the one last mentioned. The use of fine sand and rich mortars are specified not only because such mortars are practically water-tight, but because they take a fine finish.

494. The tools required for pointing are a bent iron to rake out the joints (though this should be partially done while the mortar is green), a mortar board and small trowel, a calking iron and wooden mallet, a brush for moistening the joint, and one or more beading tools. After raking out the joint it is moistened by the brush, and the mortar, which is mixed quite dry, is filled in with the trowel. When enough mortar is in place to fill half the depth of the joint, it is tamped with the calking iron and mallet much as a ship's seam is calked with oakum. The joint is then filled to the face, and again tamped. The bead is then formed by running the beading iron back and forth over the joint. This beading iron is of steel with the handle parallel to, but some two or three inches out from, the line of the blade forming the bead. The blade is three to five inches long and "hollow ground" or finished with a smooth concave surface. Only such a length of joint is pointed at one operation as may be quickly carried to completion. The wall must be kept moist for some time after the pointing is done, and it should be protected from the direct rays of the sun, as fine cracks are very likely to appear in this rich, finely finished mortar. If possible, pointing should be done in moderate weather and must be entirely suspended in temperatures approaching the freezing point.

495. Cements in Sea Water. — The theory of the action of sea water upon cements is not fully understood. It is known that some cement structures exposed to the worst conditions have given most satisfactory results, while others have failed in greater or less degree. It may be said at once, however, that many of the most eminent and conservative engineers consider that the failures that have occurred in the use of Portland cement in sea water are due to improper specifications, proportions and manipulation, rather than to any defect in Portland cements as a class.

496. It is thought the following represents, in the main, the most generally accepted theory of the chemical action. In the setting of cements that are rich in lime, the whole of the lime is not engaged in stable compounds, and when placed in the sea the sulphate of magnesia of the sea water is able to combine with the lime, forming calcic sulphate, the magnesia being precipitated. The discovery of magnesia in decomposed mortars led, at first, to the supposition that the cause of failure was the presence of magnesia in the cement when used. If the water level about the structure changes frequently, as is usual, or if the wall is at times subjected to a greater head on one side than on the other as in tide docks, the percolation of water through the wall is stimulated, and the sulphate of lime may then be washed out if the mortar is quite pervious, and more will be formed from a fresh supply of sea water attacking the lime of the cement, until the latter is destroyed. If, however, the sulphate of lime is not washed out, it may crystallize and thus cause swelling of the mortar.

497. It would appear from the above that for successful use in sea water the hydraulic index of the cement should be high; that is, that the lime should be comparatively low in order that the lime compounds may be more stable. For this reason it is not impossible that some of our natural cements, which are so much more nearly uniform than the Roman cements of Europe that have been condemned for this reason, may give fairly good results in sea water. The fact that the mortars of natural cement are more permeable than those of Portland, is, however, a serious defect.

Following a similar reasoning, Dr. Wm. Michaëlis has advanced the theory that if trass, or other pozzolanas of proper composition, be mixed with Portland cement subsequent to the burning, the hydrate of lime which separates from the cement in hardening will at once combine with the pozzolanas, forming a stable compound. This view, however, has been vigorously opposed by the Society of German Portland Cement Manufacturers, as well as by many engineers, especially of France, and the discussion is not yet at an end.

M. Candlot[1] says that, from the experiments of various engineers, "we have arrived at this conclusion, that the only remedy to adopt against decomposition is to prevent the sea water from penetrating the mortar. We are led thus to dismiss the chemical reactions of sea water on mortars and to consider their action from a purely physical standpoint."

498. To resist the attacks of sea water the mortar should not only be impervious, but also as little porous as possible. The cement should be finely ground and should not contain free lime. The content of magnesia and of sulphuric anhydride should be as low as possible, the latter not exceeding one and five-tenths per cent. The proportion of lime should not be too high, and above all, special pains should be taken with the manufacture to insure proper comminution and mixing of the raw materials, and uniform burning. The addition of sulphate of lime to regulate the setting is believed to be injurious for cements to be used in sea water; even two or three per cent. is said to cause rapid disintegration, and in the specifications for recent extensive works in dock construction, the addition of gypsum or other foreign matter was entirely prohibited.

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[1] "*Le Ciment*," September, 1896, quoted by F. H. Lewis, M. Am. Soc. C. E. Trans. A. S. C. E., Vol. xxxvii, p. 523.

Although slag cements have given good results in the sea for a short time, it is considered that they will not, in general, resist the action of sea water for long periods.

499. Sand or aggregate containing argillaceous or soft calcareous matter should be avoided for works in the sea. Two instances of failure of sea walls in which shells were used as the aggregate are mentioned by Col. Wm. M. Black,[1] and although the failures are not definitely traced to the calcareous matter in the concrete, the fact that experiments have shown that calcareous sands do not withstand the action of sea water, makes it probable that this was an important cause of the failure.

Fine sands that give porous mortars, though not easily permeable, are to be strictly avoided. Coarse sands giving permeable, though not porous, mortars are better, but still leave much to be desired as to immunity from decomposition. The best sands are those containing various grades of sizes of particles from coarse to fine, as mortars made with such sands are not only compact, but practically impermeable.

500. Since the mortar and concrete should be made as compact as possible, the precautions mentioned under the head of water-proof mortar and concrete should be taken in the preparation of mortars and concretes for use in the sea. That is, the proportion of cement should exceed the voids in the sand and the mortar should exceed the voids in the aggregate.

M. Alexandre has found that the mortars mixed to the ordinary consistency are attacked least by sea water. When specimens are merely immersed in the water, those mixed dry suffer the most, but some tests indicate that if mortars are submitted to the filtration of water soon after made, those mixed wet are most easily decomposed. As to whether fresh or salt water should be employed in mixing mortars to be used in sea water, although Mr. Eliot C. Clarke, M. Paul Alexandre and many others have investigated this subject, the conclusions are not definite and it is probable that either may be used as convenient.

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[1] Trans. A. S. C. E., Vol. xxx, p. 601.

PART IV

USE OF MORTAR AND CONCRETE

CHAPTER XVIII

CONCRETE: DEPOSITION

501. Concrete may be molded into blocks which are allowed to set and then are transported to the structure and laid as blocks of stone. This is the block system of construction. The adaptability of concrete to being built in place, however, is one of its chief merits, and consequently the monolithic method of construction is far more common Since it has been found that expansion and contraction, due to changes in temperature, affect concrete walls as they do any other walls of masonry, it has become customary to mold the concrete in sections, usually alternate sections of equal size and shape being built first, and the omitted sections built in later. This method of constructing a long wall is also called monolithic, since the blocks are of large size and are built in place.

502. When concrete is deposited either in air or in water, molds must be provided to keep the mass in the desired shape until it has lost its plasticity and acquired sufficient strength to stand alone. In foundations, the earth at the sides of the excavation may supply the place of a mold, and sometimes the mold forms a part of the permanent structure, as in the case of masonry piers with concrete hearting, and in steel cylinder piers filled with concrete.

ART. 62. TIMBER FORMS OR MOLDS

503. The construction, placing and removal of forms frequently represent a considerable percentage, from five to thirty per cent., of the total cost of the concrete, and it is therefore evident that an improper design may result in a considerable waste of money, as well as in marring the appearance of the work. The character of the form will of course depend on the character of the work; in the construction of a large number of small blocks of the same shape, where one mold may be used over and over, the thickness of the pieces should not be stinted, and the ease of knocking down the mold should be carefully considered. When a form can be used but once, the size of pieces should be no larger than necessary to give the requisite stiffness, and the ease of first construction is a main consideration. Forms should be left in place forty-eight hours to allow the concrete to set, and in the case of arches and beams a much longer time is necessary, so that the concrete may assume considerable strength before it is called upon to support its weight.

504. Sheathing. — Forms for massive walls of monolithic construction usually have vertical posts, with iron ties across, or braced by battered posts outside. The sheathing planks are then placed horizontal. In a few cases horizontal wales have been placed within the posts and vertical sheathing laid against the wales.

The strength of the sheathing must be sufficient to stand the pressure transmitted to it through the concrete when the rammer is used close to the face of the mold. The concrete is seldom built up fast enough to bring upon the sheathing a great head of fluid pressure, but the ramming brings a heavy local pressure upon it. If supported at intervals of four feet, two-inch lumber dressed to one and three-quarters inches thick is usually sufficient; for spans of more than 5 feet, 2 ¾ inch lumber is required to make a perfect face. Boards seven-eighths inch thick are suitable only when supports are not more than about 2 feet apart. In placing concrete in molds under water there is more danger of bursting the mold by the weight of semi-fluid concrete, and if the work is to be built up rapidly, this must be guarded against by sufficient bracing.

505. For exposed faces, the duty to be performed by the lagging includes leaving as smooth a finish as possible on the concrete after the removal of the forms. If green lumber is employed, the boards may shrink before use, leaving openings between the sheathing that will show plainly on the face of the work. A slight tendency of this kind may be checked by keeping the boards well wet with a hose until the concrete is placed. On the other hand, thoroughly seasoned lumber will swell when the concrete is placed; to obviate this difficulty the lower edge of each sheathing plank may be beveled on the outer edge; the thin edge on the inside will then crush when the planks swell.

The use of tongue and grooved lagging has been tried, but is not usually satisfactory, as there is no opportunity to expand, and the planks are particularly hard to place a second time. To give a good face in work under water, however, tongue and groove sheathing will assist in preventing washing of the cement. Yellow pine lumber is found to be excellent for sheathing; on account of the large amount of pitch contained, it absorbs water slowly and holds its shape. For a similar reason, fir timber would be suitable.

In order that the face of the mold shall be perfectly smooth, it is necessary to size and dress the plank on at least one side and two edges.

As it is almost impossible to avoid having some line of demarcation shown in the concrete at the joints of the sheathing planks, care should be taken that the lagging is of uniform width throughout, and laid horizontal so that consecutive sections show the joint continuous. The sheathing may be placed for the entire form before concreting is commenced, or the plank may be raised on the posts as the work advances. The former method will usually give the neater appearance, but is too expensive for high walls.

506. Lining. — The appearance of the finished concrete is much improved, and the labor of preparing the forms probably not increased, since less care may be taken in surfacing, by lining the mold with thin sheet iron. Iron of number twenty gauge (.035 inch thick, 1.42 pounds per square foot) has been used for this purpose, but where the same lining is used several times, a heavier iron is preferable. The joining of one sheet of lining to another may present greater difficulties than the joining of planks, but joints will occur less frequently.

In the construction of the Marquette Breakwater, Mr. Clarence Coleman, Asst. Engineer, used sheet steel one eighth of an inch thick for lining molds for building monolithic blocks. Concerning the use of the steel, Mr. Coleman says:[1] "Very

[1] *Report Chief of Engineers, U. S. A.*, 1898, p. 2254.

smooth surfaces were produced on the slopes of the concrete and the work of the molders was greatly facilitated on account of the comparative ease with which the concrete was compacted under the slope pieces of the molds. The steel effectually prevented the aggressive friction of the sharp particles of broken stone on the wooden surfaces of the molds, thus increasing the life of the molds and decreasing the cost of molding the concrete."

507. Oiling the Forms. — Oiling or greasing the face of the mold, in order that the latter may be removed without detaching particles from the concrete face, is usually advisable. Soap, crude oil, linseed oil, bacon fat, are some of the materials that have been used for this purpose; the first mentioned probably gives the best results, and if not applied too freely will have no injurious effect upon either the finish or strength of the work. Applying shellac to the molds improves the appearance of the concrete surface. When the forms are lined with steel, the adhesion of the concrete to the lining is more difficult to overcome. In this case the ordinary oils are not entirely successful, but fat salt pork has been found to give satisfactory results.

508. Joints and Corners. — If desired, triangular strips may be nailed to the inside of the forms in such a way as to block off the face to represent stone masonry, and in this way the marks of joints between planks or between strips of lining may be avoided. Square corners should not be allowed on exterior angles, as it is difficult to so tamp the concrete as to make the corner perfect, and they are so likely to be chipped off. Triangular strips or moldings should be tacked along the corners of the mold as a fillet to cut off the corner by a plane making equal angles with the adjacent faces. This plane may be from one inch to two inches wide.

To form water drips on projecting ledges, such as door caps and sills, abutment copings, etc., a small half-round should be nailed to the upper surface of the mold a short distance back from the projecting face. This leaves a ridge at the edge of the under side of projection so that the water must drip from the edge, and not follow back to the main wall face.

509. POSTS AND BRACES. — The sizes of posts and braces must be such as to make a practically unyielding support to the sheathing. With one and three-quarters inch lagging, posts may be four feet apart; if five feet four inches apart (three to each sixteen foot length), some yielding of the sheathing may be expected if it is less than two and three quarter inches. If sheathing is four inches thick, the distance between posts may be six or seven feet.

Fir, yellow pine, and Norway pine are suitable for posts. Three-inch by eight-inch is an ordinary size, and a post of these dimensions should be supported, either by ties or braces, at intervals of four to six feet. Where the posts are four inches by ten inches, supports may be six to eight feet centers, while with six-inch by twelve-inch posts, the distance between centers of supports may be eight to ten feet. Posts should be sized and dressed on the side which is to receive the sheathing, in order that the alignment may be perfect.

510. Methods of Bracing. — The general plan of the mold may vary according to conditions, the following methods having been employed on heavy work to support the vertical posts: 1st, With outside inclined braces, leaving the interior of the mold unobstructed. 2d, Tie rods across the interior of the mold connecting opposite posts at frequent intervals. 3d, Each post trussed vertically and tied across at top and bottom only. 4th, Horizontal trussed wales outside of posts, spaced four to five feet apart in the vertical and tied across at the ends.

511. Inclined Braces. — The sizes of inclined braces depend on their lengths, the inclination to the vertical, and the amount of shoring used. An approximate rule for the size of braces under usual conditions and using ordinary dimension stuff, not boards, is that the number of square inches area of cross-section of brace should equal length of span in feet. If thin planks are employed, they should be in pairs, one on either side of the vertical post, and made to act together by cross-pieces nailed to the two planks.

The aim should be to make the whole form practically unyielding under the action of the tampers, as it has been found that this action is usually more severe than the mere pressure of the concrete in a semi-liquid condition. The sizes of pieces cannot, therefore, be accurately computed, but the above sizes are derived from the general result of experience as to what has proved satisfactory.

The advantage of the form of construction just described is that the interior of the mold is left entirely unobstructed. On high walls, however, the amount of timber required for braces is excessive, and the braces may be almost as objectionable as tie rods, since the former prevent the laying of tracks along the side of the form.

512. Tie Rods. — When the vertical posts are supported by tie rods across the mold and the wall is thin, it may be possible in removing the mold to withdraw the bolts or rods if they have been thoroughly greased or wrapped with stiff paper before the concrete is placed. If it is designed to leave the rods in the concrete, they should be provided with sleave nuts near the end, which, when unscrewed, will leave the end of the rod within the concrete mass not less than two inches from the face. The hole left by the nut should be carefully filled with mortar after the mold is removed.

With vertical posts four feet apart, this method of support is objectionable, as it leaves a network of ties within the forms interfering seriously with the operation of a skip and with the ramming. It is not necessary, however, to place all of the tie rods to the top of the mold before beginning the concreting, as it is sufficient to keep one or two rods in place above the plane where tamping is being done.

A modification of this method is to use wires of large diameter with an eye at the end just inside the finished face of the concrete. A short bolt, with hook at one end and threaded at the other, passes through the post, hooks into the eye of the wire, and is tightened by a nut on the threaded end outside the post. After removing the nut, the rod is unhooked and the hole in the face filled with mortar, the wire remaining in the concrete.

513. Trussed Posts. — The third method of support, where the posts are trussed and provided with heavy tie rods at the top, and held at the bottom either by tie rods or some other means, seems to have fewer objections than the methods just described. Less timber will usually be required to build this form than for that where inclined braces are used, and the obstruction to operations will usually be less than with either of the other styles. This mold is also very readily taken down, though the posts are heavier and more difficult to handle.

To secure the bottoms of the posts, they may be set in the ground, or rest against sills braced to some other portion of the structure, or to piles. A suitable support may also be obtained by dumping a mass of concrete around the bottom of each post and allowing it to set. Forms erected on rock may have the posts rest against blocks bolted to the rock.

514. Trussed Wales. — The fourth method of supporting the posts is particularly applicable where the work is divided into blocks of moderate size in horizontal cross-section, say twenty feet square. In longer lengths the horizontal trussed wales become rather heavy for convenient handling. Within these limits, however, this is an excellent form. In the construction of Lock No. 2 between Minneapolis and St. Paul,[1] a form of this kind was used for blocks about twelve by fifteen feet at the bottom. The sheathing was one and three-quarters inches, lined with No. 20 galvanized iron. Verticals were four by twelve, spaced about two feet centers. The trussed wales were twelve by twelve inch, trussed with one and one-quarter inch rod, the king-post being of twelve by twelve inch about two and one-half feet long, making depth of truss three and one-half feet. The ends of opposite wales were connected by one and one-quarter inch rod passing outside of the sheathing. Each pair of the longitudinal wales was just above the corresponding pair of transverse wales, so that they did not interfere at the corners. The mold was twenty-nine feet in height.

In describing this mold, Mr. Powell says: "One complete form weighs twenty-eight tons; each piece about seven tons. Each piece is moved separately by the cable-way in forty-five to sixty minutes. The operation of removing one complete form requires from three to four hours time. After being moved, a small crew of men occupy nearly a day in plumbing and bolting together the form." "The boxes containing 1.7 cubic yards of concrete are landed on top of the form by cable-way and tipped from that position. Although the jar and strain is severe, the forms have shown no ill effects therefrom, remaining tight and secure."

[1] Major Frederic V. Abbot in charge. Mr. A. O. Powell, Asst Engr., *Report Chief of Engineers*, 1900, p. 2778.

Art. 63. Deposition of Concrete in Air.

515. Transporting to Place of Deposition. — In depositing the concrete in place, care must be taken not to undo the work of mixing. If the concrete is allowed to fall freely a distance of several feet or to slide down an inclined plane, the stones will be likely to separate from the mass, and the result will be a layer of broken stone followed by a layer of mortar. If the concrete is deposited in a pile, the stone will roll down the outside of the cone. This action is especially bad in concrete that is mixed rather dry. The author has seen a pavement foundation in which the limits of each wheelbarrow load of concrete could be distinguished, the foundation presenting the appearance of the cross-section of a honeycomb, made up of irregular hexagons outlined by broken stone having a deficiency of mortar. In all such cases, if the action cannot be avoided by some other method of dumping, then care must be taken to remix the concrete.

There is one method by which the concrete may be deposited by gravity without separation of the materials. This consists in allowing the material to slide down a tube, but the tube must be kept continually full, the concrete being allowed to run out at the bottom only as fast as it is filled in at the top. This method is only applicable where the mixing is continuous, as in the case of machine mixers.

516. Sometimes it will be found possible to mix the concrete so near to the place of deposition that it may be shoveled directly into place. In mixing by hand this is practicable, as the mixing platforms may usually be easily moved, and this method of deposition is carried out even in street work where the concrete is in thin layers and hence requires much moving of platforms.

Where a machine mixer is used that is so mounted as to be portable, the concrete may be delivered in place by a belt conveyor. Such an arrangement for the building of walls and for foundations of pavements, has already been described in Chapter XIV.

The conditions are usually such, however, as to preclude the possibility of mixing the concrete so close to the work that it may be shoveled into place or handled economically on a conveyor of the style mentioned. The next cheapest method is to use a derrick to handle skips or bottom-dump buckets, provided the work is sufficiently concentrated to have one position of the derrick serve to place a large quantity of concrete. The skips should hold about a cubic yard, and if a batch mixer is used, the skip should hold a batch, whatever that may be.

517. If the concrete is mixed on the same level and within less than two hundred feet of the work, wheelbarrows may be used, but for greater distances, carts, or, what is usually cheaper, cars running on a track, should be employed.

For large masses of concrete a cableway may be employed to advantage, provided there is sufficient use for it to repay the high original cost of plant. The selection to be made from among these common methods is dependent on economy as in handling other material, the only requirements being that the concrete shall be conveyed to place quickly, and that the materials shall not be allowed to separate as a result of any of the manipulation. In laying large quantities of concrete, the difference between success and failure from a financial standpoint may easily rest in the proper transportation of the materials to and from the mixer.

518. Ramming. — The concrete should be deposited in horizontal layers about six inches thick, leveled with a shovel and thoroughly rammed. The length of time ramming should be continued and the vigor with which it should be done depend largely on the degree of plasticity of the concrete. If the concrete is made of such a consistency that when struck a smart blow with the back of a shovel a film of moisture will just show on the surface, it should have vigorous ramming to insure a compact mass. A flushing of water to the surface will then indicate when to cease tamping.

With a little more water there is less danger of the larger stones "bridging" and leaving large voids in the mass, and less work will be required to flush water to the surface. With such a consistency, cutting the mass with a spade before starting, the ramming may assist in expelling air bubbles and preventing voids. With still wetter mixtures ramming becomes difficult, as the concrete will soon begin to quake, after which the ramming should not be long continued as the mass is then semi-fluid, and the stones may gradually work themselves to the bottom of the layer, forcing the mortar to the top.

519. Rammers are frequently made of wood, but those of iron are believed to be better. The weight of a rammer is limited by the capacity for work of the man who wields it. They are usually made to weigh from twenty to forty pounds. If a man lifts and drops a forty-pound rammer with forty square-inch face twenty times a minute, he is doing less good to the concrete than if he dropped a twenty-pound rammer with twenty square-inch face forty times a minute. If the face of the rammer exceeds thirty-six square inches, the result is apt to be a mere patting of the surface of the concrete, unless the rammer is so heavy as to require two men to operate it. Iron rammers with face, say, three by six inches, and weighing twenty to thirty pounds, are believed to be the most efficient. Still thinner rammers than this may be necessary in work involving such detail as for filling in between iron beams, and are desirable for tamping near the face of the mold.

520. Rubble Concrete. — In massive work the embedding of stones of "one-man size," or larger, in the concrete is a practice that has long been in vogue. The objection is sometimes made that this interferes with the homogeneity of the wall and that variations in expansion may result in injury to the work. It is thought, however, that in large masses this danger is more theoretical than real, and the author sees no objection to this form of construction for many purposes if properly carried out, and it is frequently permitted in important works. Thin walls, the arch rings of bridges, shallow foundations, etc., should not of course be built in this way, because the stresses to which such structures are subjected should be met by a uniform resistance, to avoid the effects of eccentric or irregular loading. In such structures as dams, lock walls, breakwaters, retaining walls, and in many cases bridge piers and abutments, the work may be considerably cheapened without sacrificing the fitness of the structure. The stones thus embedded should be perfectly sound and should not lie nearer one to another than six inches, nor should they lie nearer than this to the face of the wall. The concrete should be mixed rather wet, and much care taken that each stone is completely surrounded by a compact mass of concrete. The stones should be settled into the concrete already laid far enough to assure their having a full bed. Stones used in this manner are sometimes called "plums."

521. Another class of rubble concrete differing from the above more in degree than in kind, is formed by placing large stones in the work, and filling the joints between them with a rather wet concrete in which spalls may be rammed if desired. The difficulty of obtaining a compact wall by this method is perhaps a little greater than when smaller stone are used, but in either case if really water-tight work is desired, the inspection must be thorough.

The saving in cost by the use of rubble concrete depends upon the local conditions, but under ordinary circumstances when broken stone is employed, the cost of crushing the stone and the cost of cement, for a volume of concrete equal to the volume of the stone imbedded, are practically saved.

522. Joints in Concrete. — In the construction of large masses of concrete in place, joints cannot be avoided; that is, it is not possible to make the entire mass monolithic, as force enough could not be employed to carry up the entire structure at once. Even if this were possible, it would not be desirable, since the changes in length of the wall due to changes in temperature would probably result in cracks which would be irregular in outline and mar the appearance of the wall, if they had no more serious effect.

When the concrete is subjected to vertical forces only, as in foundations for buildings, horizontal joints are less objectionable than vertical joints. But in the construction of concrete lock walls, dams, and breakwaters, vertical joints are desirable to confine the cracks to predetermined planes. In the building of such structures, therefore, the method has been adopted of dividing the work into sections of such horizontal dimensions as may be thought best, and completing each section as a monolith. This will sometimes require the continuous prosecution of work for twenty-four or forty-eight hours. Whether this method, involving work at night, which is always more expensive and usually less thorough, is justified by the end sought, depends upon the character of the structure.

523. If this method is not adopted, and a horizontal plane of weakness is a serious defect, special means should be provided for avoiding this plane of weakness. Such provision may be made by iron dowels set in the concrete at the end of the days work and projecting above the surface to be covered by the concrete placed the next day; steps or hollows, or grooves parallel to the length of the wall, may be left to be filled by the next layer. Large stones weighing a hundred pounds or more are frequently imbedded one half their depth in the last layer of a days work to form a bond with the following layer.

In any case special care should be taken to thoroughly wash and clean the surface of hardened concrete before continuing the work, using preferably wire brooms for this purpose and removing any stones at the surface that appear to be loose. A thin layer of rich cement mortar should then be laid upon it, into which the first layer of fresh concrete is well rammed.

If the appearance of the finished face is of importance, special care must also be exercised in joining at this point. Before leaving a layer which is to be allowed to harden before continuing the work, the line limiting the height of the concrete at the face should be made perfectly horizontal, for a slight crack, or at least a noticeable line, may be expected at this point, and if not straight it will be the more unsightly.

524. If for any reason a layer of concrete cannot be carried over the whole area of the wall or foundation, it should never be allowed to taper off to a wedge, but a plank equal in width to the thickness of the layer should be set on edge, firmly secured, and the concrete tamped against it. In the construction of arches, culverts and sewers, such stop planks may well be set normal to the surface of the intrados instead of vertical. In case more than one layer is left incomplete, they should be stepped back, making an offset for each layer of at least one or two feet. The concrete should never be built up on a smooth batter if new concrete is to be joined to it later.

525. Keeping Concrete Moist. — All concrete should be kept moist from the time it is in the wall until it has become well hardened. Surfaces exposed to the air should therefore be sprinkled frequently for at least several days after placing. An excellent practice is to cover the surface with burlaps which may be kept saturated, as this not only furnishes the necessary moisture, but protects the work from the direct rays of the sun. The interior of a large mass will probably take care of itself in this regard, but the precaution has sometimes been taken of leaving vertical holes or wells in the mass, which are kept filled with water for some weeks and are then filled with concrete.

526. FINISH. — Some of the precautions that must be taken to secure a good finish to the face of concrete work have already been mentioned in considering the forms and the methods of deposition. These are usually supplemented, however, by certain special means when the appearance is of much importance.

We must say first, that the application of a plaster of cement mortar to a finished and set concrete face will almost never be permanent. It is seldom that it will adhere with sufficient strength to prevent scaling due to differences in expansion of the materials of different composition and age. If plaster must be used on the face of a wall, it should be applied before the concrete has set, but it is safer to avoid plastering. It is of course advisable to fill with rich mortar any voids that may appear in the face of the work, but such places should be few.

If the molds are removed while the concrete is still moist, the face may be coated with a thin grout and then immediately scraped off with the edge of a trowel. This results in filling the small voids in the face of the work, but does not leave a coat of plaster on the surface to scale off.

527. A good finish may be obtained when the molds are smooth if the workmen will force the blade of a spade or shovel between the fresh concrete and the mold, and pull the handle away from the mold. This has the effect of forcing the large stone back from the face and allowing the mortar to flow in. A layer of mortar is thus left next the mold with no marked line of junction between mortar and concrete, as may be the case in using a mortar facing. A similar effect may be produced by throwing the concrete against the face of the mold with such force that the larger pieces of aggregate rebound. In very finely finished work this may mar the surface of the sheathing, but ordinarily this method is effective.

528. When a special layer of **mortar** is used for **facing**, there is more danger, perhaps, of making the layer too thick than too thin. As to the richness of the mortar, two parts sand by measure to one volume packed cement is usually sufficient, though a more glossy finish may be made if desired, by using equal parts of cement and sand. It is better to avoid too great a variation between the richness of the mortar used for facing and that used in the body of the concrete.

One of the best ways of applying such a layer is to prepare a sheet of steel of width equal to the thickness of one layer of concrete, usually six to eight inches, with two handles on the upper edge to facilitate moving it. At the ends of the sheet, on the side next the mold, rivet short pieces of 1½ in. by 1½ in. or 2 in. by 2 in. angle iron. This sheet of iron with the projecting legs of the angles against the face of the molds, forms, with the latter, a space one and one-half or two inches thick, which is to be entirely filled with the finishing mortar made rather moist and tamped lightly with edge rammers. The concrete is filled in behind the iron, after which the latter is withdrawn by means of the handles, and the whole mass is thoroughly rammed. The end sought is that the finishing mortar shall have some approximately definite thickness, and that the stones of the concrete shall be tamped into the finishing mortar, but not through it, and thus destroy any sharp line of demarcation between mortar and concrete, and ensure a perfect bonding of the two. It is evident that this can only be accomplished by placing the mortar and concrete at the same time.

529. One other cautionary remark concerning the use of finishing mortar. With the present state of our knowledge concerning the rates of expansion of mortars and concretes of different composition, it is not considered wise to use too many combinations in the same structure. To illustrate, a pavement or surfacing of a large concrete structure was once built in layers as follows: first, thick natural cement grout was placed on the concrete foundation; second, natural cement concrete; third, Portland cement concrete; fourth, a richer Portland cement concrete; fifth, Portland granolithic; sixth, rich Portland mortar; and seventh, floated with dry Portland cement and sand. We cannot be absolutely sure that this is bad practice, but it would seem that this structure might have served its purpose with fewer varieties of material, and it is usually considered very doubtful whether Portland cement mixtures will always adhere well to mixtures of natural cement, although the author knows of instances where they have been used in juxtaposition apparently with good results.

530. Granolithic is a facing or surfacing mortar composed of crushed granite and cement. The granite is usually specified to contain no particles larger than $\frac{3}{8}$ inch to one inch, and about one and one-half to two and one-half parts are used to one volume of cement. This is more frequently used for foot walks and other places where resistance to wear is required, but may also be used to surface walls, to line reservoirs, etc. It will be mentioned again in connection with cement sidewalk construction.

531. Exposed concrete surfaces frequently present a **patchy appearance.** This may be the result of lack of care in placing the concrete next the mold, or it may be due to variations in the purity of the sand or in the amount of water used in mixing. On mortar-faced work this lack of uniformity is less noticeable. The use of slag sand, or of a little fine pozzolanic material, may be advantageous, and a small amount of lampblack in the facing mortar also tends towards uniformity in appearance.

A very pleasing finish may be given by applying to the set concrete a thin wash of cement and **plaster of Paris,** though the permanence of such a wash may be open to question. The sheathing should be removed as early as it is perfectly safe to do so, and the concrete surface cleaned from any oil or grease that may have come from the mold planks. The wash, which should be very thin, may be applied with a whitewash brush. A mixture of equal parts Portland cement and plaster of Paris gives a very light gray finish, and one part plaster to three parts cement gives a trifle darker shade.

532. A **rubbed finish** of excellent appearance may be given by removing the sheathing before the concrete has set very hard, say after twenty-four to forty-eight hours, and rubbing the surface with white brick or with a wooden float. If there are small voids in the surface, it may be covered with a thin grout of equal parts of cement and sand and then rubbed hard with a circular motion. The grout should not leave a scale on the work, the object being only to fill surface imperfections.

If the mold boards are removed at just the proper time, a good finish may be given by rubbing with a wooden float, without the coating of thin grout. A somewhat similar effect is produced by brushing the surface with brooms or stiff brushes.

533. "Pebble-dash." — What is called a pebble-dash finish was used in the construction of a bridge in the National Park at Washington, D. C.[1] Eighteen inches of the concrete next the face was made of one part cement, two parts sand, and five parts of gravel and rounded stone from one and one-half to two inches in their smallest diameter. After the removal of the forms the cement and sand were brushed from around the face of the gravel next the surface exposed to view. It was found by experiment that the brushing should be done when the concrete was about twenty-four hours old. At twelve hours the gravel was displaced by the brushing, and after thirty-six hours the mortar had become so hard as to be removed from the surface of the stones with difficulty. The forms were therefore designed so that sections of the lagging could be removed as desired. The cost of the brushing was said to be about sixty cents per square yard.

A somewhat similar method is employed in giving to concrete the **appearance of cut stone**. The materials used in the surfacing mortar are Portland cement and crushed rock, the character of the rock depending upon the color and texture desired in the finish. The molds having been removed after the proper time has elapsed, the mortar covering the face of the particles of crushed rock is removed by brushing or by washing the surface with a weak acid solution, followed by clean water, and finally by an alkaline solution to prevent any further action of traces of the acid which might be left on the face. This last method is said to be patented, "the patent covering the obtaining of a natural stone finish for concrete by mechanical, chemical or other means."[2] It is hoped that such a blanket patent is somewhat less formidable than it appears.

If the sheathing planks of the molds can be removed about twenty-four hours after the concrete is placed, the same effect may be produced without the use of acid. By using plenty of water the cement and finer portions of crusher dust in the face

[1] Capt. Lansing H. Beach, Corps of Engrs., U. S. A., in charge. Work described by Mr. W. I. Douglas, Engr. of Bridges, D. C., *Engineering News*, Jan. 22, 1903.

[2] *Engineering News*, May 21, 1903.

may be washed out with a stiff corn broom, leaving the facets of the crushed rock exposed.

534. Pointing and Bush-hammering. — If the molds have been left in place until the concrete is set hard and it is found that the face of the concrete is not what is desired, it may still be improved although it may not be plastered. With this object the face is sometimes tooled with the stone cutter's point to give the appearance of rough pointed or rock face masonry. Grooves may be cut to block off the work into rectangles of the proper size, then a draft of one to two inches may be left along all of these artificial joints, and within the draft line the rough pointing may be done.

A cheaper method, however, is to bush-hammer the entire face, and this tends to mask any lack of uniformity in color or smoothness. Bush-hammering may be done by ordinary laborers at a small cost, as one man can go over from fifty to one hundred square feet in ten hours, making the cost from 1¾ cents to 3½ cents per square foot, with labor $1.75 per day. Where it is decided beforehand to bush-hammer the work, less pains need be taken in dressing the lagging of the forms.

535. Colors for Concrete Finish. —The addition of coloring matter to cement and concrete is not at present widely practiced, and consequently experience has not been sufficient to indicate just what colors may be used without detriment to the work. Lampblack has been most commonly employed, giving different shades of gray according to the amount used. In any large work where the use of coloring matter is desirable and there is not time to institute thorough tests, the advice of a cement chemist should be sought. The dry mineral colors, mixed in proportions of two to ten per cent. of the cement, give shades approaching the color used. Bright colors are difficult to obtain and would not be in keeping with a masonry structure except in architecture.

When mixed with an American Portland cement mortar, containing one part cement to two parts by weight of a yellow river sand, the particles of which are largely quartz, the colors indicated in the following table are obtained.

With no coloring matter added, the mortar was a light greenish slate when dry. Ultra marine green, in amounts up to 8 per cent. of the cement, had no apparent effect on the color of this mortar. Variations in character of cement and sand will affect the result obtained in using coloring matter. The colors indicated below are for dry mortars ; when the mortar is wet the shades are usually darker. None of the materials mentioned in the table seems to affect the early hardening of the mortar, though very much larger proportions might prove injurious. With red lead, however, even one per cent. is detrimental, and larger proportions are quite inadmissible.

COLORED MORTARS.

Colors Given to Portland Cement Mortars Containing Two Parts River Sand to One Cement.

Dry Material Used.	Weight of Dry Coloring Matter to 100 Pounds of Cement.				Cost of Coloring Matter per lb. Ct.
	½ Pound.	1 Pound.	2 Pounds.	4 Pounds.	
Lamp Black	Light Slate .	Light Gray .	Blue Gray .	Dark Blue Slate .	15
Prussian Blue . .	Light Green Slate . .	Light Blue Slate . . .	Blue Slate .	Bright Blue Slate .	50
Ultra Marine Blue	. . . . .	Light Blue Slate . . .	Blue Slate	Bright Blue Slate .	20
Yellow Ochre . .	Light Green.	. . . . .	. . . .	Light Buff	3
Burnt Umber .	Light Pinkish Slate . .	Pinkish Slate .	Dull Lavender Pink	Chocolate .	10
Venetian Red . .	Slate, Pink Tinge . .	Bright Pinkish Slate . . .	Light Dull Pink . .	Dull Pink	2½
Chattanooga Iron Ore .	Light Pinkish Slate . .	Dull Pink . .	Light Terra Cotta . .	Light Brick Red . .	2
Red Iron Ore	Pinkish Slate	Dull Pink . .	Terra Cotta	Light Brick Red . .	2½

536. In some cases it may be sufficient to color the **surface** of the work by painting. Ordinary oil paints are sometimes applied after washing the surface of the wall with very dilute sulphuric acid, one part acid to 100 parts water, but the permanence of such a finish seems very questionable.

The method of obtaining a gray finish by painting with a thin grout of cement and plaster of Paris has already been described (§ 531). Similar methods may be used with the dry mineral colors, and, while their permanency cannot be vouched for, it seems a more reasonable procedure than to paint a concrete surface with oil paints. One pound red iron ore to ten pounds cement mixed dry, and then made into a very thin grout and applied to a well cleaned concrete surface with a whitewash brush, gives a pleasing brick-red color; and a rich dark red is given by one pound red iron ore to three pounds cement. The earlier this is applied after the concrete has set, the more likely is it to remain permanent.

Art. 64. Placing Concrete under Water

537. In building a concrete structure under water where the site cannot be coffered, it must be expected that the expense of the work will be increased, and the quality of concrete poorer. The methods employed for subaqueous construction are: 1st, the laying of freshly mixed concrete in roughly prepared forms; 2d, placing the fresh concrete in bags of burlap or canvas which are deposited while the concrete is still soft; and 3d, molding in air concrete blocks which are placed in the work when well set.

In the first method some cement will certainly be washed out of the concrete, the extent of this loss depending upon the condition of the water in which the work is done (*i.e.*, its depth and the amount of current and wave action) and the care with which the concrete is lowered to place. Tamping cannot be done with this method, and any movement of the concrete to level it will cause further loss of cement.

In the second method the loss of cement will be much less, but the adhesion between the different masses will be slight. In the third method there is no loss of cement and the concrete can be well rammed; but if small blocks are used, there may be difficulty in so placing them under water as to make a solid structure, while if large blocks are used, special hoisting machinery is required to handle them.

538. Depositing in Place.— The first method mentioned above, depositing fresh concrete in place, is usually the cheapest and most expeditious method, though it is not likely to give the best results. When concrete is lowered through water, there is a tendency for the cement to separate from the sand and stone. This tendency seems to be exhibited in a more marked degree with some cements than with others. In connection with the construction of the concrete foundations of the Charlestown bridge, a test was devised for determining the relative values of the different lots of cement for depositing in water.[1] Concrete was laid, through a small chute, in a cement barrel placed in a hogshead filled with salt water. It was found that while some specimens would retain their form after twenty-four hours when the barrel was removed, others showed but little cohesion after twenty-four to forty-eight hours. In the former, the cement and gravel remained well distributed throughout the mass, but in the latter much of the cement had separated from the gravel, and settled in the bottom of the barrel, where it remained in an inert state, while the central portion of the concrete, robbed of its cement, had many voids. As a result of this test, some lots of cement were not accepted for use.

The finest portion of the cement is very liable to separate from the remainder as the concrete passes through the water, and if subjected to the action of waves or a current, much of the cement will be washed away. In exposed situations it is especially necessary to inclose the site of the work with sheet piling or cribs, or a wall constructed by the bag or block method. When the water level outside the form is constantly changing, the flow of water through the joints in the sheathing is especially effective in washing out the cement, and in such conditions the sheathing should be made as nearly water-tight as possible. To this end tongue and groove lagging may be used, or the face of the mold may be covered with tarred felt, or canvas, tacked in place.

539. Laitance is the term applied to the whitish spongy material that is washed out of concrete when it is deposited in water. Before settling on the surface of the concrete, which it does slowly, it gives to the water a milky appearance, hence the name. In fresh water this semi-fluid mass is composed of the finest flocculent matter in the cement, containing generally hydrate of lime. It remains in a semi-fluid condition for a long time and acquires very little hardness at the best. In sea water the laitance is more abundant and is made up of silica, lime and magnesia, with carbonic acid and alumina, its exact

[1] Report of Mr. William Jackson, Chief Engineer. Third Annual Report Boston Transit Commission.

composition depending upon the character of the cement. This interferes seriously with the bonding of the layers of concrete, and when it has settled it should be cleaned from the surface before another layer is placed.

540. The Tremie. — A method frequently employed to prevent, as much as possible, the loss of cement, is to make use of a large tube of wood or sheet iron, made in sections so that its length is adjustable, and provided with a hopper at the upper end. Such a tube is called a tremie. The hopper is always above water, and the lower end of the tube, which may also terminate in a hopper, rests upon the bottom of the foundation.

The tremie is first filled with concrete, a box placed over the lower end serving to prevent the escape of the concrete while the tube is being lowered until the end rests upon the bottom. The tube is then lifted from the bottom sufficiently to allow the concrete to escape as fast as fresh concrete is added at the top. The surface of the concrete in the tube should be kept continuously above the water surface. The tremie may be held in position by a crane, or it may be so supported as to allow of two motions at right angles to each other. Such an arrangement was used in building the piers for the Boucicault Bridge, the tube traveling along a platform, which in turn could move on a track at right angles to the first motion. In using a tremie the thickness of a layer may be regulated at will.

In the construction of the Charlestown Bridge [1] a tube was used fourteen inches in diameter at the bottom, and about eleven inches in diameter at the neck, above which was a hopper to receive the concrete. When the attempt was made to place too thick a layer at one operation, it was found that the charge was likely to be lost, and the best results were believed to be obtained with layers two feet to two and one-half feet thick. Some experiments were made with a plug designed to keep the water from flowing up through the concrete when the tube was being refilled after a loss of the charge. This plug was made with a central core of wood and sides of canvas expanded by steel ribs. It worked fairly well, but its use was not continued.

[1] Third Annual Report, Boston Transit Commission.

541. This principle was employed by Mr. Daniel W. Mead in placing concrete in a small shaft in ninety feet of water.[1] An eight inch, wrought iron pipe was screwed together in sections, and provided with a hopper at the upper end and a wooden plug at the lower end. After lowering the pipe into the shaft, the pipe was filled with concrete and it was expected that its weight would force out the plug at the bottom when the pipe was raised. On the first attempt, however, the plug failed to drop out, and on raising the pipe the cause was apparent. The plug had evidently leaked, and as the first concrete was dropped into the pipe it had separated, the broken stone being at the bottom, the sand next, and the cement above had so plugged the pipe as to support the weight of the concrete. The second attempt, when a tighter wooden plug was used and a small pipe placed inside the larger one to assist in loosening the plug if necessary, was successful.

542. The Skip. — Since in submerged work the concrete should be deposited in as large masses as possible, the use of a large skip will probably give better results than the tremie. A box form may be used with hinged lids at the top to permit filling, and two hinged doors at the bottom which may be opened from the surface by a tripping rope when the box has reached the place for depositing the concrete.

A convenient form of skip is made in two halves, each half having a cross-section either of a right angled triangle or a quadrant of a circle. The two boxes are hinged at their upper inside corners and the pieces through which the hinge rod passes are prolonged upward, the lowering cables being attached to their ends. Two opening cables are fastened to the outer corners of the boxes. Two sheets of iron may be used as covers to the boxes, being attached to the hinge rod that serves for the two halves of the skip.

It is seen that the skip will work on the principle of a pair of ice tongs. While being filled with concrete the box is supported by the lowering cables, and the hinged lids are kept up by some simple contrivance. When full, the lids are closed and the skip lowered till it rests on the bottom; the skip being then hoisted slowly by means of the opening cables, the con-

[1] Trans. Assn. of Civil Engineers of Cornell University, 1898.

crete is gently deposited in place. Such skips are supplied by the makers of concrete machinery.

543. In depositing concrete by means of skips it is well to have the latter of large size, holding not less than a cubic yard, and preferably two cubic yards or more. The larger quantity will compact itself better on account of the greater weight, and the surface which is subjected to wash will have a lesser area in proportion to the volume of the mass. The skip should be completely filled with concrete and tightly closed while it is being lowered. It is important also that the skips be lowered slowly, in order that the inclosed air may be replaced by water without commotion.

544. The Bag. — Mr. Wm. Shield[1] devised a bag for depositing concrete under water which is said to work very satisfactorily. The top of the bag is closed, and has a three-quarter inch wrought iron bar fastened across the end with a loop to receive the hook of the lowering line. The mouth of the bag is slightly larger than the upper end, to facilitate the discharge of the concrete. The bag is inverted to be filled, and the mouth is then secured by a turn of a line provided with loops through which a small tapering pin is passed. This pin is attached to a tripping line, and when the bag has reached the place of deposition, a pull of the tripping line releases the pin; when the bag is gently lifted, the concrete is deposited in place with such slight commotion that but little cement is said to be lost.

545. Other Methods of Depositing in Situ. — For deposition under water the materials for concrete are sometimes mixed dry, but this is not good practice. The mere soaking of water into cement does not form a compact mortar; the moistened materials need to be thoroughly mixed and, if possible, rubbed together in order to obtain perfect adhesion. Then, too, if the dry materials are lowered to place and water is suddenly allowed access to the mass, much of the cement will be washed away in the disturbance caused by the sudden inrush of water.

M. Paul Alexandre[2] found by experimenting on mortars of "dry" (stiff), "wet" and "ordinary consistency," that mortars

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[1] "Subaqueous Foundations," London *Engineering*, 1892. Abstract in *Engineering News*, Vol. xxviii, p. 379.

[2] "*Recherches Experimentales sur les Mortiers Hydrauliques," par M. Paul Alexandre*, pp. 93–96.

mixed "dry" suffered the greatest decrease in strength by immersion in running water. Mortars mixed "wet" suffered the least loss, though their resistance was less than those mixed to the ordinary consistency, since when not subject to the current of water, the wet mortars gave much lower results than those of ordinary consistency.

546. In order to avoid the washing out of the cement, the concrete is sometimes allowed to partially set before deposition. Mr. Robert W. Kinipple has used this method and advocates its adoption.[1] In employing this method, the concrete, which should be deposited when of the consistency of stiff clay, requires careful watching that it does not set so hard as not to reunite after being broken up. Under ordinary supervision, this will probably not prove as successful as some of the other devices, but it may be found valuable under certain circumstances. The writer made a few experiments with this method on a small scale in swiftly running shallow water. Much of the cement appeared to be washed out by the current, but the results were somewhat better than were obtained when the concrete was deposited fresh. (See § 456.) M. Paul Alexandre made some short time experiments on this point, which indicated that but little advantage was gained in allowing the cement to partially set before deposition.

547. Depositing Concrete in Bags.— The second method of depositing concrete under water, namely, by placing the freshly mixed concrete in coarse sacks and immediately lowering them to place, is very convenient under certain conditions. This method is of especial value in leveling a foundation to receive concrete blocks, or to form a base for concrete deposited *in situ*. Small bags of concrete have been successfully used in filling the spaces between pile heads which were to support an open caisson. In such a case the bags should be lowered to a diver who places and rams them. If the bags be properly leveled and the earth firm, a part of the load is thus transmitted to the material between the pile heads, while if the earth be very unstable, the bag construction compels the piles to act together, giving lateral stiffness to the foundation and tending to prevent over turning.

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[1] "Concrete Work under Water," Proc. Inst. C. E., Vol. lxxxvii. See also "Notes on Concrete," by John Newman, pp. 116 and 117.

548. The bag method was successfully used in replacing with concrete the timber superstructure of the breakwater at Marquette, Mich.[1] The main portion of the breakwater was built of monolithic blocks on the rock-filled timber substructure. After removing a portion of the rubble filling, a bed was made for the monolithic blocks by laying concrete in place two feet thick, extending from one foot below to one foot above low water datum. This method was afterward replaced by the use of concrete in bags, which made it safe to remove a lesser amount of the rock filling of the crib at the center, and thus decreased the expense of the work. The bags were of eight ounce burlap made 6 feet long and 6 feet 8 inches in circumference, and held about one ton of concrete. They were filled while lying on a skip specially constructed, so that when the skip was in place it could be tripped and the bag placed in its exact position in the work.

549. In connection with this work a practical indication of the character of the concrete deposited in this manner was given by some small bags of concrete that were laid to protect, during the winter storms, a portion of the crib filling. Mr. Coleman says of this,[2] "Only one layer of these sacks, laid slightly overlapping from the lake side of the crib, was used. The sacks were so lightly filled that when laid as described, the average thickness of the concrete covering was not more than six inches. The crib was storm swept many times without displacing a single sack, and when they were removed in the following spring to facilitate the work, they came away, when pulled up with the floating derrick, a dozen or more at a time, so firmly were they cemented together, and in many cases large rubble stones were lifted up along with them, because of the adhesion of the cement to their surfaces."

550. The **Cost** of the concrete in bags was as follows: —

Materials, cement, sand, stone, burlaps, etc.	$5.281
Mixing concrete and filling bags	.912
Transportation	.157
Depositing	.408
Total cost per cubic yard	$6.758
Or, cost in bags, exclusive of materials	1.477

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[1] Major Clinton B. Sears, Corps of Engineers, in charge; Mr. Clarence Coleman, Asst. Engineer.

[2] *Report Chief of Engineers, U. S. A.*, 1897, p. 2620.

The cost of the first plan, placing a two foot layer of concrete *in situ*, where different methods of handling were employed, was, for labor: —

Loading scow with materials	$0.411
Mixing concrete	.846
Depositing	.524
Cost *in situ*, exclusive of materials	$1.781

551. When concrete bags are used in forming a foundation, the lower layers should usually cover a considerably greater area than that required for the top. Especially is this true if building upon insecure earth. This increased area at the bottom may be obtained by building the sides on a batter, or by the use of footing courses. If the latter are used, they should be so designed that in any case the projection beyond the course next above is not greater than the thickness of the layer.

Before filling the concrete into the bags it should be thoroughly mixed, as for deposition in the ordinary manner. The practice of using dry concrete for this purpose is reprehensible for the same reason as has been given in § 545. It has also been found that if the concrete is mixed and filled into the bags in a dry state, a layer of concrete on the outside may cake before the water has had time to reach the interior portion. The bags should be filled about three-fourths full, leaving the mass free to adjust itself to inequalities in the rock, or to the irregular surface of the previously deposited layer. When strength and compactness are desired, the bags should be placed by a diver and gently rammed. In this way the mass may be well bonded by "breaking joints."

552. Large Masses in Sacks. — Very large bags of concrete are sometimes employed, as in the construction of a breakwater at New Haven, England.[1] "The top of the breakwater has a width of thirty feet, is ten feet above high water, and is surmounted by a covered way and parapet running along the outer side, both sides battering one in eight. The breakwater is unsheltered from the force of the Atlantic, is founded on the rough, natural sea bottom, and the foundation course has a

[1] From London *Engineering*, quoted in *Engineering News*, Vol. xxvii, p. 551.

width of fifty feet; the lower portion of the structure, from the bottom up to a level of two feet above low water, consists of one-hundred-ton sacks of concrete deposited while plastic. The canvas with which the concrete was enveloped was of jute, weighing about twenty-seven ounces per square yard. The sacks were dropped into place by a specially designed steam hopper barge. The 'sack-blocks' in the finished work became flattened to a thickness of about two feet six inches. With the exception of this sack work the breakwater is built of plastic concrete laid *in situ*." Similar sack-blocks of one hundred sixty tons have been employed in breakwater construction.

It is evident that this method of depositing concrete in large sacks is peculiarly suited to forming a foundation on a soft bottom, since, if the bags are made to project well beyond the sides of the molded concrete to be deposited above, they act in the double capacity of a mattress to prevent scour, and a foundation for the upper part of the structure.

553. Other uses for Bags of Concrete. — In the construction of the Merchants' Bridge at St. Louis, bags of concrete were used to check the scour which occurred beneath the upstream cutting edge of one of the caissons while it was being grounded. The bags were thrown into the river at such a distance above the pier that they settled to the bottom at the point where the scour was taking place.

Burlap bags were used at St. Marys Falls Canal for laying concrete under water next the face of the form to prevent washing of the cement in building concrete superstructure for canal walls. As the bags were placed by hand they were made to hold only about two cubic feet of concrete.

554. Paper Sacks. — Paper sacks are sometimes employed instead of jute bags. Dr. Martin Murphy[1] describes the methods employed in filling steel cylinders for the substructure of the Avon Bridge as follows: "Bags made of rough brown paper well stiffened with glucose, were employed and slipped into the water over the required place of deposition. Each bag held about one cubic foot of concrete; smaller ones were used be-

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"Bridge Substructure and Foundations in Nova Scotia," by Martin Murphy. Trans. A. S. C. E., Vol. xxix, p. 629.

tween dowels. The bags were quickly made up and dropped one after another, so that the one following was deposited before the cement escaped from the former one. The paper was immediately destroyed by submersion, and the cement remained; it could not escape. The bags cost one dollar thirty-five cents per hundred, or thirty-five cents per cubic yard." The success of this method will depend upon the character of the sacks, for in some experiments on a small scale with sacks of stiff manila paper the author found that the bags were not destroyed, and that no adhesion took place between the separate sacks.

555. THE BLOCK SYSTEM OF CONCRETE CONSTRUCTION. — The advantage of the block system of construction lies in the fact that the individual blocks may be made with the greatest care, and as they are allowed to harden thoroughly before being put in place, the loss of cement incident to the other systems is avoided. There is, however, the difficulty of forming a joint between adjacent blocks. The joints are of great importance when small blocks are employed, since the latter may not have sufficient weight to escape being washed out of the work. Large blocks may make a very solid structure by being simply superimposed, but special hoisting machinery will be required to place such blocks.

Sometimes a large bed of mortar is laid in coarse sacking and carefully lowered and spread on the block last laid, the next block being placed upon it immediately. A very rich mortar should be used for this purpose. Usually, however, it is not attempted to place mortar in the horizontal joints in concrete block work laid under water, but it is considered that all vertical joints should be filled with rich Portland cement mortar when the work is to be exposed to wave action. If settlement is anticipated, and large blocks are used, no attempt should be made to break joints in the direction of the longer dimension of the work, but the blocks should bond in a direction transverse to the wall. Concrete blocks may be advantageously employed to form the faces of a structure built under water or exposed to wave action, the concrete hearting or backing being built *in situ*.

556. For convenience in handling, a groove to receive a chain or cable should be left down two sides and across the bottom of the blocks to enable them to be placed close together and to facilitate the withdrawal of the hoisting chain. These grooves may afterward be filled with concrete; such recesses are sometimes molded for the sole purpose of filling them with fresh concrete when in place, and thus binding the work together. The molds for forming the blocks should be carefully made in order that the finished blocks may have good bearings one upon another. If the corners are rounded, they are less likely to be chipped off in handling or by having an undue strain come upon the corner when in place.

If any recesses are desired in the blocks, the pieces placed in the mold to form them should be trapezoidal in cross-section with the longer parallel face against the side of the mold. If such filling pieces are made rectangular, difficulty will be experienced in removing them when the concrete has set. The molds should, of course, be so constructed as to be readily taken apart to be used again. The opposite sides may be kept from spreading by rods which pass through the mold, but such rods are an inconvenience in packing the concrete into the mold, and it is therefore better to truss the mold outside. If such tie rods are used, they may be left imbedded in the concrete, or removed with the mold, as desired.

557. Cost of Molding Blocks. — An illustration of the use of the block method is furnished in the United States breakwater at Marquette.[1] The general plan of this breakwater has already been briefly noted and two methods of laying a two foot layer of subaqueous concrete, as a foundation for monolithic blocks forming the superstructure proper, have been described. A third method was to mold footing blocks, seven feet by five feet in section and two feet high, which were afterward laid flush with the lake side of the substructure cribs and filled in behind with concrete laid in place. The footing blocks thus assured a good quality of concrete beneath the toe of the monolithic block on the lake side where it was most necessary to provide a good foundation, and also served as a protection behind which the remainder of the two foot layer could be placed with greater facility.

Many of these blocks were built during the winter in a shed

[1] *Report Chief of Engineers*, 1897, p. 2624.

artificially heated, the materials being thawed out as required. The molds were of six by six inch and four by four inch pine, lined with two by eight inch plank dressed on one side. Strips of trapezoidal cross-section, nailed inside the mold, provided for two parallel grooves on the bottom and two sides of the block to receive hoisting chains. A dovetail at the back of the block was also formed by three wedge-shaped pieces placed against the back face of the mold. The cost per cubic yard of making forty blocks is as follows: —

1.42 bbls. Portland cement, at $2.75	$3.90	
.45 cu. yd. sand, at $0.45	.20	
1.0 cu. yd. stone screenings passing ¾″ sieve, at $1.10,	1.10	
Cost materia's in concrete per cu. yd.		$5.20
Superintendence, labor and watchman	$2.21	
Fuel	.31	
10 per cent. of cost of warehouse and molds	.52	
Total cost of making per cu. yd.		3.04
Total cost per cu. yd. of blocks ready to place in work		$8.24

CHAPTER XIX

CONCRETE-STEEL

558. The ratio between the compressive and tensile strengths of steel is nearly unity. The same thing is approximately true of wood and some other materials of construction. In cement and concrete, however, the conditions are quite different, the strength in compression being from five to ten times the strength in tension. Concrete cannot, therefore, be economically used to resist tension, and in structures requiring transverse strength concrete is at a great disadvantage.

559. The idea of supplementing the tensile strength of concrete by the use of iron in combination with it, seems to have been suggested independently by a number of men. It is known that combination beams were tested by Mr. R. G. Hatfield as early as 1855. In 1875 Mr. W. E. Ward,[1] M. Am. Soc. Mech. Engrs., constructed a dwelling entirely of "béton," the floors, roofs, etc., being reinforced with light iron beams and rods. These early uses of the combination have some bearing upon the ability of patentees to cover in their blanket patents more than the peculiar form of the steel member which they advocate in their particular system.

ART. 65. MONIER SYSTEM

560. A much more picturesque beginning of the concrete-steel industry is furnished in the story, quite true, that about 1876, a French gardener, Jean Monier, used a wire netting as the nucleus about which to construct his pots for flowers and shrubs, and seeing that the practice might be extended, he called to his aid engineers and capitalists who developed the Monier system of construction.

This system consists of imbedding in the concrete two sets of parallel rods at right angles to each other, the rods of the two sets being tied together with wire at all intersections.

[1] Proc. Am. Soc. Mech. Engrs., Vol. iv, p. 388.

The larger wires run in the direction of the greater tensile stresses and are usually spaced two to four inches apart. The rods at right angles to these main tension members are to assist in distributing the stress to the main members and may be of smaller diameter.

The iron rods in this system are designed primarily to resist the tension only, and the form of the bars is not such as will stiffen the structure while the concrete is fresh. In an arch, two systems of netting are used, one near the intrados and one near the extrados.

561. The main advantages which this system has over some of its competitors are the simple shapes required, that is, round rods, which may always be obtained without difficulty, and the fact that these may be so readily put together by ordinary workmen under supervision. This system is especially adapted to vertical walls, whether curved or straight, and found its first extensive use in the construction of tanks and reservoirs. It has been extended, however, to the construction of sewers, floors, roofs, and arch bridges.

One of the practical disadvantages of the system is that the nets are somewhat difficult to handle and keep in position, and in thin sections it has not been found practical to imbed the nets in concrete containing broken stone of the ordinary size. The use of cement mortar, usually one part cement to three sand, has been found necessary in order to get a perfect connection between the wires and the body of the work. This, of course, increases the cost. Another objection has been urged against it, namely, that the transverse rods do not in general have any duty to perform, and are simply a waste of material so far as the final strength of the structure is concerned. While this may be so in certain forms of construction, it may be met by the statement that these cross-rods may be made as small as desired if they are to act merely as spacers for the main rods. In slabs, walls, etc., however, these cross-rods have a purpose, and in some other systems members are supplied to fulfill this necessary function.

562. Some very bold arches have been built on the Monier system, including three bridges in Switzerland having 128 foot span, 11 foot rise, and a thickness of but 6¾ inches at the crown and 10 inches at the abutments.

A Monier arch of 32.8 foot span, rise one-tenth of span, width 13.2 feet, in which the mortar at the crown was six inches thick and eight inches at the abutments, was tested in Austria in 1890. It held a fifty-three ton locomotive on half the arch, and finally failed at the abutments under a load of 1,700 pounds per square foot over half the span.

563. Pipes are now made by this system at yards and transported to the place of use. It has also been used as a substitute for iron in cylinders for bridge piers. A novel use of this system consists in making a pipe covering for piles exposed to marine borers. The pipe, which is long enough to reach from above the water surface to below the bed of the waterway, is slipped over the head of the pile and settled a short distance into the mud or silt of the bottom with the aid of a water jet. A question, however, has been raised as to the action of concrete and iron in combination in sea water on account of the possible setting up of galvanic action.

ART. 66. WÜNSCH, MELAN, AND THACHER SYSTEMS

564. Wünsch System. — This system, which was invented in 1884 by Robert Wünsch of Hungary, consists of two iron members of angle irons and plates imbedded in concrete, the lower member being arched and conforming to the outline of the soffit, while the upper one is horizontal and continuous. The two members are riveted together at the crown, and at the abutment are rigidly connected by a vertical member. The several systems of rib bracing thus constructed are connected laterally at the abutment by channel bars running transverse to the arch and riveted to the bottom of each vertical in the abutment. Assuming that the abutments are stable, it is evident that we have here not simply an arch, but also some elements of the cantilever. The spandrels being built up solid of concrete, there is no definite arch ring, and the quantity of material required, especially in long spans, is likely to be much greater than in other systems. On the other hand, the great depth at the springing permits the use of concrete only moderately rich in cement.

565. A bridge of this type, built at Neuhausel, Hungary, consists of six spans of about 56 feet each, rise 3.7 feet, thickness at crown 9.8 inches, and at springing line 54.3 inches.

The total width of the arch was 19.7 feet and contained thirteen systems of arch ribs. Concrete in the abutments below water was made mainly of Roman cement. Above water it was composed of one part Portland to eight or ten parts sand and gravel. Ten to twelve inches of the arch was built of strong Portland concrete rammed in layers at right angles to radial lines of the arch, special care being taken with that part below the bottom arched member. An arch was usually completed in one day, and the centers remained in place thirty to forty days, the greatest settlement on the removal of centers being two-thirds of an inch. This bridge contained 1,346 cubic yards of concrete and 88,180 pounds of iron, and cost, complete, $13,700.

566. Melan System. — This system, invented by an Austrian engineer, Joseph Melan, consists of arched ribs between abutments as in bridges, or between beams or girders as in floor construction, the space between the ribs being filled with concrete. Steel I-beams curved to the proper form are usually employed for the reinforcement, though angle iron flanges with lattice connections have been used in some of the large bridges. The steel members extend into the piers or abutments and are there connected by angles or other shapes, and firmly imbedded in the concrete.

567. This system as adapted to bridge construction has probably met with greater favor among American engineers than any other form. Perhaps this is because of the stiffness of the form of iron beam used, and because by assuming a rather high fiber stress for steel the reinforcement may be designed to withstand the entire bending moment without excessive dimensions for the steel members. There is thus a feeling of security in its use that is not felt in the same degree with other systems. The arch dimensions are determined by computing the forces and required thickness of arch ring after assuming certain safe working stresses for the steel and concrete; but if desired, the size of steel members may then be increased slightly where necessary to such dimensions that with unit stresses of, say, one-half the elastic limit, the entire bending moment shall be taken by the steel. Some of the largest bridges built after this system in the United States are the five-span bridge at Topeka, Kan., and the three-span bridge at Paterson, N. J.

568. Thacher System. — A modification of the Melan system is that invented and patented by Mr. Edwin Thacher. Steel bars are used in pairs and imbedded in the concrete near the intrados and extrados of the arch and extending well into the abutments. The bars of each pair may be connected by bolts or stirrups, though Mr. Thacher's original idea seems to have been to have no connection between two bars of a pair except through the concrete. The bars are provided with projections which may be in the form of rivet heads, lugs, or bolts, to increase the resistance of the bars to slipping in the concrete.

569. Mr. Thacher has more recently designed a special form of rolled bar having projections that serve the same purpose as the rivet heads mentioned above. Several bridges have been built on this system, one of the most notable of these being the Goat Island bridge at Niagara Falls, one span of which is 110 feet in length.

570. In the construction of arch bridges many of the other systems are simply modifications of the Melan. The shapes of the steel members may have different forms, and the connections between the pairs of bars forming the arch ribs may vary to suit the idea of the inventors. But though these systems lose their identity in long-span arches, their distinctive features are more apparent in the construction of floors, roofs, columns, etc.

Art. 67. Other Systems of Concrete-Steel

571. The Hennebique System. — The rods are here arranged in pairs, one above the other, in a vertical plane. In girders, the bar in the tension side is straight, while the other one of the pair is horizontal for a short distance along the center of the span, the ends being inclined upward near the ends of the beam. The two bars are connected by bent straps or U-bars so that the steel reinforcement may be compared to a queen post truss within the concrete. This system has been used in the construction of bridges, both arch and girder, floors, roofs, stairways, etc., but it is in beams and girders that its distinguishing characteristics are best displayed.

572. A beautiful arch on this system is the bridge over the river Vienne at Chatellerault, France, consisting of three spans, the central one of which is 164 feet long, with rise of 15 feet, 8 inches. Four arch ribs 20 inches deep support the roadway, 25 feet wide, by posts forming a skeleton spandrel.

573. Kahn System. — In this system, which is somewhat similar to the Hennebique, the distinguishing feature is the care taken to provide against shear, or against that combination of tension and shear which tends to cause failure in a beam by cracks that extend diagonally upward toward the center of span from near the points of support. The steel plates forming the tension members are sheared longitudinally at intervals, and short ends are bent up at an angle of forty-five degrees with the horizontal. These ends, which may be compared to the tension diagonals of a truss, are thus a part of the main steel member, and the stress is transferred directly to the latter without dependence on the concrete.

The advantages are the great resistance offered by the bar to being pulled out of the concrete and the thorough manner in which all tension stresses may be provided against. The main disadvantages would seem to be the necessity of detailed shop work for each size of girder, the inconvenience of shipping the steel in its complete form and the difficulty of thoroughly tamping the concrete around the diagonals.

574. The Ransome System. — One of the earliest patents to be issued in this country for a method of using concrete and iron in combination was that issued to Mr. E. L. Ransome in 1884. The valuable and distinctive feature of this system is the use of a square bar that has been twisted cold. This twisting not only insures a good bond between the concrete and iron, but actually somewhat increases the strength of the bar.

In building beams with twisted bars as tension members, the latter are given a slight inclination from the center upward toward the ends. For use in buildings, as in floors and columns, and for covers to areaways, and similar uses, this system is largely employed.

575. Roebling System. — As its name implies, wire forms the main feature of this system, and in a general way it resembles the Monier. Its application thus far is found principally in floor construction, two distinct methods being used. In the arched floor a wire netting, stiffened by round steel rods woven through it is sprung between the lower flanges of the main

I-beams of the floor. This netting, further stiffened and held in place by iron rods running parallel to the axis of the arch, forms a permanent center for the placing of the concrete, which fills all of the space to the level of the top of the I-beams. A level ceiling below is obtained by a similar netting laid flat against the under side of the I-beam and fastened thereto. This acts as a wire lath to receive a coat of plaster. If the level ceiling is not necessary, the plaster may be applied to the under side of the arch netting, in which case the lower flange of the I-beam should be encased in concrete to protect it from corrosion and fire.

576. For lighter loads, flat bars are placed at suitable intervals above and below the I-beams and clamped to the flanges. To these bars the wire netting is attached, a thin layer of concrete laid on the upper wire incasing the bars, and plaster applied to the lower netting forming the ceiling. Cinder concrete is usually employed with this system.

577. Expanded Metal. — The use of what is commonly known as expanded metal lath has been extended to concrete-steel construction. As in the Monier and Roebling systems, the strength and stiffness of the structure are increased by the use of steel rods in connection with the expanded metal, the chief duty of the latter, where great strength is required, being that of a distributing member. Expanded metal is made from sheet steel by shearing short slits parallel to the grain, and extending the sheet at right angles to the slits, resulting in a network of diamond shaped openings. The metal used is of all weights up to one-quarter inch thick with meshes six inches long.

578. The steel bars used in connection with expanded metal by the St. Louis Expanded Metal Fireproofing Co. are square, with frequent corrugations surrounding the bar. These corrugations serve only to prevent the slipping of the bars in the concrete without adding to the strength.

The applications of this system include conduits, sewers, and walls of buildings, as well as floors and roofs.

Art. 68. The Strength of Combinations of Concrete and Steel

579. While we have in this country been somewhat slow in acknowledging the worth of concrete-steel construction, there is now a strong interest displayed in the subject; many experiments are being made in our educational and commercial laboratories and the theory of the action of concrete and steel in combination is being rapidly developed. It is natural that in the investigation of a form of construction permitting so many variations in methods of preparation, that the opinions now advanced, based on insufficient data, should be more or less conflicting.

580. Experiments. — The experiments of M. A. Considère, made in France between 1898 and 1901, which have been made more available to us through the translation and collection of his articles on the subject by Mr. Moisseiff,[1] are exceedingly valuable. The effect of the quality of the steel and the concrete, of repeated loads, of changes in volume in hardening, and many other points are carefully analyzed by experiment and theory.

One of the most important deductions drawn by M. Considère is that fibers of concrete within what may be called the sphere of influence of a reinforcing rod of iron or steel, is capable of enduring very much greater elongations without visible fracture than similar concrete without reinforcement. The explanation advanced for this is that the steel so distributes the stress throughout the length of the concrete in tension that the development of insipient fractures or excessive elongations at the weaker sections of the concrete is prevented until each section has taken its maximum load. The conclusion to which this theory leads is that the resistance of the concrete throughout the area of influence of the steel reinforcement, is maintained far beyond that degree of deformation which, in concrete not reinforced, would cause its rupture.

581. Neglect of Tensile Strength. — Notwithstanding these conclusions, it is believed that it is sufficient in most cases of design to neglect the tensile strength of the concrete in concrete-steel combinations. This course may be defended by the following considerations. The tensile strength of concrete is, at best, not usually above two hundred to four hundred pounds per square inch. If the stress on the extreme fibers of a beam

[1] "Reinforced Concrete," by Armand Considère, McGraw Publishing Co., New York.

is three hundred pounds, and we consider that this stress decreases uniformly toward the neutral axis, the mean stress is but one hundred fifty pounds per square inch. Again, if we disregard M. Considère's conclusions, we find that since the modulus of elasticity of steel is, say, fifteen times that of concrete, the former is only stressed to forty-five hundred pounds per square inch when the imbedding concrete has reached its ultimate strength.

582. The resistance of concrete to tension may easily be destroyed or impaired by accident, especially when fresh. The properties of concrete vary so much with the materials, the proportions, and the manipulation, and the investigation of the behavior of concrete and steel under stress is as yet so incomplete, as to make refinements in theoretical treatment not only unwarranted but really undesirable for practical purposes, since they lead to the appearance of greater accuracy than is in reality attainable.

It is true that by the judicious selection of values for the constant appearing in formulas for the strength of concrete-steel beams, the results of such formulas sometimes show a remarkable agreement with the results of that series of actual tests for which the constants have been selected; but one has only to recall his experience in other lines, hydraulics for instance, to realize the importance of the almighty constant. The opinion sometimes advanced, that the strength of a given concrete-steel beam may be as accurately derived by formula as can the strength of a steel beam, the writer does not believe to be tenable, at least in the present state of our knowledge concerning the behavior of concrete.

583. To neglect the tensile strength of the concrete will result in a slight increase in the required area of steel reinforcement, and, in so far as the tensile strength of the concrete may be developed, will tend to make the compression side of the beam weaker than the tension side. The only objection to this is that the failure of the beam, though at a higher load, may be more sudden. This possibility, however, seems less serious than the error of depending on the tensile strength of the concrete only to find it lacking at the critical moment.

Since the aim here is to develop a formula that may be used with safety in the design of structures, and since to neglect the tensile strength of the concrete is to add an unknown, though probably small, factor of safety, the tensile strength will not be considered in the following analysis.

ART. 69. CONCRETE-STEEL BEAMS WITH SINGLE REINFORCEMENT

584. Definitions. — In this discussion the word strain has its technical meaning, the relative change in length of a piece under stress. It is usually expressed as the ratio of the elongation (or shortening if in compression) to the original length of the piece. But for our purpose it is the ratio of the increment of change in length, occasioned by a given increment of stress, to the length of the piece before the increment of stress was applied. These two expressions for strain are usually considered equivalent, since, according to Hooke's law, the ratio between stresses and corresponding strains, for a given material, is constant within the elastic limit. But in dealing with concrete it is found that, even before the stresses become excessive, Hooke's law does not hold true. Bearing in mind, then, the meaning of the word strain, we represent as usual the ratio of stress to strain by E, the modulus of elasticity, or

$$E = \frac{\text{stress}}{\text{strain}}.$$

Let E_s = modulus of elasticity of steel.

E_c = modulus of elasticity of concrete in compression.

f_s = tension in steel, lbs. per sq. in.

f = compression in concrete, lbs. per sq. in.

a = thickness of steel considered as a flat plate, or the area of imbedded steel bars per inch of width of beam z.

y_1 = distance the extreme fiber of concrete in compression is from the neutral axis.

y_2 = distance the center of the steel reinforcement in the tension side of the beam is from the neutral axis.

i = depth of concrete below reinforcement.

d = $y_1 + y_2$ and $h = d + i$.

λ_1 = unit compression of extreme fibers of concrete in compression.

λ_2 = unit elongation of steel in tension.

Represent $\frac{E_s}{E_c}$ by R, and $\frac{f_s}{f_c}$ by r.

585. Formulas for Constant Modulus of Elasticity. — The cross-section of the beam, the graphical representations of the strains and of the stresses are shown in the following diagrams:

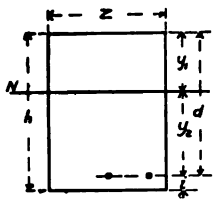

FIG. 10. CROSS-SECTION.

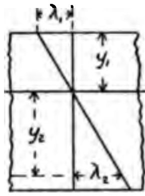

FIG. 11. STRAINS.

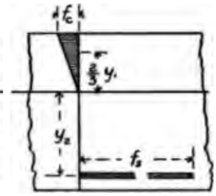

FIG. 12. STRESSES.

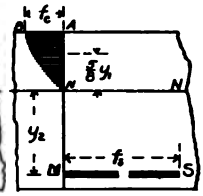

FIG. 13. STRESSES.

Figure 12 shows the conditions when the stresses are so small that the modulus of elasticity of the concrete may be considered constant, and this case will be first considered.

In the strain diagram, λ_1 represents the deformation of the extreme fiber of concrete in the compression side of the beam, and λ_2 the deformation of the steel. Since a section plane before bending is considered to be plane after bending, the steel is considered not to slip in the concrete, and NN is the neutral axis,

$$\frac{\lambda_1}{\lambda_2} = \frac{y_1}{y_2}; \quad \text{but} \quad E_s = \frac{f_s}{\lambda_2}, \quad \text{and} \quad E_c = \frac{f_c}{\lambda_1}$$

$$\therefore \lambda_2 = \frac{f_s}{E_s} \quad \text{and} \quad \lambda_1 = \frac{f_c}{E_c},$$

or

$$\frac{\lambda_1}{\lambda_2} = \frac{y_1}{y_2} = \frac{f_c}{f_s}\,\frac{E_s}{E_c},$$

and

$$y_2 = \frac{f_s}{f_c}\,\frac{E_c}{E_s}\,y_1 = \frac{r}{R}\,y_1. \qquad \text{(Eq. 1.)}$$

In the stress diagram the triangle N A B represents the total compressive stress on the concrete for unit width of beam, and is equivalent to a single force $\frac{f_c y_1}{2}$ applied at the center of gravity of the triangle.

The total compressive stress for section of width z is

$$P = z\,\frac{y_1}{2}\,f_c.$$

The total tension in the steel is $T = zaf_s$.

As we disregard the tensile strength of the concrete, and as the total normal compression and total normal tension on a section must be equal, as they are the two forces of a couple, we have

$$P = T, \quad \text{or} \quad z\frac{y_1}{2}f_c = zaf_s,$$

whence $$a = \frac{f_c}{f_s}\frac{y_1}{2} = \frac{y_1}{2r}. \qquad \text{(Eq. 2.)}$$

The point of application of the force P is $\frac{2}{3}y_1$ above the neutral axis, while the point of application of T is y_2 below the neutral axis; the arm of the couple is therefore $\left(\frac{2}{3}y_1 + y_2\right)$, and the moment of resistance is equal to either force into this arm,

or, $$M_o = zf_c\frac{y_1}{2}\left(\frac{2y_1}{3} + y_2\right);$$

substituting the value of y_2 given in (1) and reducing,

$$M_o = zf_c\left(\frac{1}{3} + \frac{1}{2}\frac{f_s}{f_c}\frac{E_c}{E_s}\right)y_1^2 = zf_c\left(\frac{1}{3} + \frac{1}{2}\frac{r}{R}\right)y_1^2. \qquad \text{(Eq. 3.)}$$

586. Formulas for Varying Modulus of Elasticity. — The foregoing formulas are based on the supposition that the compressive stress in the extreme fiber of the concrete has not passed the point beyond which equal increments of stress no longer produce equal increments of strain or deformation. They are based, in other words, on the common theory of flexure, except so far as we have departed from the application of this theory in neglecting the tensile strength of the concrete. It is well known that even for steel and wooden beams this common theory does not, and is not meant to, apply outside the elastic limit. In the case of concrete, however, it has been found that, even for quite moderate stresses, the modulus of elasticity is not constant (Art. 56), but that after a certain stress is reached the modulus decreases with increasing stress. The effect of this upon the internal forces may be illustrated by the curve $N B$ in Fig. 13. The extreme fiber is supposed to be subjected to the stress f_c; the fibers nearer the neutral axis have a smaller stress per square inch, and the modulus of elasticity for this smaller stress is greater; but in order that a section that is plane before flexure shall be plane after flexure, the *strain* must be proportional to the distance from the neutral axis. It follows, then, that the *stresses* in the inner fibers do not decrease according to the ordinates of the triangle, but are greater than indicated by such ordinates. The exact form of the curve $B N$ is not known, but the examination of a number of deformation curves has indicated that it is parabolic, and for the purpose of this discussion it may be considered a parabola with axis $A B$ without serious error, although it is known the axis does not coincide with $A B$ for stresses below the elastic limit of the concrete.

587. While the formulas derived in § 585 may represent, then, the conditions existing in a beam subjected to very moderate stresses, it appears that beyond the limit of stress at which the modulus of elasticity of concrete becomes variable, they should be so modified as to take into account this variable modulus.

Then if $A B$ in Fig. 13 now represents f_c and $M S = f_s$, we have as before,

$$y_2 = \frac{f_s}{f_c}\,\frac{E_c}{E_s}\,y_1 = \frac{r}{R}\,y_1. \qquad \text{(Eq. 4.)}$$

The total stress on the concrete above the neutral axis is now represented by the area within the parabola, or $\frac{2}{3} f_c y_1$, and the total compression on section of width z is

$$P' = \frac{2}{3} z y_1 f_c,$$

and the total tension

$$T' = z a f_s.$$

As these are the two forces of a couple

$$\frac{2}{3} z y_1 f_c = z a f_s;$$

whence

$$a = \frac{2}{3}\,\frac{f_c}{f_s}\,y_1 = \frac{2}{3}\,\frac{y_1}{r}. \qquad \text{(Eq. 5.)}$$

The point of application of P' is on a line through the center of gravity of the parabola, or $\frac{5}{8} y_1$ from the neutral axis, while the point of application of T' is at distance y_2 below the neutral axis; the arm of the couple is, therefore, $\frac{5}{8}y_1 + y_2$, and the moment of resistance

$$M_o = \frac{2}{3} z y_1 f_c \left(\frac{5}{8} y_1 + y_2\right)$$

$$= \frac{5}{12} z f_c y_1^2 + \frac{2}{3} z f_c y_1 y_2. \qquad \text{(Eq. 6 a.)}$$

Substitute value of y_2 given in (4)

$$M_o = \frac{5}{12} z f_c y_1^2 + \frac{2}{3} z f_c y_1 \frac{f_s}{f_c} \frac{E_c}{E_s} y_1.$$

$$= z f_c \left(\frac{5}{12} + \frac{2}{3}\frac{r}{R}\right) y_1^2. \qquad \text{(Eq. 6.)}$$

In applying these formulas, it must be remembered that (1), (2), and (3) are applicable where the stresses are below the point at which the modulus of elasticity of the concrete begins to diminish, while (4), (5), and (6) illustrate the conditions for stresses above that limit.

588. Example. — Design a beam of 10 foot span to carry a load due to 20 feet head of water.

Load per square foot = 20 × 62.5# = 1250#.

Total load per foot width of beam = 125,000# = W_1.

First, using Eqs. 1, 2, and 3.

$$M = \frac{WL}{8} = 187{,}500 \text{ inch-lbs. on beam 1 ft. wide, } (z = 12).$$

Assume

$$f_s = 12{,}500, \quad f_c = 500, \quad r = \frac{f_s}{f_c} = 25;$$

$$E_s = 28{,}000{,}000, \quad E_c = 2{,}000{,}000, \quad R = \frac{E_s}{E_c} = 14.$$

From (3)

$$M_o = 187{,}500 = 12 \times 500 \left(\frac{1}{3} + \frac{25}{2 \times 14}\right) y_1^2.$$

$$y_1^2 = 25.5, \qquad y_1 = 5.05 \text{ inches.}$$

From (2)

$$a = \frac{y_1}{2r} = \frac{5.05}{2 \times 25} = .101 \text{ inch,}$$

$az = .101 \times 12 = 1.21$ sq. in. of steel for beam 12 in. wide.

From (1)

$$y_2 = \frac{r}{R}\,y_1 = \frac{25}{14} \times 5.05 = 9.02 \text{ inches.}$$

If i = thickness of concrete below center of steel bars = 2 inches,
h = total depth beam = 5.05 + 9.02 + 2.00 = 16.07 inches.

Second, using Eqs. 4, 5, and 6.

Assume

$$f_s = 50{,}000, \quad f_c = 2{,}000, \quad r = \frac{f_s}{f_c} = 25;$$

$$E_s = 28{,}000{,}000, \quad E_c = 1{,}400{,}000, \quad R = \frac{f_s}{f_c} = 20.$$

As the stresses per square inch given above are approximately the breaking strengths of the materials, we must supply a factor of safety, say 4; *i.e.*, design the beam to withstand four times the required bending moment before the stresses assumed above are attained.[1]

From (Eq. 6)

$$M_0 = 4\,M = 4 \times 187{,}500 = 12 \times 2000\left(\frac{5}{12} + \frac{2}{3} \times \frac{25}{20}\right)y_1^2;$$

whence $$y_1^2 = \frac{187{,}500 \times 4 \times 12}{12 \times 2000 \times 15} = 25,$$

or, $$y_1 = 5.$$

From (Eq. 5)

$$a = \frac{2}{3}\,\frac{5}{25} = .133 \text{ inch,}$$

and az = 1.6 square inches of steel for 12-inch width of beam.

[1] The method of using the breaking strengths of the materials, and computing the ultimate resistance equal to a certain number of times the desired strength, is considered inferior to that of assuming safe working stresses and computing directly the safe load. These safe working stresses should be fixed with reference to the elastic limit of the materials, rather than with reference to ultimate strength. The use here of the term factor of safety is for the momentary purpose of emphasizing the fact that the conditions assumed in deriving equation (6) are such as are supposed to exist under comparatively high stresses; but the formulas may evidently be applied to the safe working stresses the same as equations (1), (2) and (3), and in the present example the same size beam will result by eliminating "factor of safety" and using working stresses equal to one-fourth the values of the stresses assumed.

From (Eq. 4)

$$y_2 = \frac{r}{R} y_1 = \frac{25}{20} y_1 = 1.25 \times 5'' = 6.25 \text{ inches.}$$

If $i = 2$ inches as before,

$$h = \text{total depth beam} = 5.00 + 6.25 + 2.00 = 13.25 \text{ inches.}$$

It is seen that equations 4, 5 and 6 give, for the assumption made, a lesser depth of beam with more reinforcement than is given by equations 1, 2 and 3 with the corresponding assumptions as to stresses and moduli.

589. An inspection of the equations shows that to increase the amount of steel reinforcement in the tension side of the beam tends to move the neutral axis nearer to the tension side, and bring a greater area of cross-section of concrete into compression. If we arbitrarily decrease the depth of the beam which must withstand the same bending moment, it will increase the required area of reinforcement, and if carried too far will eventually raise f_c beyond a safe value. On the other hand, if we take the beam as designed in accordance with equations 1, 2 and 3 and subject it to a greater bending moment than that for which it is designed, then so long as R remains constant, r also remains constant, that is, the steel and concrete are equally overstressed; but since R increases with the load, r will also increase, that is, the increment of stress in steel will be relatively greater than that in concrete.

590. Excessive Reinforcement. — In the solution of the above example if we introduce the requirement that the total depth of the beam shall be but 12 inches, while the quality of the concrete is not improved, we may assume, as before, E_s = 28,000,000 and E_c = 1,400,000. Let us introduce the same factor of safety, 4, by using $f_c = \frac{2000}{4} = 500$ pounds instead of designing the beam for four times the required bending moment; as we have seen, this does not affect the result. Since the depth of the beam is fixed, f_s and r cannot be assumed, but must be found, together with a.

We have

$$d = y_1 + y_2 = 12 - 2 = 10 \text{ inches, and } y_2 = 10 - y_1.$$

From (6 a)

$$M_0 = \tfrac{5}{12} \times 12 \times 500\, y_1^2 + \tfrac{2}{3} \times 12 \times 500\, y_1 (10 - y_1) = 187{,}500.$$

Solving, we have $y_1 = 6$ inches nearly,

and $y_2 = 10 - 6 = 4$ inches.

From (4) $$\frac{y_2}{y_1} = \frac{f_s E_c}{f_c E_s}.$$

Substituting values of y_2, y_1, f_c, E_c and E_s, we have

$$f_s = 6{,}667 \text{ lbs. per sq. in.}$$

From (5) $$a = \frac{2}{3}\frac{f_c}{f_s} y_1 = \frac{2}{3} \times \frac{5000}{6667} \times 6 = .30 \text{ in.}$$

and $az = 3.6$ sq. in. of metal to each foot width of beam. This is more than double the amount of reinforcement required for a 13.25 inch beam, while the steel is stressed only 6,667 lbs. per square inch.

It may be asked why not use a smaller area of metal, say 2 sq. in., stressed to 12,000 lbs. per square inch, giving the same total tension; but a moment's consideration shows that in order that the metal should assume this higher stress, its elongation must increase proportionally, involving a corresponding increase of strain in the concrete in compression with an accompanying increase in stress beyond the assumed safe limit of 500 lbs. per sq. in.

591. To pursue this subject of excessive reinforcement a little further, let us examine some tests of concrete-steel beams made by Prof. Gaetano Lanza and reported in Trans. Am. Soc. C. E. for June, 1903.

In these beams the width $z = 8$ inches, $h = 12$ and $d = 10$ inches nearly. The span was 11 feet. Proportions in concrete by volume 1 part Portland cement, 3 parts sand, 4 parts broken trap that would pass 1 inch ring, and 2 parts of the same rock that would pass ½ inch ring. Both plain and twisted square steel bars were used as reinforcement, the plain bars having a tensile strength of about sixty thousand pounds per square inch and the twisted steel about eighty thousand pounds per square inch.

If we assume the ultimate strength of the concrete to be 2,000 pounds per square inch, the modulus of elasticity at this high stress to be 1,400,000 and the modulus of the steel to be 28,000,000, we have,

$$R = \frac{28{,}000{,}000}{1{,}400{,}000} = 20,$$

and for twisted bars,

$$r = \frac{80,000}{2,000} = 40.$$

From Eq. (4) $y_2 = \frac{r}{R} y_1 = 2\,y_1,$

$$\therefore\ 3\,y_1 = 10 \text{ inches},\ y_1 = \frac{10}{3} \text{ inches}.$$

From Eq. (5) $a = \frac{2\,y_1}{3\,r} = \frac{2}{3} \times \frac{10}{3} \times \frac{1}{40} = \frac{1}{18} = .055$, and $az = .444$.

That is, .444 sq. in. of twisted steel reinforcement is required in the beam 8 inches wide in order that the stresses in concrete and steel shall simultaneously reach the values of 2,000 and 80,000 lbs. per square inch, respectively.

From (6) $$M = 8 \times 2000 \times \left(\frac{5}{12} + \frac{2}{3} \times \frac{40}{20}\right) \frac{100}{9}$$

$$= 311,100 \text{ inch-pounds.}$$

One beam having .56 sq. in. reinforcement, or an area very close to the theoretical amount called for above, broke under a bending moment of 470,000 inch-lbs. Eight other beams having a greater area of reinforcement gave moments of 355,000 to 443,000 inch-lbs., and the average of the nine bars was 403,000, or 30 per cent. greater than the value derived by formula.

592. Included in the series of tests were three beams, in each of which were placed two 1¼ inch twisted rods. As we have seen, the correct amount of steel to develop the full strength of both steel and concrete is about .444 sq. in.; the three bars mentioned had 3.12 sq. inches of steel, or a large excess of reinforcement. To determine the theoretical moment of resistance of these beams, assume as before:

$$E_s = 28,000,000,$$
$$E_c = 1,400,000,$$
$$f_c = 2,000.$$

From (4) $$y_2 = \frac{f_s}{f_c}\frac{E_c}{E_s} y_1 = \frac{f_s}{40,000} y_1, \qquad (a)$$

$$a = \frac{1.25^2 \times 2}{8} = .39.$$

From (5) $$a = .39 = \frac{2}{3}\,\frac{2{,}000}{f_s}\,y_1, \qquad (b)$$

$$y_2 = 10 - y_1. \qquad (c)$$

Solving (*a*), (*b*) and (*c*), we obtain

$f_s = 22{,}000$, $y_1 = 6.45$ inches, and $y_2 = 3.55$ inches;

whence $$r = \frac{f_s}{f_c} = 11,$$

and from (6),

$$M_o = 8 \times 2000\left(\frac{5}{12} + \frac{2}{3} \times \frac{11}{20}\right)(6.45)^2 = 522{,}000 \text{ inch-pounds.}$$

These three beams developed the following moments of resistance: 553,550, 663,700 and 783,500, mean 667,000 inch-lbs., or 28 per cent. greater than that derived by formula. None of them failed, however, by crushing of the concrete at the top of the beam, but by longitudinal shearing "at or a little above" the reinforcing rods.

593. It appears, then, that by increasing the area of steel reinforcement over 600 per cent., or from .44 sq. in. to 3.12 sq. ins., the strength of the beams was increased about 68 per cent. by theory, or 66 per cent. according to the few tests cited. The cost of the beam, however, was increased about one hundred per cent.

This method of increasing the moment of resistance of a beam is not economical; it is better to improve the quality of the concrete. It may, however, be necessary at times to use excessive reinforcement on account of restrictions on the size of beam, but one may easily carry this so far that he passes outside the true theory of concrete-steel construction, and it becomes a question of the steel being sufficient to carry the entire load. In such cases double reinforcement may be adopted.

594. Tables of Strength. — In Table 160, equations (5) and (6) have been reduced to simpler forms by the introduction of values of E_s and f_s. Selecting in the table the division corresponding to the modulus of elasticity of the concrete which is to be used, and the line opposite the assumed stress in the concrete, M_o = quantity in column *a* times the square of the depth of beam, *d*; and the area of steel in a beam of 12 inch width, *i.e.* 12 *a*, equals quantity in column *b* times the depth

TABLE 160

Concrete-Steel Beams. Moment of Resistance and Area of Steel in Terms of Depth of Beam or Slab

If d = depth, in inches, from top of beam to center of steel.

Coefficient in column "a" multiplied by d^2 = moment in ft.-lbs. per foot width of beam (or inch-pounds per inch width of beam);

Coefficient in column "b" multiplied by d = area steel in square inches per foot width of beam;

Column "c" gives area steel expressed as per cent. of area cross-section of beam.

Mod. Elas. Concrete	1,000,000.			2,000,000.			3,000,000.			4,000,000.		
		Steel.			Steel.			Steel.			Steel.	
Working Stress of Concrete in Compression.	Moment Equals d^2 Times.	Sq. Ins. Area Equals d Times.	Per Cent. of Area Section.	Moment Equals d^2 Times.	Sq. Ins. Area Equals d Times.	Per Cent. of Area Section.	Moment Equals d^2 Times.	Sq. Ins. Area Equals d Times.	Per Cent. of Area Section.	Moment Equals d^2 Times.	Sq. Ins. Area Equals d Times.	Per Cent. of Area Section.
Lbs. per Sq. In.	a	b	c	a	b	c	a	b	c	a	b	c
100	14.1	.018	.15	8.2	.013	.11	5.9	.007	.06	4.5	.006	.05
200	43.1	.060	.50	28.2	.046	.38	20.9	.027	.23	16.4	.021	.18
300	78 1	.114	.95	54.7	.090	.75	42.2	.055	.46	34.4	.044	.37
400	115.0	.174	1.45	86.2	.142	1.18	68.1	.092	.77	56.4	.074	.62
500	155.0	.240	2.00	120.0	.200	1.67	97.1	.133	1.11	81.7	.109	.91
600	195.0	.309	2.58	156.0	.262	2.18	129.0	.180	1.50	109.4	.149	1.24

NOTE: — Above table derived from equations (4), (5) and (6) by making the following assumptions: E_s = 30,000,000, f_s = 10,000 lbs. per sq. in.

of beam, *d*. Column *c* gives the area of cross-section of steel expressed as the per cent. of the area of section above the center of steel reinforcement.

595. For **example,** suppose we wish to know the strength of a beam ten inches deep ($d = h - i = 10$ in.) and the amount of steel required to develop a stress in the concrete of 400 lbs. per square inch when the stress in steel is 10,000 lbs. per sq. in., and the modulus of elasticity of the concrete is assumed at 3,000,000. In column *a* under 3,000,000 modulus, and opposite 400 lbs. stress, we find 68.1; then the moment of resistance of a beam one inch wide is 68.1 inch-lbs. × 10 × 10 = 6,810 inch-lbs., and the resistance of a beam 12 inches wide is 6,810 foot-lbs. The area of steel required in 12 inches width of beam is .092 *d* or 0.92 sq. in. This beam is reinforced with .77 of one per cent. steel. Similar tables may be prepared for other values of E_s and f_s if desired.

596. In **Table 161** the equations have been completely solved for certain typical values of E_c and f_c, assuming the values for E_s and f_s of thirty million and ten thousand respectively, as in Table 160. Having computed the bending moment, and fixed upon the probable safe working stress and modulus of elasticity of the concrete which it is proposed to use, it is only necessary to take from the table the required depth of beam and the amount of steel reinforcement required.

For **example,** a girder 10 feet long supported at the ends carries two loads of 5,000 pounds, each load being 2.5 feet from a support.

If the width of girder is 15 inches, working stress of concrete 300 lbs. per sq. in. and modulus of elasticity of concrete 1,500,000, what is the required depth of girder and area of steel in tension side?

The maximum bending moment (neglecting weight of beam) is 12,500 ft.-lbs. throughout the central five feet. The required moment of resistance for twelve inches in width is $\frac{12}{15}$ of 12,500 = 10,000 ft.-lbs. Looking in the table for this bending moment under 300 lbs. stress and 1,500,000 modulus, we find it is between $d = 12$ and $d = 14$, or at about $d = 13$ inches. If we allow 2 inches below center of steel reinforcement, we have total depth of beam, $h = 13 + 2 = 15$ inches. In the same

TABLE 161

Strength of Concrete-Steel Beams

d = depth in inches from top of beam or slab to center of steel reinforcement.
Moments in ft.-lbs. per foot width of beam (or inch-pounds per inch width).
Area steel in square inches per foot width of beam.

Working Stress of Concrete in Compr.	200 Lbs. per Sq. Inch.		300 Lbs. per Square Inch.				400 Lbs. per Square Inch.				500 Lbs. per Square Inch.				
Mod. Elast. Concrete.	1,500,000.		2,500,000.		1,500,000.		2,500,000.		1,500,000.		3,500,000.		2,500,000.		d
d = Depth.	Moment.	Steel.	Moment.	Steel.	Moment.	Steel.	Moment.	Steel.	Moment.	Steel.	Moment.	Steel.	Moment.	Steel.	
Inches.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	Ft.-Lbs.	Sq. In.	In.
1	34	.05	48	.06	65	.09	76	.11	99	.14	89	.12	108	.15	1
2	136	.09	191	.13	258	.18	303	.21	396	.29	355	.24	433	.30	2
3	307	.14	429	.19	581	.27	682	.31	891	.43	800	.36	975	.45	3
4	546	.18	763	.26	1034	.36	1213	.42	1584	.57	1420	.48	1733	.60	4
5	852	.23	1192	.32	1615	.45	1895	.52	2475	.71	2220	.60	2707	.75	5
6	1228	.27	1717	.39	2326	.54	2729	.63	3564	.85	3190	.72	3900	.90	6
7	1671	.32	2337	.45	3165	.63	3714	.73	4851	1.00	4350	.84	5310	1.05	7
8	2182	.37	3053	.51	4134	.72	4850	.83	6336	1.14	5680	.96	6930	1.20	8
9	2762	.41	3864	.58	5233	.81	6140	.94	8020	1.28	7190	1.08	8770	1.35	9
10	3410	.46	4770	.64	6460	.90	7580	1.04	9900	1.42	8875	1.20	10830	1.50	10
12	4910	.55	6870	.77	9300	1.08	10910	1.25	14260	1.71	12780	1.32	15600	1.80	12
14	6680	.64	9350	.90	12660	1.26	14860	1.46	19400	1.99	17400	1.68	21230	2.10	14
16	8730	.73	12210	1.03	16540	1.44	19400	1.67	25340	2.27	22700	1.92	27720	2.40	16
18	11050	.82	15450	1.15	20930	1.62	24560	1.87	32080	2.56	28740	2.16	35090	2.70	18
21	15040	.96	21040	1.35	28490	1.89	33430	2.19	43660	2.98	39120	2.52	47770	3.15	21
24	19640	1.10	27480	1.54	37210	2.16	43660	2.50	57020	3.41	51100	2.88	62400	3.60	24
27	24860	1.24	34770	1.73	47090	2.43	55260	2.81	72170	3.84	64700	3.24	79000	4.05	27
30	30690	1.37	42930	1.92	58140	2.70	68220	3.12	89100	4.26	79900	3.60	97300	4.50	30
33	37140	1.51	51940	2.11	70350	2.97	82550	3.43	107800	4.69	96600	3.96	117900	4.95	33
36	44200	1.65	61820	2.31	83720	3.24	98240	3.75	128300	5.11	115000	4.32	140300	5.40	36

NOTE: — Above table derived from equations (4), (5) and (6) by making the following assumptions: Mod. Elast. of Steel, E_s = 30,000,000, Stress in Steel, f_s = 10,000 lbs. per sq. in.

(Tensile strength of concrete is neglected.)

lines we find area of steel for 12 inch width between 1.08 and 1.26, or, say, 1.17; then for 15 in. width the required area is $\frac{15}{12} \times 1.17 = 1.46$ sq. in. The bars should not be more than 3 to 6 inches apart. We may use, then, 5 bars $\frac{9}{16}$ inch square or $\frac{5}{8}$ inch diameter, spaced three inches apart. In large beams it is necessary to consider the bending moment occasioned by the weight of the beam after making a first approximation to the size required.

597. The above tables are prepared on the assumption that the stress in concrete shall be equal to the value selected when the stress in the steel reinforcement reaches 10,000 lbs. per sq. in. From the equations, other tables may be prepared if desired, in which the working stress in steel shall be 12,500, 16,000 or any other assumed value. The tables are not suited to the computation of beams in which excessive reinforcement is used.

As to **actual tests** of the performance of concrete and steel in combination, the possible variations in material are so diverse and the cost of experiments so great that the results thus far obtained appear somewhat fragmentary, but each investigator has selected a small branch of the subject for experiment. Among the more valuable tests in this line may be mentioned the following: —

Tests at Massachusetts Institute Technology, Prof. Gaetano Lanza, Trans. Amer. Soc. C. E., vol. 50, p. 486.

Tests at Purdue University, Prof. W. K. Hatt, Jour. Western Soc. Engrs., June, 1904.

Tests at Rose Polytechnic Institute, Prof. Malvard A. Howe, Jour. Western Soc. Engrs., June, 1904.

Tests at University of Illinois, Prof. A. N. Talbot, Proc. Amer. Soc. for Testing Materials, 1904.

Tests at University of Wisconsin, Prof. F. E. Turneaure, Proc. Amer. Soc. for Testing Materials, 1904.

Art. 70. Concrete-Steel Beams with Double Reinforcement

598. We have seen that when the depth of a beam is limited by structural considerations we may increase the normal load by excessive reinforcement, but that this method results in low stresses in the steel and is not usually economical. We may now consider the effect of placing reinforcing rods in the compression side of the beam as well as in the tension side.

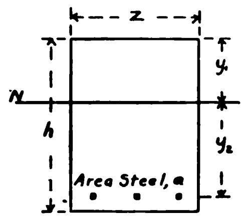

FIG. 14.
CROSS-SECTION
(Single Reinforcement.)

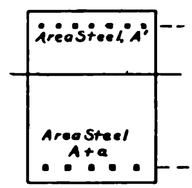

FIG. 15.
CROSS-SECTION
(Double Reinforcement.)

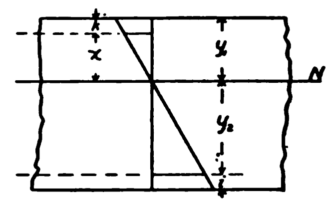

FIG. 16.
STRAIN DIAGRAM.

Let Fig. 14 represent the cross-section of a beam reinforced on the tension side with sufficient steel, area a, to develop the proper working stresses in the materials, and let the position of the neutral axis be $N\ N$. If at distance x from the neutral axis we add an area of steel A' in the compression side, the position of the neutral axis would be changed for similar loading; but if at the same time we place in the tension side an additional area of steel A such that $\frac{A}{A'} = \frac{x}{y_2}$, the position of the neutral axis will be unchanged. Let f_s' = stress in steel in compression; then since the steel must suffer the same deformation as the surrounding concrete $\frac{f_s}{f_s'} = \frac{y_2}{x}$. Multiplying the last two equations, we have, $f_s A = f'_s A'$, that is, we have added equal forces to the two sides of the beam, and have increased the moment of resistance by $f_s A (x + y_2)$ inch-pounds.

599. To illustrate the application of this principle we may take the beam considered in § 591, in which $z = 8$, $R = 20$, $r = 40$, $az = .444$, $a = \frac{.444}{8} = .055$, $f_s = 80{,}000$, $y_2 = \frac{20}{3}$ inches, $y_1 = \frac{10}{3}$ in., and $M = 311{,}100$ inch-pounds.

When the area of reinforcement in the tension side of this beam was increased to $az = 3.12$ sq. in. or $a = .39$, the theoretical bending moment was increased to 522,000 inch-pounds (§ 592). What will be the result of a similar increase in steel distributed between the two sides of the beam?

Let k = distance from top of beam to center of reinforcement on compression side = 2 inches,

then $$x = y_1 - 2'' = \frac{10}{3} - 2 = \frac{4}{3} \text{ inches},$$

$$\frac{A}{A'} = \frac{x}{y_2} = \frac{4}{3} + \frac{10}{3} = 0.4 \quad \text{or } A = 0.4\,A'.$$

$$A + A' = .39 - .055 = .335$$

$1.4\,A' = .335$	$A' = .24$	$A'z = 1.92$
	$A = .095$	$Az = .76$
whence	$a = .055$	$az = .44$
	$A + a = .150$	Total steel, 3.12 sq. inches.

$$f_s' = \frac{f_s x}{y_2} = .4\,f_s = 32{,}000.$$

Added moment of resistance equals

$$Az\,(x + y_2)\,f_s = .095 \times 8 \times \frac{24}{3} \times 80{,}000 = 486{,}400 \text{ in.-lbs.}$$

And total moment of resistance equals

$$311{,}100 + 486{,}400 = 797{,}500 \text{ inch-pounds.}$$

None of the bars in the series mentioned in § 591 had as large an area of reinforcement as 1.92 sq. in. on the compression side.

It is noticed, first, that the double reinforcement gives better results than such excessive reinforcement on the tension side; second, that the stress in steel on the compression side is less per square inch than that in tension; and third, that in case a large addition of steel is made, this results in a greater area of steel in compression than the total area of steel in tension. In practice the area of steel in compression is usually made equal to, or less than, the area in tension, but beams with double reinforcement are seldom accurately designed.

ART. 71. SHEAR IN CONCRETE-STEEL BEAMS

600. There are several methods of failure of concrete-steel beams other than those considered above, direct tension in the steel or direct compression in the concrete due to the bending moment. These other methods of failure are popularly called failures in shear, although some of them cannot properly be so classed.

601. We have seen that the shearing stress of concrete is usually considered to be somewhat in excess of the tensile strength (§458) and that the latter is one-fifth to one-tenth the compressive strength. With a beam having only a normal amount of reinforcement, then, there is little danger to be feared from simple vertical shear, and as a matter of fact, tests have not developed instances of such weakness. In comparatively short spans, however, failures have occurred near the quarter points, in cracks starting at the under side of the beam and extending upward in a direction inclined toward the center. This method of failure has the appearance of being due to a combination of shear and tension in the lower section of the beam, since the cracks are approximately at right angles to the theoretical "lines of direct tension." Such failures, however, are almost always accompanied by a slipping of the steel bar in the concrete, and may frequently be prevented by taking proper precautions against such slipping.

602. A more frequent cause of failure is a longitudinal shear in the plane near the steel reinforcement and on that side of it lying nearer the concave side of the beam.

It is evident that a failure caused by slipping of the bar in the beam, although caused primarily by shearing forces, is really a failure in adhesion, yet the two forms of weakness are so closely connected that it is simpler to consider them together.

603. *Comparison with Plate Girder.* — In a steel plate girder the lower flange is considered to carry the tension, the upper flange the compression; the web connects the two flanges, causing them to act together as one beam, and we may think of the web as preventing the ends of the compression flange sliding beyond the ends of the tension flange. When the web is not able to accomplish this without buckling, it is stiffened by vertical angles.

In a concrete steel beam we have considered the entire tension to be carried by the steel reinforcement, and the entire compression to be carried by the concrete on the other side of the neutral axis. The connecting web is also concrete. This web is thick and not liable to buckle, but it may shear in a longitudinal plane as a wooden beam may do when short and deep. All of the tension in the steel reinforcement must be transmitted through the surrounding concrete. If there are no projections on the steel bar, the adhesion of the concrete to it may, under certain circumstances, be not strong enough to safely carry this stress; and if the adhesion is sufficient, then the shearing strength of the concrete may be too low to transmit the stress to contiguous fibers or layers.

604. *Illustration.* — Let us consider a concrete-steel beam twelve inches wide, twelve inches deep and of ten foot span, supported at the ends; reinforcement, one square inch of metal properly distributed in a plane two inches above the bottom of the beam. Let us suppose this beam carries a uniform load of 600 pounds per foot, giving a maximum bending moment of 90,000 inch-lbs., and a stress in steel of 10,000 pounds at the center. The ends of the steel bars are of course without stress. Since the bending moment at any section of such a beam is proportional to the product of the segments into which the section divides the span, the bending moment one foot from the ends will be

$$\frac{1 \times 9}{5 \times 5} \times 90{,}000 = 32{,}400 \text{ inch-pounds.}$$

Let us consider the neutral axis in the same position at the end of the beams as near the center. (This is not strictly true, because of the lighter stress near the ends of the beam, but the error made by such an assumption will be unimportant for our present purpose.) Then the tension in the steel will have the same proportion, or, tension in steel one foot from the end $= \frac{9}{25} \times 10{,}000 = 3{,}600$ pounds.

The stress in steel, then, which is zero at the end, has increased to 3,600 lbs. in one foot of length. To provide against poor contact near the end, consider two-thirds of this length, or eight inches, to be operative. If the reinforcement consists of four one-half-inch square bars, the necessary adhesion per square inch is $\frac{3600}{8 \times 8} = 57$ lbs. per sq. in.; but if only one bar is used one inch square, the required adhesion is 114 lbs. per sq. in. The latter would not be good practice, not only because of high adhesion required, but because the steel is not properly distributed.

Where the stress in adhesion is greater than can be safely relied upon for plain rods, it is necessary to use some kind of deformed bar, or to anchor the bar securely at the end. This may be done by passing the end of the tension bar around a rod transverse to the beam near the end. Care should be taken that the safe value of adhesion is not assumed too high.

605. *Value of Shear.* — The same total stress of 3,600 lbs. must be transferred through the concrete immediately above the bar. If the reinforcement is so distributed that the entire width of the beam has practically the same stress, and we consider, as before, that two-thirds of the length of the end foot is operative, we have mean shear $= \frac{3,600}{12 \times 8} = 37.5$ lbs. per sq. in. The value of stress in shear should not exceed one-tenth the safe value in compression, and there is a general tendency to use not more than one-twentieth.

If the same form of beam had a span of but five feet with same bending moment, the value of the shearing stress by this method becomes 75 lbs. per sq. in., and it will be necessary to provide against this stress coming upon the concrete.

Another approximate method is the ordinary one for rectangular beams, viz. to consider the shear in horizontal plane just above the steel reinforcement to be $\frac{3}{2}$ times the total shear at any section, divided by the area of vertical section of the beam.

606. Provision is sometimes made for relieving the concrete of all shearing stresses. In this case the beam is divided into imaginary panels of length equal, say, to the depth of the beam, and the diagram of maximum shear is drawn. The shear in each imaginary panel is then provided for by a vertical or inclined bar of the proper dimensions. Or, what is usually better, the shear bars are all of one size and the proper number of them are distributed throughout each panel length; the spacing of the shear bars thus becomes wider near the center of the beam.

607. Resistance to Shear. — When provision against shear is made by using small steel rods placed either vertical or inclined downward toward the center of the beam, as mentioned above, these rods may well be made in the form of inverted U-shaped stirrups, with their ends securely fastened to the reinforcing metal in tension.

In many cases all the provision necessary is given by the use of two longitudinal bars, parallel and close together near the center of the span, but one of them leading to a plane near the top of the beam at the supports. This system is very conveniently applied in concrete slabs supported by I-beams, one bar of the pair being hooked over the upper flanges of the I-beam and sagging toward the center. The Hennebique system (§ 571) is a combination of the inclined bar and U-shaped stirrups.

608. A modification of the single inclined bar is the Cummings system, wherein there are several pairs of bars of varying lengths; these are all horizontal and near the bottom along the center of the beam; a short distance from the center the shortest pair turns up at an angle of about forty-five degrees; a little farther toward the end a second pair of bars is turned up, and so on, leaving a single pair to go through straight to the support.

Another, and more radical modification, is the Kahn system (§ 573), in which the bar is square with wings of metal on opposite corners which are sheared and bent up at angles of forty-five degrees, so that the outline of the steel work in a beam resembles the tension members of a Pratt truss.

CHAPTER XX

SPECIAL USES OF CONCRETE: BUILDINGS, WALKS, FLOORS AND PAVEMENTS

ART. 72. BUILDINGS

609. While the use of concrete and steel for the walls and floors of buildings is about fifty years old, yet it is only in comparatively recent years that its value has become generally known. It is now applied to all classes of structures, warehouses, factories, residences, station and office buildings, and it is anticipated that in the next twenty years concrete-steel will be as familiar in architecture as steel skeleton, stone, and brick are now.

610. It happens that at present the concrete-steel building industry is largely in the hands of companies who are exploiting some particular form of steel rods or bars applied according to some one of the many "systems" of reinforcement. This condition has both good and bad features. A reputable concern of this kind will have in their employ engineers who should satisfy themselves that each design is a safe one, for the failure of a building will cast disrepute on their particular system. It is this fact that leads the companies to keep the construction entirely, and the design largely, in their own hands. Another advantage is that these concerns are able to perfect methods of construction by experience, and to lessen the expense of one structure by making use of the concrete plant and the molds that have been used on another.

611. In making plans for a building, the owner is usually represented in the first instance by an architect whose business it is to dictate the design. If concrete-steel is considered, the architect may call an engineer in consultation and they may together harmonize the features of utility and appearance with economy and strength, but in letting the contract it is found that the competition is limited to one or two companies using the particular system which the engineer considers the best adapted to the particular conditions in question.

On the other hand, the architect will hesitate to go to the construction company for assistance, since he must first select the system he shall use, a question upon which his ideas may be neither clear nor well grounded, and he is then having the prospective contractor assist in the design. Under these circumstances the architect will usually consider concrete-steel construction as something he wishes to avoid if possible. But this condition will correct itself in time, for owners will demand a consideration of this form of construction, engineers will become familiar with its use and will be employed to design the engineering features, while reliable contractors in every city will obtain permission to build in accordance with any "system" under the supervision of a competent engineer.

612. Roof. — While a pitch roof is sometimes built of concrete-steel, this form of construction is particularly adapted to so called flat roofs. The roof is constructed much the same as a floor slab (Art. 65–67), except that expansion joints are sometimes provided, and the roof is covered with tar and gravel, or some of the patent roofings ordinarily used. While the roof loads are usually light, permitting a greater span of slab between beams than for floor construction, it will seldom be economical to introduce these longer spans because of the changes necessary in the molds. In most buildings it is necessary to provide against condensation, and for this purpose a flat ceiling may be suspended at the level of the under side of the beams giving an air space.

613. Floor System. — The floors may be constructed in conformity with the principles stated in Chapter XIX. The strength of short span arches, such as are used for floors, where the haunches are built up level with the top of crown of arch, is a matter of experiment and cannot be accurately determined theoretically. Empirical formulas may be derived for a certain system based on a sufficient number of tests. The principles underlying the strength of slabs may be considered the same as those applying to beams (Art. 69), although if the length of slabs is not much greater than the span, they are not strictly applicable, but will err on the safe side.

614. A decision must first be made as to the size of bays into which the floor space is to be divided. This will of course depend on the use of the building, the engineering features conforming to requirements of utility. If the bays are not square, the girders should usually take the shorter span between columns. This length is then divided into the number of slab spans that will give maximum economy. The shorter these spans the less the amount of material required in slabs and the greater the number and cost of floor beams. Computations should be made, therefore, for two or three arrangements to determine this point. As this distribution for maximum economy will vary with the loads to be provided for, it is well, if the floors are not all to carry the same load, to take for this computation a load intermediate between the heaviest and lightest, and use if possible the same arrangement of spans throughout the building.

The strength of slabs for given bending moments may be taken directly from Table 161, after deciding upon the working stress to be allowed in the concrete and the probable modulus of elasticity. The beams and girders, if single reinforcement is used, are taken from the same table or computed by the methods of Art. 69.

615. In some instances it may be found economical to use concrete-steel slabs for floors supported by concrete protected steel beams and girders. One advantage of this system is that the forms for building the protecting concrete and for the floor slabs may be hung from the steel girders and beams. For this method of construction the enveloping concrete should not be less than one and one-half inches thick over the edges of flanges, and wire fabric or metal lath wrapped about lower flanges of beams will insure the concrete remaining in place. This is not properly concrete-steel construction, but simply concrete protected steel, and except in case the concrete extends well above the steel, forming an independent compression flange, no added strength should be computed for the concrete covering.

616. Columns. — In the foundations of buildings of moderate height the supporting columns may be built entirely of concrete. Since, however, the pressure on the concrete, even when it is constructed with the greatest care, should not exceed two hundred to three hundred pounds per square inch, the required area of cross-section in the lower stories is usually so great as to preclude the use of columns built entirely of concrete.

617. Concrete Filling and Covering. — A steel column of any of the ordinary styles, built up of steel shapes may be used, and protected from corrosion and fire by filling and covering with concrete. This not only serves as a protection against rust, but materially increases the stiffness and permits the use of a somewhat higher working stress in the steel. The concrete filling should be mixed quite wet in order that it shall work into all angles. The edges of the metal should not approach nearer than one and one-half inches to the exterior of the concrete, and flat surfaces of metal should have a covering of at least two and one-half inches. Where it is necessary to cover large, flat surfaces, they should be first covered with expanded metal or wire fabric, locked on by twisting around the edges of the plate or channel.

618. COLUMNS OF CONCRETE STEEL. — Concrete-steel columns differ from the above in that the main dependence is placed on the concrete rather than on the steel. For such columns longitudinal reinforcement has generally been employed. Steel bars extending from end to end of the column are distributed throughout the cross-section, and are tied together at intervals of four to twelve inches by smaller bars forming loops to hold them in place. The splicing of the bars is effected by placing a small tube over the upper end of the lower bar and projecting above it, and then setting the lower end of the upper bar within the tube resting on the lower bar. Where this is done it is essential that the two ends be planed perfectly square, and it is much better to avoid splices in a column between lateral supports. In a building the reinforcing rods project up through the floor above and are spliced into the bars of the columns in the next story.

619. Strength of Columns. — When a column reinforced with longitudinal bars is subjected to pressure, the concrete and steel must shorten together. The relative stresses in the two materials will then be proportional to their moduli of elasticity. From this follows the formula,

$$P = f_c (C + RS)$$

where P = total pressure on column,

f_c = stress in concrete,

C and S = areas of concrete and steel respectively, and $R = \frac{E_s}{E_c}$, or ratio of the modulus of elasticity of the steel to that of the concrete.

In a series of tests of twenty-one columns made by Prof. Gaetano Lanza,[1] but three failed under a lower stress than that computed by the above formula. The columns were eight to ten inches square, six to seventeen feet long and reinforced with either one or four bars, the latter being from ¾ inch to 1¼ inches square.

The lowest breaking load was fifty tons on an 8 by 8 inch column with one bar one inch square, and the strongest column, 10 by 10 inches, with four ¾ inch longitudinal bars, was not crushed with a load of one hundred fifty tons, the limit of the testing machine. The lowest result was twenty per cent. less than that given by the formula, and the greatest excess strength over the theoretical was fifty per cent.

620. While longitudinal reinforcement undoubtedly strengthens a long column against flexure, as well as adds to the resistance to crushing, yet the added strength is gained at the expense of considerable additional cost. Suppose we have a ten inch square column, twelve feet long, made of concrete with a breaking load of 1,800 lbs. per square inch, or 180,000 lbs. total breaking load. Suppose eight ¾ inch square bars to be built into this column as longitudinal reinforcement, and that the modulus of elasticity of the steel is ten times that of the concrete. Then the strength of the reinforced column would be, by the formula above,

$$P = 1{,}800\ (95.5 + (10 \times 4.5)) = 252{,}900.$$

The longitudinal reinforcement has thus resulted in an increase of strength of 40 per cent., while by the addition of 180 pounds of metal, the cost of the column has risen from about $3.00 to say $8.50, an increase of about 180 per cent. without counting the cost of lateral ties, and the additional trouble in building a reinforced column.

621. Hooped Concrete. — In extended experiments on what he has called "hooped concrete," M. Considère[2] has shown that

[1] Trans. A. S. C. E., Vol. l, p. 487.

[2] *Comptes Rendus de l'Academie des Sciènces*, 1898–1902. **Translation,** "Reinforced Concrete," by Armand Considére, translated by Leon S. Moisseiff, McGraw Publishing Co., New York.

reinforcement is much more important and beneficial in a transverse or circumferential direction than if longitudinal. This may be accounted for by the fact that the natural method of failure of concrete prisms, is by splitting along planes parallel to the direction of pressure, and the ordinary method of failure by shear along inclined surfaces is induced by the friction of the plates transmitting the pressure to the prism. It was also shown that while concrete reinforced by longitudinal bars with the ordinary amount of lateral ties breaks suddenly, hooped concrete fails gradually under a much heavier load.

622. M. Considère concluded from his experiments that the circumferential ties should not be farther apart than one-seventh to one-tenth the diameter of the column, even when longitudinals were used to assist in completing the network, and that the results were more successful the nearer together the hoops or ties were placed. He found that spirals were better than individual single ties and that longitudinals were of value chiefly in assisting to confine the concrete, transmitting the bursting pressure at a given plane to the contiguous spirals above and below.

623. M. Considère says[1] that the "compressive resistance of a hooped member exceeds the sum of the following three elements: —

"1. Compressive resistance of the concrete without reinforcing.

"2. Compressive resistance of the longitudinal rods stressed to their elastic limit.

"3. Compressive resistance which could have been produced by imaginary longitudinals at the elastic limit of the hooping metal, the volume of the imaginary longitudinals being taken as 2.4 times that of the hooping."

To subject hooped concrete to a practical test, M. Considère constructed, in 1903, a truss bridge of sixty-five foot span with parabolic top chord of seven and one-half feet rise,[2] the compression members being of hooped concrete, and the tension members of concrete-steel with longitudinal reinforcement, or concrete protected steel. A central panel of the truss was con-

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[1] "Reinforced Concrete," p. 159.

[2] *Engineering News*, May 5, 1904.

structed with a reduced section of top chord about eight inches diameter reinforced by eight longitudinal bars .43 inch in diameter and a helix 6¼ inches in diameter of .43 inch metal coiled to a pitch of about one inch. This reduced top chord section showed signs of failure when the computed stress reached about 5,000 pounds per square inch.

624. FORMS FOR BUILDINGS.—One of the most serious problems in the construction of concrete-steel buildings is the designing of the forms. They must be as light as is consistent with strength to facilitate handling. They should be of simple construction so that they may be set up and removed without too much supervision, and they should be so assembled with bolts and screws that they may be used repeatedly. In erecting a large building sufficient forms are usually provided to set up one floor complete, including columns, beams, girders and floor slabs. After placing the reinforcement, the concrete is filled in as rapidly as possible, making the slabs, girders and columns practically monolithic.

The forms for the girders usually rest upon the column molds and are supported at intermediate points by posts resting on the completed floor below. While column molds are sometimes filled from the top, better work is assured by having one side of the mold built up as the concrete is filled in from the side.

The mold to receive the concrete forming the floor slab is either a part of, or is supported by, the pieces forming the sides of the girders and beams. Provision is sometimes made for leaving supports at intervals under the completed beams and girders after removing the forms from the sides of the beams and the bottom of floor slabs. This is done by making the bottom piece of the girder mold separate, and attaching the side pieces to it by screws which may be removed without disturbing the bottom. The caps of the supporting posts are then made long enough to permit the lower edges of the side pieces to rest directly on them. This method was adopted in building the Central Felt and Paper Company's factory at Long Island City.[1]

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[1] Wight-Easton-Townsend Company, Contractors, *Engineering Record*, Jan. 16, 1904.

625. In the same building the walls were built with molds three feet high and sixteen feet long, placed in pairs on opposite sides of the wall. When one section was completed, the molds were "lifted until the lower edges were two inches below the top of the concrete. In the new position they were supported by horizontal bolts through their lower edges, across the top of the concrete; the upper edges were tied together by transverse wooden strips nailed to them about three feet apart, and they were braced to the false work supporting the roof and column molds." "The bolts passed through sleeves which were left permanently embedded in the walls. At first, iron pipes were used for this purpose, but afterwards it was discovered that pasteboard tubes were equally efficient and much easier to trim and point after the molds were removed."

626. An excellent system of molds was used in the construction of the Kelley and Jones Company's factory at Greensburg, Pa.[1] The floor molds were especially convenient, being made collapsible by a hinge joint at the top along the longitudinal center line. These floor molds were in reality cores between adjacent floor beams; when in place the top surface was horizontal, to form the under side of the floor slab, and the vertical side pieces formed the sides of the floor beams. When the concrete had set sufficiently, the lower edges of the form were made to approach each other, thus coming away from the concrete gradually. A special light wooden framework or tower, with a working platform six feet below the floor, and a rope sling to receive and lower the floor mold, permitted of removing the molds rapidly and without injury. A special truck was also used for moving the floor molds about the building.

627. A convenient adjunct for the construction of concrete wall forms consists of a short section of I-beam having a width between flanges equal to the thickness of the plank to be used. These plank holders are laid in pairs, with web horizontal, one on either side of the wall, and connected by a bolt passing through them and through the wall.[2] Two rows of planks on edge are first placed around the building so as to inclose the pro-

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[1] Mr. E. L. Ransome, Architect and Engineer, *Engineering Record*, Feb. 6 and 13, 1904.

[2] Patented by Thomas G. Farrell, Washington, N. J.

posed wall. At the upper side of each junction between two planks in the same horizontal row is placed one of these plank holders. Another horizontal row of planks may now be placed, with the iron plank holders at the joints as before. As the wall is built up, the lower planks and holders may be removed and placed on top, and thus few forms are required. Tees and L-forms are provided for partition walls and corners.

When an air space is desired in a wall a special terra cotta tile or building block may be built into the wall, but this is quite expensive, and an interior collapsible form may be made of timber by the use of two planks held apart by a wooden brace which may be knocked out. Special means of handling the interior plank should be provided, and the building of a high wall cannot be continuous with this method.

628. New York Building Regulations. — While city building regulations are not always criteria of good practice, yet the Regulations of the Bureau of Buildings of the Borough of Manhattan concerning the use of concrete-steel construction are exceptional. Emanating from a bureau that has been distinctly hostile to concrete-steel, they are naturally conservative, but are, on the whole, excellent, and work conscientiously done in accordance with them will not bring discredit on concrete construction.

It is specified that the cement shall be only high grade Portland standing certain tests, that the sand shall be clean and sharp, aggregate, broken trap, or gravel of a size that will pass a three-quarter inch ring, and that the proportions used shall be one cement, two sand and four of stone or gravel, or that the concrete shall have a crushing strength of two thousand pounds per square inch in twenty-eight days. Only the best quality of concrete is thus permitted.

629. The Regulations concerning the design are then stated as follows: —

"Concrete-steel shall be so designed that the stresses in the concrete and the steel shall not exceed the following limits: —

Extreme fiber stress on concrete in compression,	500 lbs.	per	sq. in.
Shearing stress in concrete	50	"	"
Concrete in direct compression	350	"	"
Tensile stress in steel	16,000	"	"
Shearing stress in steel	10,000	"	"

"The adhesion of concrete to steel shall be assumed to be not greater than the shearing strength of the concrete.

"The ratio of the moduli of elasticity of concrete and steel shall be taken as one to twelve.

"The following assumption shall guide in the determination of the bending-moments due to the external forces: Beams and girders shall be considered as simply supported at the ends, no allowance being made for the continuous construction over supports. Floor plates when constructed continuous and when provided with reinforcement at top of plate over the supports, may be treated as continuous beams, the bending-moment for uniformly distributed loads being taken at not less than $\frac{W L}{10}$; the bending-moment may be taken as $\frac{W L}{20}$ in the case of square floor plates which are reinforced in both directions and supported on all sides. The floor plate to the extent of not more than ten times the width of any beam or girder may be taken as part of that beam or girder in computing its moment of resistance.

"The moment of resistance of any concrete-steel construction under transverse loads shall be determined by formulas based on the following assumptions: —

"(*a*) The bond between the concrete and steel is sufficient to make the two materials act together as a homogeneous solid.

"(*b*) The strain in any fiber is directly proportionate to the distance of that fiber from the neutral axis.

"(*c*) The modulus of elasticity of the concrete remains constant within the limits of the working stresses fixed in these Regulations.

"From these assumptions it follows that the stress in any fiber is directly proportionate to the distance of that fiber from the neutral axis.

"The tensile strength of the concrete shall not be considered.

"When the shearing stresses developed in any part of a construction exceed the safe working strength of concrete, as fixed in these Regulations, a sufficient amount of steel shall be introduced in such a position that the deficiency in the resistance to shear is overcome.

"When the safe limit of adhesion between the concrete and steel is exceeded, some provision must be made for transmitting the strength of the steel to the concrete.

"Concrete-steel may be used for columns in which the ratio of length to least side or diameter does not exceed twelve. The reinforcing rods must be tied together at intervals of not more than the least side or diameter of the column.

"The contractor must be prepared to make load tests on any portion of a concrete-steel construction, within a reasonable time after erection, as often as may be required by the Superintendent of Buildings. The tests must show that the construction will sustain a load of three times that for which it is designed, without any sign of failure."

Art. 73. Concrete Walks

630. One of the most important uses of concrete is in the construction of street and park walks. It has not only driven stone flagging almost out of use, but it is being employed to a large extent in towns and villages where board walks have formerly been used almost exclusively.

A concrete walk is made up of a sub-base or foundation, a base, and a wearing surface.

631. Foundation. — As in other structures, one of the most important essentials for success lies in the preparation of the foundation, and the care that must be bestowed on it will depend upon the character of the soil and the climate. In the higher latitudes of the United States, frost may soon destroy a walk the foundation of which is not well drained.

The excavation should be made to the sub-grade previously determined upon, any objectionable material such as loam or organic matter being removed, and the bottom of the excavation smoothed and well rammed. Upon this is laid the sub-base, its thickness varying from nothing to twelve inches. In a sandy soil with good natural drainage and little danger from frost, and where light traffic is expected, it may be unnecessary to provide any special sub-base, since the soil itself furnishes a good foundation for the concrete, but in clay soil in northern climates, twelve inches of sub-base may be required. The best material for this sub-base is broken stone varying in size from one-half inch to two and one-half inches. Usually broken stone is considered too expensive, and gravel, coarse sand, cinders, or broken brick is employed. A layer four inches thick is usually sufficient for good materials, but six to twelve inches of cinders are sometimes required. It should be well rammed to a level surface, and when completed should be firm but porous.

The most important point is that this course shall have good drainage, otherwise it may be a menace to the walk. If it is more porous than the retaining soil, it will naturally drain this soil, and if the water is not able to escape into the sewer or elsewhere, it may be frozen and heave the walk. An excellent plan sometimes adopted is to lay at intervals of twenty to twenty-five feet, a blind stone drain from the walk foundation to the foundation of the curb. In exceptional cases it may be necessary to lay a tile drain in the sub-base to lead the water away from the walk.

632. Base. — The base is the body of the walk giving stiffness to the structure. Its functions are to furnish a solid foundation for the wearing surface and to give transverse strength to the walk, transmitting the pressure uniformly to the sub-base. The base is of concrete, which need not be very rich for ordinary traffic. A proportion of one part packed Portland cement to two and one-half volumes of dry sand and six volumes broken stone is excellent, and proportions of one, three and seven parts cement, sand and stone, respectively, will usually be found sufficient, though the richer the concrete in the base the better will the top dressing adhere to it.

The broken stone for this concrete should be of a size not exceeding one and one-half inches in any dimension, some cities requiring three-quarters inch or less. Crushed granite and trap are excellent, though limestone or any other moderately hard rock may be used that is suited to making concrete for ordinary purposes. If of a hard rock, the screenings may well be left in the broken stone, and when this is done, the dose of sand should be diminished. (See Art. 37.)

The thickness of the layer of concrete should not be less than three inches. Four inches is much better and is recommended for general use in sidewalks, while in exceptional cases six inches is required. The top of the concrete base should be finished to a plane parallel to the proposed surface of the walk and at a distance below it equal to the proposed thickness of the top dressing.

633. Wearing Surface. — The preparation and application of the wearing surface require much care if satisfactory results are to be obtained. The most evident service of this layer is to withstand wear, and it should therefore be made of rich Portland cement mortar. With a sand consisting principally of quartz particles, it is found that a mortar composed of equal parts cement and sand gives about the best results in tests of abrasion. If the mortar is used richer than this, it is likely to check or crackle in setting, marring the appearance of the walk. Mortar containing two parts cement to three parts sand gives nearly as good results, and two parts sand or fine crushed granite to one of Portland cement is usually satisfactory. The sand for the mortar should be quartz if possible, or crushed granite or trap. It should be screened through a quarter inch mesh, and there should not be a large proportion of very fine particles.

The thickness of the layer of top dressing is usually about one inch, and this is probably the maximum thickness ever required. One-half inch of top dressing is believed to be sufficient when the wear is not excessive, provided the base has been carefully leveled.

634. The Construction of the Walk. — If the walk has not a considerable longitudinal slope, it should be given a transverse slope of about a quarter inch to the foot to provide for draining the surface.

Stakes for grade and line having been given, a maitre cord is stretched along the line stakes to mark the sides of the excavation. After the material has been excavated to the proper sub-grade and all soft material in the bottom removed, the bottom of the trench is well rammed. If tile drain is necessary, it is laid with open joints on this foundation. The material to form the sub-base is now wheeled in and rammed to the proper thickness, water being used freely if it facilitates the packing. The top of the sub-base is brought to a level plane at the proper distance below the grade stakes.

The **molds** for the walk are now to be laid. These are made of two by four or two by six inch scantling, sized and dressed on at least one side and one edge. Stakes are first securely driven, about five or six feet apart, with their faces two inches back from the side lines of the proposed walk, and their tops at grade. Against these stakes the scantlings are placed on edge with dressed side toward the walk, and smooth edge level with the grade stakes. These molds are held in place by nailing through the supporting stakes into the scantling, and if these nails are not driven "home," they may easily be pulled to release the mold when the work is completed. On the upper edges of the mold are then marked off the sizes of blocks desired, being careful that the marks defining a joint are exactly opposite each other on the two scantlings.

635. The concrete materials having been previously delivered near the work, the concrete is mixed, either by hand or machine, according to the methods already given, and rammed in place after the sub-base has been well wet down to receive the concrete. The concrete should be just short of quaking, and in ramming care must be taken not to disturb the molds. For tamping next the molds, the makers of cement working tools offer a light rammer with square face at one end and blunt, chisel shaped tamper at the other. The surface of the base is brought to a plane parallel to the proposed finished surface of the walk, and at a distance below it equal to the thickness of the top dressing. A straight edge, long enough to span the walk and notched out at the ends so that when placed on the molds the straight edge will define the correct grade of the base, is a convenience here.

636. The concrete is now cut into blocks exactly corresponding to the proposed blocks in the top dressing. For this purpose a straight edge is laid across the walk in line with marks previously made on the molds to define the joints, and with a spade or special tool the concrete base is cut entirely through to the sub-base. This division is necessary to allow for expansion and contraction, and prevent cracks in the top dressing elsewhere than at the joints. This joint in the base should then be filled with clean sand. If preferred, these joints in the base may be made by placing thin steel strips across the molds to be removed after the concrete for the next block is in place.

The end block made from a given batch of concrete should be limited by a cross mold set exactly on line of a proposed joint. When the base is continued, this cross mold is removed. A part of a block should never be molded and then built on after having stood long enough to begin to set. Any concrete left over from finishing a block should either be mixed in with the next batch, if this is to follow in a very short time, or it should be wasted. A disregard of this rule will probably result in a crack in the top dressing above the line of division between adjacent batches.

637. When a block of base is finished, the top dressing or wearing surface should be applied immediately. The lack of adhesion between the base and wearing surface is one of the most frequent causes of failure in cement walks. The mortar should not merely be laid on in a thick layer and then struck off to grade, but it should be worked and beaten into close contact with the concrete at every point. The mortar should be tamped with a light rammer and beaten with a wooden batten, and to accomplish this properly the mortar must not be very wet. The surface is then to be struck off with a straight edge bearing on the top of the mold planks. Some hollows or rough places will remain, and the straight edge should be run over a second or perhaps a third time, a small amount of rather moist mortar, made from thoroughly screened sand, having been first applied to such places.

When the surface film of water is being absorbed, the surface is worked with a wooden float. The exact time when the work should be floated will soon be known by experience. After the floating is completed, the trowel may be used to give a smoother surface, but this makes the walk so slippery that it is not usually desirable.

638. If the top dressing is worked too long, the cement is brought to the surface, robbing the next lower layer of its cement and resulting in scaling. The top dressing is now cut entirely through on exact line above the joints in the base. This may be done by a trowel working against a straight edge, but special tools are made for cutting through the mortar and rounding the edges of the joint at one operation. A quarter-round tool is also run along the edges of the mold to give a neat finish. When desired, an imprint roller run over the walk gives it the appearance of having been bushhammered.

It is important that the top dressing be applied before the concrete has begun to set, and it must not be applied to a portion of a block and then some time allowed to elapse before applying the remainder. The edge of the top dressing must be cut off squarely at the end of the block. If desired, the wearing surface may be colored by the use of lamp black in the mortar, giving a uniform gray color to the walk. (§ 535.)

639. When the walk is completed, it should be fenced off so that animals may not walk over it while still fresh, and it should be protected from a hot sun. The surface should be kept moist, and this may be done after the first twenty-four hours by spreading a layer of damp sand over the walk and wetting the sand with a rose nozzle as often as may be needed. The walk may be opened to light travel after about four days, but it is better to remain covered with the damp sand for a week.

640. Cost of Concrete Walk. — The cost of concrete walks varies from ten cents to twenty-five cents per square foot. A fair price for a walk of average quality where there are no special difficulties is twelve to eighteen cents per square foot.

As an instance of a walk built with special care, the one constructed about the top of the bank of the Forbes Hill Reservoir may be mentioned.[1] The sub-base of this walk was of stone and twelve inches thick, the layer of concrete was five inches thick at the center of the walk and four inches at the sides. The top was of granolithic finish one inch in thickness. The walk was laid in separate blocks about six feet square. The average gang employed on the concrete consisted of six men and one team, while the finishing was done by two masons and one tender. The amount laid per day was about forty square yards. The cost per square yard was as follows: —

⅓ cu. yd. stone in foundation or sub-base, at $.40 per cu. yd.	$0.133	
Labor, placing stone at $1.50 per day	.502	
Total cost stone foundation per sq. yd. of walk		$0.635
.158 bbl. cement, at $1.53 per bbl.	$0.242	
.065 cu. yd. sand, at $1.02 per cu. yd.	.066	
.109 cu. yd. stone, at $1.57 per cu. yd.	.170	
Labor, mixing and placing concrete	.450	
Total cost concrete base per sq. yd.		$0.928
.11 bbl. cement, at $1.53 per bbl.	$0.168	
.022 cu. yd. sand, at $1.02 per cu. yd.	.022	
Lamp black	.008	
Labor, preparing and finishing surface	.149	
Total cost top dressing or wearing surface		$0.347
Total cost walk per sq. yd. { Materials $0.81; Labor 1.10 }		$1.910

[1] C. M. Saville, M. Am. Soc. C. E., *Engineering News*, March 13, 1902.

641. The following is given as an estimate of cost of items in a walk built with six inch cinder sub-base, four inch concrete base and one inch top dressing.

	Cost per sq. yd. of Walk	
	Materials	Labor
Preparation of foundation, excavation and ramming . . .		$0.20
Sub-base, 6 in. cinders $\frac{1}{6}$ cu. yd., at $0.40 cu. yd.	$0.07	
Placing and ramming cinders		0.04
$\frac{1}{9}$ cu. yd. concrete, at $3.00 per cu. yd. for materials alone .	0.33	
$\frac{1}{9}$ cu. yd. concrete, placing, at $1.80 per cu. yd.		0.20
Top dressing $\frac{1}{36}$ cu. yd. mortar, at $9.00 per cu. yd.	0.25	
Placing top dressing and finishing walk		0.25
Superintendence and molds		0.10
Totals	$0.65	$0.79
Total cost per sq. yd., $1.44, or 16 cents per sq. ft.		

642. As an example of a low priced walk, the concrete walks in San Francisco[1] are but three inches thick, two and one-half inches of concrete composed of one part Portland cement, two parts beach gravel, and six parts of crushed rock of size not exceeding one inch; the top dressing being one-half inch thick of equal parts Portland cement and beach gravel. With cement $2.50 per bbl., crushed rock and gravel from $1.40 to $1.75 per cu. yd., and wages twenty cents an hour for laborers and forty cents for finishers, this walk is constructed at from nine to ten cents per square foot. It is stated that a gang of three or four men will lay 150 to 175 square feet per day.

Art. 74. Floors of Basements, Stables and Factories

643. The principles governing the laying of walks apply also in a general way to the construction of floors that rest directly on the ground.

For **residences,** basement floors may be laid with three inch base of concrete and one-half inch wearing surface. The thickness of sub-base will depend upon the character of the soil. Where natural conditions do not assure good drainage of the foundation, this should always be provided for by either a blind stone or tile drain laid around the outer edge of the building and leading to the sewer or other outlet. The finished surface of the floor should always have a slight slope toward the center

[1] *Engineering News,* March 4, 1897.

or one corner of the basement, and a trapped sewer connection set at this lowest point in such a way that it is accessible for repairs and cleaning.

644. Wet Basements. — Where much ground water is encountered, and especially where a basement is subjected to a head of water from without, special precautions must be taken in building the floor. The concrete must be made thick enough so that its weight and the arch action set up, shall be able to withstand the upward pressure of the water. In building such a floor it is necessary to keep a sump hole, preferably in the center, towards which the construction proceeds from the sides. A pipe placed in the sump hole permits pumping until the concrete is laid about the pipe, when the latter may be filled with rich cement mortar. In such cases the side walls of the basement should be plastered with Portland cement mortar on the outside and special care taken in joining the floor to the wall.

645. Size of Blocks. — As the changes in temperature in a building are usually much less than in open air, the blocks of concrete may be of much larger size, say ten feet square, and many basement floors are laid without any joints, though sooner or later they will probably crack if so laid. In factories for certain purposes, however, the floors may be subjected to greater changes in temperature than walks laid in the open air. In such cases the blocks should not be more than three or four feet on a side, and the joints may well be filled with asphalt, especially if water-tightness is desired.

646. Stable floors may be made of six inch cobble or broken stone sub-base, six inches of concrete made with mortar containing three parts sand to one cement, and one inch of top dressing containing three parts sand (mixed sizes) or crushed granite to two parts cement.

Factories having heavy machinery with much vibration require strong floors. Such a floor may be made of six inches of cobble stone sub-base covered by six inches of a lean concrete made with one-to-four mortar, and above this, three to five inches of rich concrete made with mortar containing two and one-half parts sand to one cement, and one inch of top dressing, equal parts cement and sand or cement and crushed granite.

647. Example and Cost. — In the construction of the new printing building for the Government Printing Office at Washington, the basement floor is nine inches thick, made as follows:[1]—

1. Concrete sub-base, six inches thick of one part natural cement, two parts sand and four and one-half parts broken brick.

2. Concrete base, two and one-half inches thick of Portland cement one part, sand two parts and fine broken gneiss four parts.

3. Top dressing, one-half inch in thickness, of two parts sand to one part Portland cement.

The cost of this floor was about $1.50 per square yard, or about seventeen cents per square foot.

Art. 75. Concrete in Pavements and Driveways

648. Pavement Foundations. — The principal use of concrete in connection with city pavements has been as a foundation, the wearing surface being of some other material, as brick, asphalt, cedar blocks, etc.

Concrete for pavement foundations should not be less than six inches in thickness, and a greater thickness will be required where the ground is insecure. The excavation having been made to the required sub-grade, and all loose soil removed and the places refilled with broken stone, the earth is thoroughly rolled to a smooth surface parallel to the surface of the proposed pavement. Drainage for the foundation should be provided where necessary by broken stone or tile drains beneath the curb. Before beginning the placing of concrete, stakes may be driven in the foundation, with their tops at grade, at intervals of five to ten feet over the entire pavement, to assist in securing the proper grade of concrete surface.

649. The stone for the concrete should be broken so that no piece is larger than two and one-half inches in its greatest dimension. If the stone is of good quality, it need not be screened except to remove the finest dust, if this is present in considerable quantities. Sufficient mortar should be used to fill the voids in the stone, this mortar being composed of about two parts sand to one of natural cement, or better, two and one-half or three parts sand to one of Portland cement. This con-

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[1] Report of Capt. John S. Sewall, *Report Chief of Engineers*, 1896.

crete is thoroughly rammed in place, care being taken that adjacent batches as laid in the street mingle with each other so as to show no line of demarcation. In stopping work for the night, the concrete should cut off sharply on a straight line parallel to the direction of the proposed joints in the wearing surface. Joints extending across the street should be left at intervals of thirty to forty feet to allow for expansion and contraction.

650. The concrete is finished to a surface parallel with the proposed street surface, a templet being employed to secure this. The concrete should be kept damp for a few days, and no traffic allowed upon it until the wearing surface is laid. If the wearing surface is of brick or wooden blocks, a layer of sand about one inch thick is first spread over the concrete.

The advantages of a concrete foundation for street pavements are its strength and durability and water-tightness.

651. CONCRETE PAVEMENT. — Concrete has not been a popular material for a street surface except for short driveways and in courts where both vehicles and pedestrians must be accommodated. One reason for this is that concrete is slippery, and another, that owing probably to carelessness or ignorance, the wearing qualities have not been good. The first objection may be largely removed by cutting the surface into blocks, four by eight inches, by deep grooves, or by the use of a deep imprint roller on the wearing surface. As to wearing qualities, there seems to be no good reason why a concrete cannot be made tough enough to withstand heavy traffic. It will of course be necessary to divide the work into blocks of twenty to twenty-five square feet, with expansion joints of sand, asphalt, or tarred paper between. A third objection is the glare of the surface in summer. A partial remedy for this may be had by placing some coloring matter, such as lamp black, in the top dressing.

652. The sub-base may consist of a six inch layer of broken stone, or twelve inches of cinders, well drained and thoroughly compacted by rolling. For exceptionally heavy wear it may be advisable to use a five inch layer of lean concrete for the sub-base, after rolling the bottom of the excavation and providing drainage.

Upon the sub-base should be laid a base, composed of four inches of concrete made with first class stone, such as granite, trap or hard limestone crushed to pass a ring one and one-half inches in diameter, and containing enough mortar, one part Portland cement to two or three parts sand, to fill the voids in the stone. The top dressing, a layer of granolithic one and one-half or two inches thick, should then be immediately applied. This mortar should be made with one or two parts granite, trap, or other hard rock crushed to pass a five-eighths inch screen, to one part Portland cement.

These two layers are placed in much the same manner as that described for laying concrete sidewalks, but the joints in base and top dressing should run at angles of forty-five degrees with the curb to prevent ruts following the lines of the joints. A roller making deep imprints is then run over the finished surface to furnish a foothold for horses, or, for this purpose a special roller may be used to mark the top dressing into blocks approximately four by eight inches, with deep (one-half inch) grooves.

When completed, the pavement should be kept moist, preferably by a layer of damp sand, and no traffic should be allowed upon it for at least a week or ten days.

653. Concrete pavement laid in Bellefontaine, Ohio, was found to be in good condition after ten years' service;[1] the only serious defect apparent being that, since the blocks were marked off parallel to the curb, ruts have sometimes formed along these joints. This pavement was made with four inches base concrete, laid directly on sub-grade where foundation is gravel, sand or porous soil; or if soil is impervious, the base was laid on four inches of broken stone or cinders. The top layer was two inches thick, equal parts cement and sand or pea granite. Sub-drains of three inch tile were laid inside each curb line, and the curb is formed as part of the outer blocks. Both the base and top dressing were cut through in squares, five feet on a side. The cost of the pavement is said to have been $2.15 per square yard, and very few repairs have been found necessary.

In Germany a cement macadam, made with six inch sub-

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[1] *Municipal Engineering*, December, 1900, and *Engineering News*, **Jan. 7, 1904.**

base of broken stone or gravel, with a wearing surface of hard macadam stone mixed with cement, has been successfully used.

ART. 76. CURBS AND GUTTERS

654. The use of concrete for curbs and gutters is rapidly increasing. Curbing is sometimes molded and afterward put in place like stone curbing, but the greatest advantages in the use of concrete for this purpose are only attained by molding in place the curb and gutter as one structure.

The Parkhurst combined curb and gutter is a patented form that has proved very satisfactory. This form has a projection of about one inch at the back and another along the bottom just below the curb, this feature being patented.

A combined curb and gutter may consist of a curb four to six inches wide at the top, and five to seven inches at the bottom, and have a face of six to seven inches above the gutter. The upper face corner of the curb and the angle between curb and gutter should be rounded with a radius of one and one-half to two inches. The gutter is sixteen to twenty inches wide, and from six to nine inches thick, with top surface conforming to the grade of the street.

655. The sub-base should consist of a layer of broken stone six inches thick, or six to twelve inches of cinders thoroughly rammed. The preparation of the foundation should be similar to that required for a pavement, care being taken that the sub-base be thoroughly drained, tile being used if necessary. Forms to receive the concrete are held in place by stakes, the molds being carefully set to grade. The sub-base may now be covered by a layer of four to six inches of Portland concrete of only moderate richness, as one to three to six, and the concrete to form the curb and gutter placed upon it before it has set, or a six inch layer to form the gutter may be placed directly on the sub-base.

656. Concrete to form the curb and gutter should be of good quality, not more than two and one-half parts sand to one part Portland cement being used for the mortar, and sufficient mortar used to entirely fill the voids in the stone. The broken stone for this concrete should be rather fine, with few, if any, pieces larger than one inch in greatest dimension. The exposed faces receive a top-dressing, or wearing surface, of one-half inch to one inch of granolithic containing not more than one and one-half parts of trap or granite, pea size, to one part Portland cement. This coating is applied as soon as possible after the concrete is placed, as in sidewalk work. The surface is troweled or floated, but a smooth, glossy finish is avoided.

The curb and gutter may well be laid in alternate blocks about six feet long, but a somewhat neater appearance is secured by making the work continuous, and cutting it entirely through at intervals of six feet to provide for slight movement. As the molds may be used repeatedly, they should be substantially made. Special forms are of course required at corners, catch basins, etc. As in other concrete construction, the work should be protected from injury and kept moist for at least a week.

657. On business streets it is desirable to build the sidewalk close to the curb, with only a joint between, the grade of the walk conforming to the curb and sloping up toward the building line one-quarter inch to the foot. On residence streets the walk should be separated from the curb by a park strip, the walk being high enough to give drainage toward the curb.

Steel facing is sometimes used for curbs subjected to exceptional wear, as in front of shipping warehouses and freight sheds. Where these are applied, they should cover the top and the upper part of the face of the curb and must be well anchored, by bolts or special webs, to a substantial mass of concrete, otherwise they will work loose and defeat the object for which they are used.

658. Cost of Concrete Curb and Gutter. — At Champaign, Ill.,[1] a curb was built seven inches high and five inches thick, the gutter, six inches thick, extending nineteen inches into the roadway from the face of the curb. The foundation consisted of six inches of gravel or cinders well rammed. The concrete was composed of one part Portland cement to five parts fine gravel, and the finishing coat, one inch thick, was of one part Portland cement to one part clean, sharp, coarse sand. The cost per foot was thirty-nine cents, including all excavation.

A similar curb at Urbana, Ill., was 4½ inches thick at the top, 5 inches at the base and 7½ inches high; the gutter being

[1] W. H. Tarrant, Engineer, Proc. Ill. Soc. Engr. and Surveyors, 1899.

5 inches thick and extending 18 inches into the roadway. The foundation was composed of eight inches of cinders or gravel. The concrete was of one part Portland cement to five parts clean gravel, and the finishing coat was one inch thick, composed of one part Portland cement to two parts sharp sand. The price per linear foot, including the excavation, removal of old curbing, and refilling, was forty-six cents.

At South Bend, cement curb alone, 6 inches wide at top, 7 inches at bottom and 16 inches depth, with the upper half composed entirely of one to two Portland cement mortar, has been constructed for eighteen cents per linear foot.

ART. 77. STREET RAILWAY FOUNDATIONS

659. The heavy motor cars used on city and urban electric railways subject the track to very severe service. As the head of the rail must be practically flush with the pavement on city streets, cross-ties, when used, are so far beneath the surface that they decay rapidly and their renewal entails the tearing up of the pavement. As there is not the same necessity for a cross-tie on street tracks as on railroads, since the rails are held to gage by the pavement, these objections to the cross-tie have led to the adoption of a concrete girder under each rail. The rails and ties (if ties are used) should not only rest upon the concrete, but should be imbedded in it. Track in which the rails rested upon concrete, but were not imbedded in it, has been found to yield laterally and get out of alinement, while on the other hand, if the ties rest upon earth or gravel and are filled between with concrete, the track is likely to settle, breaking the bond of the concrete.

660. The **method** of placing concrete beams for street railway tracks in Minneapolis was as follows:[1] The rails were first spiked to cross-ties at intervals of six to eight feet, and the rail joints cast-welded. In laying the street pavement foundation of natural cement concrete, a rough groove, fifteen inches wide at the bottom and eighteen to twenty inches at the top, was left under each rail. This groove was immediately filled between ties with concrete made of one part Portland cement,

[1] F. W. Cappelen, M. Am. Soc. C. E., *Engineering News*, Oct. 14, 1897; *Municipal Engineering*, November, 1896.

two and one-half parts sand, and four and one-half parts broken stone.

The rails were tied together every ten feet with wrought iron tie bars, three-eighths inch by two inches, set on edge. These tie bars were rounded at the ends, threaded and attached to the web of the rail by two nuts, one on either side of the web. The rails were then spiked to the concrete beam, the temporary wooden ties removed, and the spaces left by them filled with concrete, completing the beam. As the concrete beam was eight inches thick and the rail five inches, the sub-grade was thirteen inches below the top of the rail.

On the gage side of the rail were placed toothing blocks of granite, 3½ by 9 inches by 4½ inches deep, held away from the rail 1¼ inches by temporary wooden strips. After removing these strips, cement grout was poured into the groove to fill 2½ inches over the base of the rail, the remaining 2½ inches to the top of the rail being filled by asphaltic cement which remained soft enough to permit a flange groove to be made by the first car over the track. The asphalt wearing surface was laid against the rail on the outer side. Mr. Cappelen, in describing this construction, says that a rail six inches high with six-inch base should be used, with granite toothing blocks, six by nine inches by five and one-half inches deep.

The **cost** per foot of rail for the concrete beam construction only, was twenty-six to twenty-seven cents, and for the filler, five cents per foot. The cost per mile of double track, exclusive of rails and pavement, was about $8,670.00.

Somewhat similar methods have been employed in Toronto and Montreal. Canada, Indianapolis, Ind., and Scranton, Pa., Denver, Detroit and Cincinnati.

661. At Scranton, Pa.,[1] the rails were laid directly on the six-inch concrete base of the pavement. This thickness was increased to twelve inches under the joints (which were reinforced by an inverted rail four feet long) and under steel cross-ties spaced ten feet centers and formed of old girder rails inverted and riveted through the flanges at the intersection. Flat steel tie bars, threaded at the ends, spaced ten feet centers, were also used here as at Minneapolis.

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[1] Description of the systems employed in several cities are given in *Engineering News*, Dec. 26, 1901.

The concrete mixing plant was mounted on a car running on the track; the materials were delivered to the machine by hand measuring boxes, and the Drake mixer deposited the concrete directly into the trench. The total **cost** per foot of track is given as $2.65, $1.17 of which was for grading, rolling, concreting and brick paving at $1.97 per square yard, and for extra concrete at joints and ties at $0.72 per square yard.

662. At Toronto, Canada, the six-inch concrete base of the pavement is increased to eight inches in thickness for twenty inches width under each rail, and the base of the latter is imbedded one inch in the concrete. A 6½-inch grooved girder rail is used, with mortar rammed between the web and the adjacent paving blocks.

663. At Cincinnati the bottom of the concrete stringer is nine inches below the base of the nine-inch grooved girder rail, and the concrete is built up from three to six inches on the web, according to the thickness of the wearing surface of the pavement. The space between the upper part of the web and the adjacent paving is then filled with cement mortar, thus supporting the head of the rail as well as protecting the web from corrosion.

CHAPTER XXI

SPECIAL USES OF CONCRETE (CONTINUED). SEWERS, SUBWAYS, AND RESERVOIRS.

ART. 78. SEWERS

664. There seems to be no very good reason why concrete is not more generally employed in the construction of all large sewers. With sizes less than two or two and one-half feet in diameter the difficulty of removing the centers prohibits the use of concrete in the ordinary way, and although some appliances have been devised for building these small sewers as monoliths by a mold that advances as fast as the concrete is tamped in place, they have not proved popular. The difficulty of obtaining a perfect grade, and the undesirable feature of leaving the green concrete unsupported, are probably reasons sufficient for this lack of popularity.

For the larger size sewers concrete has several advantages over brick. First may be mentioned the very smooth finish that may be obtained on the invert, appreciably increasing the velocity of flow over that usually obtained with brick inverts. Cheaper labor may be employed in concrete work with less danger of annoyances from strikes. The cost is from one-third to one-half less than for brick.

665. METHODS OF CONSTRUCTION. — The City of Washington was one of the first to use concrete extensively in sewer construction[1]. For sizes up to twenty-four inches internal diameter the concrete is used only as a foundation and bedding for the ordinary **sewer pipe**. For a twenty-four inch sewer the pipe rests in a bed of concrete twenty-seven inches wide at the bottom, flaring to forty inches wide at the level of the center of the pipe, and then carried up with plumb sides for six inches, and finally finished by planes tangent to the upper curve of the pipe. At the joints there are bands of concrete

[1] Described by Capt. Lansing H. Beach, Corps of Engrs., U. S. A. Report Operations District of Columbia, 1895.

extending over the top, so that at these places the pipe is entirely inclosed. Similar forms are used for the smaller sizes with corresponding decreased dimensions. For all sewers between ten inches and twenty-four inches the sub-grade is six inches below the exterior of the pipe, and in all cases the band about the joint is four inches thick at the top.

666. The method of laying these sewers is as follows: The trenches are 2½ to 3 feet in width, with "headers" about 2 feet wide, left at intervals of 10 to 16 feet, which are tunneled through. The grade and line pegs are placed in the headers at the ground surface, and a cord is stretched on the sewer line over at least four stakes, at a convenient height above the grade, and thus parallel to the bottom of the sewer.

When the trench is to the required grade, a six inch layer of concrete, made with one barrel natural cement, two barrels sand and four barrels gravel, is placed. This concrete is rammed with iron rammers weighing sixteen pounds, and having eighteen square inches ramming surface. The pipe is then laid upon this bed and each section is tested for line and grade. For the former, a plumb bob is used with its cord held against the grade cord already mentioned, and for testing the grade a graduated pole is used, with a projection at the bottom which sets on the interior of the pipe, just within the open end.

Concrete is then lowered in buckets, deposited on top of the pipe and allowed to fall down on the sides so as not to disturb the alinement. When enough concrete to secure the pipe has been thus placed, it is rammed and the concreting continued until the required form is obtained, as already described. The concrete in the bands carried over the joints is not rammed but is beaten with wooden paddles and heavy trowels to compact it and bring it to the desired form, four inches thick and four inches wide at the top, and flaring to twelve inches wide (in the direction of the sewer) at the top of the pipe.

667. Cost. — The quantities of concrete materials required to lay one hundred linear feet of pipe sewers as described above are given as follows: —

Size of sewer	8 inch	12 inch	18 inch	24 inch
Cement, bbls.	6.76	10.58	14.77	19.14
Sand, cu. yd.	2.07	3.23	4.52	5.85
Gravel, cu. yd.	4.16	6.47	9.04	11.70

With natural cement costing $0.79 per barrel in sacks, sand $0.47 per cu. yd., gravel $0.75 per cu. yd., and laborers $1.50 to $1.75 per day, foremen, masons and inspectors $4.00 per day, the average cost of laying pipe sewers in this manner was approximately as follows, exclusive of the cost of the pipe: 8-inch, $1.11; 12-inch, $1.14; 15-inch, $1.46; 18-inch, $1.60; 21-inch, $1.67; 24-inch, $2.32 per foot.

668. Sewers at Chicago. — In the construction of some 17,000 feet of sewers for the Chicago Transfer and Clearing Yards,[1] concrete was used for all sewers of thirty-six inches diameter and over. The excavation was mostly in blue clay and done by steam shovel to a depth of twenty feet, the remainder being removed by hand shovels and swing derrick. The material was such that in general the bottom of the trench could be trimmed to the form of the exterior of the sewer. The thickness of the ring of concrete was 8 inches for 36 and 42-inch sewers, 10 inches for 48-inch, and 12 inches for 84 and 90-inch sewers.

The concrete was composed of one part "Steel Pozzolana" (slag) cement, three parts sand and five parts broken stone. The cement was of course very finely ground and showed high seven-day tests. The cost was $1.30 per barrel delivered. The sand was the Chicago "torpedo" sand, coarse and of good quality, and cost about ninety cents per cubic yard delivered. The stone was a limestone from Summit, Ill., crushed in two sizes, namely, 1 to 2½ inches and ½ to 1½ inches. These two sizes of stone were mixed in proportions one part of the coarser to two of the finer. The cost of stone was about $0.80 per cubic yard delivered.

The concrete was mixed by a rotary mixer of the continuous type provided with radial blades. The mixer was mounted on a flat car, with engine and upright boiler. Three cars of stone, the mixer car, two cars of sand and one of cement made up the concrete train, which ran on a track laid close to the trench and was kept near the work by a small locomotive. The mixer was supplied by wheelbarrows running from the material cars on plank runways attached to the cars. The concrete was also transported in wheelbarrows from the mixer to the trench.

[1] E. J. McCaustland, Trans. Assoc. C. E., Cornell University, 1902.

669. The bottom of the trench being cut to form, the concrete for the invert was laid directly on the sub-grade, tamped in layers carried up until the invert occupied about one hundred forty degrees of arc. The form of the inner face of the invert was maintained by template, grade stakes being set $12\frac{1}{2}$ feet apart along the trench. The remainder of the sewer was laid on centers resting on the invert. The ribs for this centering were made in a complete circle, of three thicknesses of one by twelve inch boards nailed together and cut to a true circle. Ribs were placed four feet center to center, and covered with lagging two inches thick and three inches wide, planed to radial joints. The strips of lagging were held in place at each end of a section by a $\frac{3}{16}$ by 2 inch iron band passing over all of the strips, and turned in at the ends, forming a hook in which rested the lower lagging strip, the other strips being supported by this one. The lower part of each rib rested on the invert, the upper portion being cut to a diameter four inches less (that is, smaller by twice the thickness of the lagging). While the trench was near enough to the outside of the sewer ring not to measurably increase the amount of concrete over and above the desired thickness, the trench served as the outside form. Above this point, planks were inserted and braced to the sides of the trench. From the haunches to the crown the exterior was finished with a template.

When completed, the exterior form planks were removed, and a light covering of earth placed on the surface to protect it from drying too rapidly. This was especially necessary in this case on account of the kind of cement used. The centers were removed usually after forty-eight hours, by swinging the ribs about the vertical diameter and removing the lagging. As soon as the centering was removed, the inner surface was plastered with a mortar composed of three parts lake sand to one part cement.

670. Cost. — The company furnished the materials used in the sewer ring and manholes, and delivered it on the work, while the contractor furnished all tools and labor to dig the trenches, complete sewer and manholes, and do the back filling. The contract prices per foot are given by Mr. McCaustland, the resident engineer, as follows: —

36-inch sewer	in trench	averaging	11 feet deep,	3,340 feet,	at $2.30.
42 "	"	"	14 "	2,660 "	3.00.
48 "	"	"	17 "	4,540 "	3.57.
84 "	"	"	22 "	1,000 "	5.91.
90 "	"	"	24 "	5,400 "	6.68.

From the data given we have computed the approximate quantities of concrete per foot of sewer, and assuming the cost of the materials for a cubic yard at $3.00, we obtain the following approximate costs: —

Size Sewer.	Depth Trench.	Materials.		Construction Contract Price per Foot.	Estimated Total Cost per Foot.
		Approximate Cubic Yards Concrete.	Approximate Cost Concrete.		
36 in.	11 feet.	.285	$ .85	$2.30	$3.15
42 "	14 "	.325	.97	3.00	3.97
48 "	17 "	.47	1.41	3.57	4.98
84 "	22 "	.93	2.79	5.91	8.70
90 "	24 "	.99	2.97	6.68	9.65

671. Special Molds for Small Sewers. — In the construction of a thirty inch sewer at Medford, Mass.,[1] Mr. William Gavin Taylor made use of a very convenient form. The lower 240 degrees of the sewer was of concrete, the upper 120 degrees being of brick. To construct the concrete portion as a monolith, the forms were constructed in lengths of ten feet, separating on a vertical line into two halves. The two halves were connected by clamps, and held at the proper distance apart by dog irons in the end ribs of each form. After smearing the forms as usual, the concrete was deposited and rammed. When it had partially set, the dog irons were removed and turn-buckles used to slowly pull the two halves together. This method prevented the green concrete being broken, although the concrete extended up on the sides thirty degrees above the horizontal diameter.

672. The centers used for the brick arch were also ingeniously arranged, and since they might have been used for a concrete arch they may be described here. These centers were also in ten foot lengths. The ribs, of two inch plank, were

[1] Abstract from Annual Report of City Engineer, *Engineering Record*, Nov. 7, 1903.

spaced two feet centers, with lagging $\frac{7}{8}$ inch thick by $1\frac{1}{2}$ inch wide, with one bevel edge to make a tight upper surface. The rear end of each center was supported by wedges securely fastened to the outer end of the preceding section, the forward end being supported by a screw jack.

After turning the arch, these centers were removed by the aid of a special truck the axles of which were bent at such an angle as to make the cast iron wheels fit the concrete invert. The axle of a roller was first fastened to the outer rib of the center to be removed; the truck was then run back a foot or so under the center and the screw jack supporting the forward end of the center released. This allowed the forward end to drop a short distance, the roller resting on the running board of the truck. The latter was then pulled into the sewer far enough to let the roller run off the end of the truck and lock itself. The truck being then pulled out of the sewer toward the finished end, drew the center away from the wedges supporting the rear end, allowing the form to drop on the truck and be wheeled out of the sewer. By this method the centers were successfully removed without injuring the concrete.

673. Cost. — From data given, the cost of this sewer — about sixteen hundred feet in length — is approximately as follows, labor costing twenty-five cents an hour: —

1.25 cu. yds. excavation and back fill, at $.59	$0.74
.15 cu. yd. concrete, at $6.70	1.00
.037 cu. yd. brick masonry, at $12.05	.44
Cost of linear foot, exclusive of manholes, estimated at	$2.18
The total cost per linear foot is given as	$2.39

674. New York Sewers. — In connection with the construction of the New York Rapid Transit Railway, some of the sewers were built of concrete. This work was done with exceptional care, and on a large scale, and it was found that the concrete sewers cost one-third less than similar sewers of brick.

The method of construction of one section may be described as follows:[1] The forms for the invert of the straight lengths of sewer were twelve feet in length, consisting of a strong framework covered with closely matched lagging, planed smooth and

[1] *Engineering News*, March 6, 1902.

greased with machine oil. After the trench was prepared, concrete was placed and rammed until the top of the concrete was within about one-half inch of the flow line of the invert. To accomplish this, a straight edge was used, bearing on the finished invert in the rear and a template secured to the trench timbering just ahead of the section under construction.

The invert centers were then placed, resting on the finished invert at the rear and on a solid foundation accurately set to grade at the forward end. Mortar composed of equal parts Portland cement and sand was then tamped between the invert form and the bottom concrete already laid. When the flow line had been thus accurately formed, the center was braced and vertical planking set to form the outside of the walls. The concrete was then rammed in place.

Joists of two inch by four inch scantling laid along the center of the top of each side wall of the invert section, formed, when removed, a mortise into which the fresh concrete of the arch section was rammed to form a bond. Similar mortises were also made in the forward end of each section as built. After twenty-four hours or more the forms were removed, and a thin cement wash was applied to the interior, sufficient only to fill any slight imperfections in the surface.

The arch centers, similar in construction to the forms for the invert, were put in place and plastered with one inch of rich Portland mortar. Concrete was then placed sufficient to make the arch eight inches thick, the outside of the walls being formed by inclined boards braced to the trench, and the top of the extrados was formed by hand.

675. Steel Forms. — Two novel types of centering have been devised, in which the surface next the concrete is of steel. In one of these[1] the forms are in sections about three feet long. Two of the pieces of steel are of a width suitable to reach from the bottom of the sewer to just above the spring line of the arch, while a third piece forms the arch center. The strips are bent at an acute angle at the sides, thus projecting into the sewer along an element of the surface where the plates join; the two sides of adjacent plates, which flare away from each other, are then connected by a continuous U-shaped clip of steel slipped

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[1] *Engineering Record*, Jan. 9, 1904.

on from the end of a three foot section, and the intervening space in the clip filled with clay or melted paraffin. The form is assembled outside the trench, and after the paraffin is in place, the center may be handled. When the sewer is completed, the paraffin is melted by a suitable heater, or the clay is washed out, and the form may be collapsed and removed.

676. In the other form [1] the steel plates are in continuous strips about six inches wide and are applied by setting up the wooden form on an improvised axis, revolving the form and wrapping the steel sheet about it as it is revolved. The wooden form is in two parts, upper and lower, firmly connected while in use, but the two parts may be made to approach each other by driving out the wedges between them. After the winding, the center, with its sheet steel jacket, is lowered into the trench. When the concrete is completed, the form is collapsed and removed, leaving the spiral of steel in place to support the concrete until the latter is well set. The steel is then removed by simply pulling on one end. As it comes away from the concrete it is wound into a coil, and is then ready to be rewound on the wooden form. Both of the above styles have been patented.

Art. 79. Concrete Subways and Tunnel Lining

677. The advantages of concrete in subway construction and in tunnel lining are now well established. In subways built in open cut, the side walls and invert are of concrete built in place, while the roof is frequently made with I-beams with concrete arches turned between them. The I-beams are supported directly on the side walls, which are usually made monolithic with the invert.

678. Special precautions have to be taken to exclude water from a subway, and for this purpose tarred felt and Portland cement plaster are employed.

The specifications for the New York Rapid Transit Subway [2] were carefully framed to secure a **waterproof construction.** On the sub-grade was placed a layer of concrete, smooth and level on top. This was covered by alternate layers of hot asphalt and felt, from two to six layers of each being used as deemed

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[1] *Engineering News*, Feb. 18, 1904.

[2] Abstracted in *Engineering News*, Feb. 13, 1903.

necessary for the conditions encountered. The remainder of the concrete forming the floor was then laid upon the top layer of asphalt. In dry, open soil the felt was not required, and in dry rock excavations above water level both the asphalt and felt were omitted. Similar provisions were made for waterproofing the side walls and roof, resulting in a complete layer of asphalt and felt imbedded in concrete about the entire tunnel, the waterproofing being protected both inside and out by concrete.

679. In the construction of the Boston Subway[1] the portion built in open cut was made as follows: The work was divided into sections of convenient length, about twelve feet, so that work on a section could be carried on continuously until completed. Upon the prepared grade were laid three thicknesses of tarred felt with six-inch lap joints, well pitched between the layers, and the top of the upper layer thoroughly covered with the pitch. When the latter had hardened, the invert was laid over the entire width of the section.

At each side a back wall six inches thick was built up to a convenient height and braced. The forms were then removed and the face of this back wall was plastered with rich Portland cement mortar. The main side walls were then built up between this layer of plaster and the forms defining the interior face of the wall. This portion of the subway had an arch roof, two feet thick at the crown, which was laid on wooden centers. The exterior of the roof was plastered like the side walls, and then covered with four inches of concrete to protect the plaster from injury. The centers were removed after from ten to thirty days; the span of the arch was about twenty-three feet.

680. Tunnel Lining in Firm Earth. — In building tunnels in earth that is sufficiently firm not to require extensive timbering, concrete is well adapted for lining. An instance of this is furnished by the extensive system of tunnels constructed for telephone and telegraph service under the streets of Chicago.[2] The trunk conduits for this system are about thirteen by four-

[1] Annual Report Boston Transit Commission, 1900; also described in *Engineering News*, April 4, 1901.

[2] Mr. George W. Jackson, Engineer, Proc. W. Soc. Engrs., 1902; also in *Engineering News*, Feb. 19, 1903.

teen feet inside, and the laterals about six by seven feet, all of the five center horseshoe form.

The excavation was in hard clay which stood up well. Shafts were located in basements of buildings rented for the purpose, and in these basements were placed the compressed air plants, material bins, concrete mixers, etc. The large air locks, some of which would hold ten small construction cars, were placed at the bottoms of the shafts. Work was done in three shifts, working eight hours each. The two night shifts could excavate about twenty-one feet of lateral tunnel in the sixteen hours, and the day shift placed the lining.

681. The concrete was in general composed of five parts of broken stone and screenings, or of mixed gravel and sand, to one part Portland cement. For intersections but four parts aggregate were used. This should make a very strong concrete. The centers for the smaller conduits were made of three-inch channels, each rib being in five parts bent to the proper form and connected by flange plates bolted to the inside of the channels at the ends. These ribs were placed three feet apart, and two-inch plank used for lagging.

The ribs for the trunk sewers were of similar construction, but with heavier channels braced with angles. Steel lagging was used, made of plates about twelve by thirty-six inches, stiffened by 1½ inch angles on four edges. There were also provided bulkheads or steel end plates of voussoir shape, twelve inches along the intrados and twenty inches high, for the purpose of retaining the end of each section of lining and permit thorough tamping. These bulkhead sheets, or "end flights," were also stiffened along three edges, and could be attached to the webs of the channel ribs by short bolts.

The concrete was mixed at the shaft head and conveyed to the work in cars twenty inches wide and four feet long, running on a fourteen-inch gage track. The floor of the tunnel was first laid in the excavation, the steel ribs then put in place on the floor, and the lagging placed at the bottom and built up the sides just ahead of the concrete. When near the crown, short pieces of lagging three feet in length covering but two ribs were used, and the concrete rammed in from the end of these short sections until they were complete, and then another row of short pieces placed and the operations repeated.

The concrete floor of laterals was designed to be thirteen inches, and the sides and arch ten inches thick, but in all cases the entire space between the lagging and the sides of the excavation was filled with concrete.

682. In such work as this only the best materials should be used, and, as early strength is desired, the use of Portland cement is general in order that the centers may be removed within a reasonable period. The ends of the sections into which the work is divided should, if possible, be brought up square, the bulkhead sheets described above being an ingenious and effective method of providing for this. Where it is not practicable to finish with a square end over the entire area of section, then the work on the sides should be stepped back from the bottom toward the crown, each step being bounded by planes corresponding to coursing and heading joints in a masonry arch.

683. Tunnel Lining in Soft Ground. — For tunnels in soft ground requiring the use of a shield, some difficulties in using a concrete lining are apparent. The principal one of these lies in the fact that the fresh concrete is not capable of taking the thrust of the jacks used in forcing the shield ahead. Attempts have been made to overcome this difficulty by so constructing the centers that the jacks may bear against them instead of on the fresh concrete.

Another difficulty is that in materials requiring almost continuous support, the temporary timbering is in the way of the centering for the concrete construction; and still another is the difficulty of properly tamping the arch at the crown where the tail of the shield confines the working space. Concrete blocks were tried in the construction of sewers in Melbourne, but without entire success. Such blocks were successfully employed in the underground road system of Paris, though attempts to use fresh concrete in shield tunneling for this work proved a failure.

684. East Boston Tunnel. — In the construction of the East Boston Tunnel Extension of the Boston Subway, however, a monolithic concrete lining has been successfully built, the tunnel being excavated by shield.

This tunnel is about twenty by twenty-four feet for double track electric line. The arch ring and the walls are thirty-three inches in thickness, while the invert is twenty-four inches. Two side drifts, eight feet square, were first driven a certain distance and timbered. The bottoms of these drifts were then excavated, and the side foundations of concrete were placed in lengths of sixteen to twenty feet. When the foundations had set, the interior forms for the side walls were placed upon them, supporting the caps, the exterior plumb posts removed, and the concrete side walls, three feet thick, built up to within sixteen inches of the springing line of the arch. This work was kept about one hundred feet in advance of the shield.

The shield, provided with live rollers, rested upon these side walls, the rollers running in a flanged plate placed on top of the walls. The shield was forced ahead thirty inches at a time, and sections of the arch thirty inches in length were turned directly behind the shield.

685. The centers of the arch were of curved, ten inch steel channels spaced thirty inches apart, and the lagging, four inches thick, was placed from the bottom toward the key as the concrete was built up. Each section of arch is keyed with concrete pressed through two holes in the rear girder at the top of the shield, special rammers being used to tamp the concrete into the space at the crown of the arch, the concrete being directed into place by curved sheet-iron troughs.

In each section of arch sixteen cast iron bars, three and one-quarter inches in diameter and thirty inches long, are built into the concrete in position to receive the thrust of the shield jacks. Wooden bulkheads on the jack plungers serve to confine the fresh concrete, but the reaction is taken on the cast iron bars which, being butted end to end in successive sections of the arch, carry the stress back to concrete that is able to sustain it. As the shield advanced, the space left over the completed arch by the tailpiece of the shield was filled with grout under pressure. The centers remained in place thirty days. The invert was excavated and laid in ten-foot sections about twenty-five feet in the rear of the shield. The concrete was mixed at the bottom of the shaft and passed through the air lock on cars. The concrete cars ran on a higher level than the muck cars, in order not to interfere with the excavation.

686. Lining Tunnels in Rock. — If the rock through which a tunnel is driven is seamy and insecure, concrete is in most cases the cheapest and best lining. The cost of the lining is, of course, less if it can be built in connection with the excavation, but it is frequently difficult to foresee how a given rock will stand exposure to the air and water, and it becomes an exceedingly nice question to determine at the time of building a tunnel whether lining is required. In many cases this question is settled in the affirmative by other considerations than the character of the rock, as the resistance to flow, in waterworks and sewers, or the ease of ventilation and the necessity of a good appearance, as in street or steam railway tunnels.

687. New York Subway. — In the construction of portions of the rapid transit subways of New York, a traveling center which served also to support a working platform was carried on six wheels running on a track laid on the footing courses of the side walls. This center carried at the side, sections of lagging curved to the required form of the side walls. This lagging was adjusted in place, and braced from the platform or center by means of wedges. Directly behind this traveling center was a similar platform carrying a derrick; and behind this, the traveling center carrying the lagging for the roof. This third platform was jacked up to place the roof lagging at the correct elevation, and firmly supported by wedges.

The concrete was brought in skips on cars that ran on the floor level and stopped beneath the derrick platform. The derrick hoisted the skips through a hole in the platform and placed them on cars on either the side wall or the roof platform, so that the concrete was delivered either to the side wall forms in advance, or the roof forms in the rear as required. The concrete was rammed in a direction transverse to the tunnel axis until the roof was completed, except for a space about five feet wide at the crown. The arch was then keyed by tamping the concrete in from the end of the form. The two platforms carrying the forms were each forty feet long, and the derrick platform was eighteen feet.

688. The excavated rock was crushed for the concrete on a working platform erected over and around the shaft head. Cars delivered the excavated material at the shaft in steel skips, which were hoisted to the working platform, set on push cars and dumped into bins, from which stone was delivered to the crusher; these cars then passed under the crushed stone bins, were loaded with broken stone, run back to the shaft head, and the broken stone dumped into bins mounted over the mixer. The skips were then lowered into the shafts by the derricks, to be run to the headings and reloaded. The stone and sand were fed to a measuring box by means of a hopper, the measuring box discharging directly into a cubical mixer, which was high enough above the tunnel floor to dump directly into skips on the cars.

689. Cascade Tunnel. — In the construction of the Cascade Tunnel of the Great Northern Railway a somewhat different arrangement was used.[1] The working platform in the tunnel was erected five hundred feet in length, and cars hauled by cable up an incline to the platform. The side walls were built in alternating sections, eight to ten feet in length, the support of the arch timbering being thus gradually transferred from the plumb posts to the concrete of the side walls. Arch sections were built in twelve foot lengths, the centers being made of four by sixteen inch plank without radials, so as to leave a clear way for concrete cars on the working platform. The latter were high enough to allow the material cars to run beneath them.

690. Concrete vs. Brick. — There are frequent instances in engineering construction where brick masonry might well have been replaced by concrete, and the use of brick for tunnel lining is still adhered to in many cases. This is partly because somewhat less elaborate centers can be used for brick arches, and the centers may be struck somewhat earlier, and partly because of extreme conservatism on the part of the designer, although without doubt there are cases where the use of brick is entirely warranted.

An interesting instance of the greater adaptability of concrete under unforeseen conditions, however, is presented by the Third Street concrete and brick lined tunnel at Los Angeles, Cal.[2] This tunnel was excavated mostly through an argillaceous sandstone. The side walls were of concrete up to the haunches, the upper part of the arch being of six courses of brick. A streak of yellow clay was encountered, and it "was

[1] Mr. John F. Stevens, M. Am. Soc. C. E., *Engineering News*, Jan. 10, 1901.

[2] J. H. Quinton, M. Am. Soc. C. E., *Engineering News*, July 18, 1901.

soon demonstrated that the six ring brick arch, which occupies the central portion of the roof, was not strong enough to hold up the immense weight above it, and the temporary timbering was crushed and broken in a most alarming way." The strength of the arch was increased by using nine rows of brick instead of six until the clay seam was passed. In such portions of the six ring arch as had cracked, it was found that the inner ring of brickwork had separated from the second ring, and in places the second ring had separated from the third. The concrete walls had shown no evidence of weakness.

To repair the brickwork, steel concrete beams or arches were inserted in the brickwork at intervals of four feet, and extending from one concrete wall to the other. These beams were twelve inches wide and eight to twelve inches deep, made of rich concrete, and had imbedded in each beam two pieces of three inch by three-quarter inch steel. The steel ribs were set in recesses cut out of the brickwork, and rested at the ends upon the concrete of the side walls. Substantial centers were used for building the concrete beams, and when the latter had set, the defective brickwork between adjacent beams was cut out and replaced by rich concrete.

691. Aspen Tunnel. — Another illustration of the adaptability of concrete when unexpected difficulties arise, is furnished by the construction of the Aspen Tunnel on the Union Pacific Railroad.[1] The original design provided for sets of timbers to support the excavation, spaced about three feet, center to center, but for nine hundred feet of the tunnel such pressures were encountered that in places a solid wall of twelve by twelve inch timber was forced in. For a portion of this section the lining was built of a combination of concrete with steel ribs. The latter were 12-inch, 55-pound I-beams spaced from twelve to twenty-four inches, center to center, curved to conform to the interior of the tunnel. The concrete was built up around and between the beams, the inner flange being covered by from four to seven inches, and the total thickness of the walls two to three feet.

692. The **Perkasie Tunnel** of the Philadelphia and Reading Railroad was constructed through a firm rock, which, however, was intersected by several strata of seamy rock. As trouble

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[1] W. P. Hardesty, *Engineering News*, March 6, 1902.

was experienced from rock falling from these strata, it was decided to line the tunnel at such places. This lining had a minimum thickness of eighteen inches at the crown and twelve inches at the sides. Traffic through the tunnel was not obstructed during the work of placing the lining. In laying about five hundred cubic yards of concrete, the cost was about ten dollars and eighty cents per cubic yard, exclusive of cost of centering and dry filling.[1]

693. Water Works Tunnel. — The lining of portions of the Beacon Street Tunnel of the Sudbury River Aqueduct was undertaken some fourteen years after its excavation, and at a time when it was necessary to use the tunnel intermittently to supply water to the city of Boston. The methods employed are described by Mr. Desmond FitzGerald in Transactions American Soc. C. E. for March, 1894.

A substantial track of 2 feet $1\frac{1}{4}$ inch gage was laid from a manhole furnishing access to the sewer to the portion of the tunnel to be lined. The rails, weighing thirty-six pounds to the yard, were supported on small but substantial trestles, built of three by four inch spruce joists, and placed eight feet between centers. Every third trestle was braced from the sides and roof of the tunnel to prevent the track being floated when the tunnel was in use. The trestles also carried five rows of planks for the workmen to walk on in pushing the cars. The track was elevated by these trestles, so the work was not seriously interfered with by a small amount of water in the tunnel. The track cost about eighty-seven cents a foot.

Cars to run on these tracks to deliver materials and concrete had frames five feet by one foot nine inches, with twenty inch wheels, and cost about fifty-six dollars each.

694. Centers. — The centers were in three parts, two for side walls and one for roof. The ribs were of three thicknesses of two by ten spruce plank, without interior bracing for the roof section. The side sections had each an inclined brace. Wedges were inserted between the tops of the side sections and the bottoms of the roof ribs to hold the latter in place. The lagging was two by four inch spruce, in eight foot lengths, with beveled edges and planed both sides. The centers were

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[1] P. D. Ford, M. Am. Soc. C. E., Trans. A. S. C. E., March, 1894.

spaced four feet apart, and seventy-five full centers were built; these, with the lagging, contained 14,000 feet B. M. of lumber, and cost $1,460.55, or $104.30 per thousand feet B. M.

695. Methods of Work. — Broken stone, sand and cement were stored in shanties over and around the manhole leading to the tunnel, and arrangements made by which the materials could be delivered through chutes down the manhole to the cars As it was found more convenient to work in winter, special provision was made for storing large quantities of material in the shanties. The sand was piled around an iron lined, wooden bulkhead, in the center of which was a large stove.

The concrete was mixed within the tunnel as close to the work as possible, and in places where the cross-section had been sufficiently enlarged by falls of rock to permit easy working. The materials, delivered to the material cars down the chutes already mentioned, were pushed to the mixing platforms and combined in the proportions of 18.56 cubic feet of crushed stone and 7.35 cubic feet of sand to one barrel of Portland cement, being approximately 1 to 2 to 5½. The above quantities of materials made 20 to 21 cubic feet of concrete. When mixed, the concrete was shoveled into cars, conveyed to the work and then shoveled into place.

The tamping was done principally with oak rammer five inches square, twelve inches long, with a short wooden handle in one end. In tamping the key of the arch, long-handled iron rammers were used. Much care was requisite here to prevent the aggregate separating from the mortar and lodging next the lagging, as it always has a tendency to do, thus resulting in voids in the face of the work when the lagging is removed. The concrete was built up on the sides in horizontal layers and stepped back by inserting bulkheads, so that the adjacent sections bonded together.

696. Cost. — The cost of this concrete lining, which was built under great disadvantages, amounted to $16.15 per cubic yard. This cost must be considered reasonable in view of the fact that the materials had to be transported an average distance of more than one-half mile on small push cars, and the work in the tunnel was suspended for three days of each week to allow the tunnel to be used to maintain the water supply of the city.

Art. 80. Reservoirs: Linings and Roofs

697. Although the choice of the material with which to construct a reservoir may in some cases be varied by local conditions, it is found that under ordinary circumstances concrete offers the greatest advantages for a minimum cost. For the side walls of small reservoirs, concrete furnishes the requisite strength and water-tightness with a moderate thickness; earthen embankments and floors may be made practically impervious with concrete and mortar, combined with asphalt when considered necessary; while for the roofs, groined arches or beams and slab construction, with supporting piers, all of this material, make a neat, permanent, and altogether satisfactory covering, at a smaller expense than would be required for brick or stone masonry.

698. Details of Construction. — In the walls and floors, water-tightness is a prime consideration, and this is best attained by a layer of mortar on the inner surfaces or between two layers of concrete.

As in floors, walks, etc., the necessity of providing for expansion and contraction will depend upon the extremes of temperature to which the surface is to be subjected. In covered reservoirs which are to be almost constantly filled with water, or in very equable climates, the blocks may be large, say twenty feet square, while under more severe conditions the blocks may not contain more than twenty square feet. The joints between the blocks may well be wide enough to be filled with asphalt. This furnishes an elastic joint which is compressed as the blocks expand, and swells when the blocks again contract.

699. Reservoir Floors. — One of the principal difficulties experienced in the construction of floors is from settlement of the foundation. The floor should, therefore, have strength enough to bridge any small irregularities in the foundation that may result from inequalities in settlement. For a similar reason, it is not well to make the blocks too large, as smaller blocks with compressible joints will more readily conform to an uneven surface without permanent injury. In order that the reservoir shall not leak even if the foundation settles, the concrete and mortar may be covered with one or more layers of asphalt.

In building the floor lining, alternate blocks are sometimes placed first in molds and the intermediate blocks built in later. In other cases the blocks are laid consecutively. The advantage of the former method seems to lie principally in the ease of construction, as access may be had to all sides of the block.

700. In hard clay soil not liable to settlement, four inches is sufficient thickness for the floor, the concrete to be covered before it has set with a half-inch layer of rich Portland mortar, troweled to a smooth surface. If the reservoir when empty will be subjected to hydrostatic pressure from without, the floor must be designed to resist this pressure. In this case, if seepage from without into the reservoir is objectionable, a layer of mortar may be placed over the first layer of concrete and protected by the concrete laid upon it. This outside pressure may be provided for in a covered reservoir by making the floor of inverted arches between piers, the weight of the floor, piers, roof, and earth filling over the roof, being made sufficient to balance the upward pressure on the floor. If there is no objection to the water from without being led into the reservoir, a porous layer of broken stone or gravel beneath the floor may be connected with the interior of the reservoir through pipes provided with check valves, and the outside pressure be thus removed. Where it can be accomplished, it will usually be better to lead this ground water through a pipe to a sewer or a lower level rather than into the reservoir.

701. Walls. — The thickness of the wall is determined by methods similar to those used in designing a retaining wall or a dam according as the pressures are greater from the embankment without or the water pressure within. In the case of a covered reservoir, the thrust of the roof arches may convert any vertical section of the wall into a beam, the earth pressure from without being supported by the floor at the bottom and the roof at the top. Or in case there is no back pressure from earth filling, the thrust of the roof may be added to the inner water pressure. In circular covered reservoirs the arch thrust is usually taken by steel bands laid in the concrete and encircling the reservoir near the top of the wall. In narrow reservoirs rectangular in plan, tie rods may be used, or the wall may be buttressed to take the roof thrust. Concrete side walls are usually built vertical, or nearly so, on the inside, and with a batter on the outside.

702. Linings. — Linings of sloping earthen embankments are laid the same as the floors, and similar precautions are required. There is greater danger of settlement of embankments than of the floor foundation, and the blocks, therefore, may well be made smaller. Some difficulty may be experienced with laying horizontal asphalt joints on a sloping face, and some sliding of the lining may be expected under ordinary conditions, the asphalt joints being compressed. For this reason it would seem to be better to use asphalt in the inclined joints only, and a mastic in the horizontal joints. Another method which would probably prove satisfactory is to lay first a tier of blocks next the floor, and when these have set, apply a very thin coat of asphalt to the upper edges of these blocks, following with another tier, and so on.

703. ROOFS. — Where it is necessary to cover a reservoir, either to prevent the formation of ice, or the growth of algæ, or for other reasons, the **groined arch** is an excellent design for the roof on account of the small amount of concrete required, the clear head room given, and the ease of ventilation. The extending use of reinforced concrete will also probably enter this field to a greater extent in the future than it has heretofore.

The determination of the stresses in a groined arch roof is complicated not only by the peculiar form of the arch itself, but by the fact that the spandrels of the arches are filled with concrete over the piers to the level of the extrados at the crown. This evidently results in making of any given unit of the roof, having a pier as its center, a cantilever, and the arch action is interfered with. Unless, however, tension members of steel are laid in the concrete near its upper surface, it is not wise to count on the strength of the cantilever except to consider it a factor of ignorance on the safe side. If one wishes to depart from the ordinary and tried dimensions for groined arches in concrete, such departure had better be based on some special experiments and tests on full sized sections. Some of the dimensions that have been used are given in the examples cited below.

704. Forms. — The preparation of forms or centers for groined arches is one of the most difficult and expensive details of the construction of such a roof. It will probably be best to have each section of the form cover the space, square in plan, between four piers. The ribs of the centering may well be built up of planks, nailed together and sawed to proper form. The lagging should be planed to size, and have radial joints to make a smooth and even top surface. Care is necessary to make a neat fit along the valley extending diagonally between piers, and a small fillet may well be fitted into this valley to avoid a sharp corner on the finished concrete, as well as to cover up possible imperfections in the joints. The forms should, of course, be designed to take the thrust of the adjacent completed arches, and if sufficient forms are not built to cover the entire reservoir, and thus transmit the thrust to the walls, the piers at the border of the forms must be thoroughly braced to the opposite side walls or the piers will be toppled over and the roof wrecked. This accident occurred to one reservoir roof during construction, the pier braces having been removed without the knowledge of the engineer.

705. In laying the concrete, joints between the work done on consecutive days should cut the arches at right angles to their axes, and bulkheads should be used to make such a joint a vertical plane. The covering of each unit between four piers is made monolithic, and care is necessary to prevent the stones working to the bottom of the mass and thus becoming exposed when the forms are removed. This may be prevented by plastering the forms with mortar and placing the concrete upon it before the mortar has begun to set.

706. A roof consisting of a network of **concrete-steel beams** intersecting at right angles, supported by piers and covered by concrete-steel slabs, makes a very simple design. The forms are much easier to construct, and forms for only a limited area need be erected at one time. An excellent article on "Covered Reservoirs and Their Design," by Mr. Freeman C. Coffin, M. Am. Soc. C. E., is contained in the July, 1899, number of the Jour. of the Assn. of Engr. Soc. An article on the "Groined Arch," by Mr. Leonard Metcalf, Assoc. M. Am. Soc. C. E., appears in Trans. A. S. C. E. for June, 1900; and Mr. Frank L. Fuller presents an article on "Covered Reservoirs," in Jour. Assn. Engr. Soc. for Sept., 1899.

707. Examples of Concrete Reservoirs. *Wellesley.* — The reservoir at Wellesley, Mass.,[1] a part of the water supply system, was designed by Mr. Freeman C. Coffin. It is eighty-two feet in diameter, walls fifteen feet high, four feet thick at bottom and two feet at top. The walls are of concrete and rubble masonry. In the construction of the walls, concrete was used containing three parts sand and five parts of stone to one of cement, one cubic yard of concrete containing about 1.2 barrels of cement. The bottom of the walls, which were designed to be built of concrete three feet four inches thick, were actually built of rubble four feet thick, as a large quantity of bowlders was at hand. The excavation was in hard clay containing but little water, and the floor was made only four inches thick, of concrete of the same quality as that used in the walls.

The floor and side walls were plastered with two coats, the first, one-half inch thick, of mortar containing two parts sand to one of Portland cement, and a coat about one-eighth inch thick, of neat Portland carefully rubbed and smoothed with trowels. Such a plaster coat should be applied before the concrete has set. The two plaster coats cost twenty cents per square yard.

708. The piers to support the groined arch roof were two feet square, and built of brick. The span of the arches was 12 feet, rise 2.5 feet, and the concrete 0.5 foot thick at the crown. A channel iron ring or band was set in the concrete walls at the springing of the roof arches to take the thrust of the latter. The centers were placed over one-fourth of the area at a time, the piers being braced to take the thrust of the arches until the roof was completed. The concrete in the roof was composed of two and one-half parts sand and four and one-half parts broken stone to one part Portland cement. The centering cost twenty-two and one-half cents per square foot of area covered. The spandrels were filled in level with top of concrete at crown. On top of the concrete roof was placed six inches of clean gravel for drainage and to prevent the earth freezing to the concrete. This gravel was drained by four inch vitrified pipe discharging at the toe of the slope wall.

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[1] *Engineering News*, Sept. 30, 1897; Jour. Assn. Engr. Societies, July 1899; Trans. A. S. C. E., June, 1900.

One foot of earth filling and one foot of loam were placed upon the gravel.

709. *Astoria.* — The reservoir for the Astoria City Water Works[1] was designed and built by Mr. Arthur L. Adams, M. Am. Soc. C. E. The reservoir has a capacity of six and one-fourth million gallons, walls twenty feet high. The excavation was in hard clay and sand mixed with clay, which in some places resembled a soft sandstone. The embankment was in general about five feet, the remainder of the depth being in excavation.

The floor consisted of six inches of concrete, $\frac{3}{8}$ inch cement mortar, one coat liquid asphalt and one coat harder asphalt. The slope lining was of six inches concrete, one coat asphalt, one layer of brick dipped in asphalt and laid flat, and a final finishing coat of asphalt. The concrete was composed of one barrel Portland cement, one-tenth cubic yard sand, five-tenths cubic yard gravel and nine-tenths cubic yard of crushed stone, these quantities of the ingredients making one cubic yard of concrete. Here we have an instance of the use of a mixture of broken stone and gravel, a practice which has already been commended as resulting in a small amount of voids.

The concrete of the floor was laid in blocks twenty feet on a side, molds of two by six inch plank forming the outside edges of a block, and serving as a guide to the straight edge used in finishing, as in concrete walk construction. The finishing coat was of two parts fine sand to one of Portland cement and was applied, before the concrete base had begun to set, by two finishers with smoothing trowels. When the next block was to be laid, the plank were replaced by one-half inch weather boarding. When the concrete had thoroughly set, these boards were removed and the joints so formed were run full of asphalt, when the first layer of this material was spread.

The concrete on the sides was also six inches thick and laid in sheets ten feet wide, extending up and down the slopes, expansion joints being provided on the inclined joints only. The finishing coat of mortar was not used here, but all inequalities in surface were smoothed by using a little mortar from the next batch of concrete.

710. Each concrete gang was composed of twenty men and

[1] Trans. A. S. C. E., December, 1896.

one water boy. All concrete was mixed by hand on movable platform in half-yard batches. On the entire work 1.84 cubic yards of concrete per day were mixed and placed per man employed, and on the floor alone this quantity was increased to 2.35 cubic yards, an excellent showing for this class of work.

The **cost** of concrete per cubic yard, without profit, was as follows: —

On Slopes: — Cement, at $2.45 per bbl.	$2.82
Other materials	1.94
Labor	1.07
Total per cubic yard for 600 yards	$5.83
On Floor: — Cement, at $2.45	$2.64
Other materials	1.92
Labor	.68
Total cost per cubic yard for 680 yards	$5.24

The costs of the slope lining and floor complete, per square foot, are given as follows: —

Slope: — 6 inches concrete	$0.1187
.649 inch asphalt	.0100
Brick in asphalt	.0889
.851 inch asphalt	.0131
Chinking crevices	.0030
Ironing	.0036
Total cost per square foot of slope	$0.2373
Bottom: — 6 inches concrete	$0.1031
Cement mortar finish	.0113
.537 inch coat asphalt	.0077
.573 inch coat asphalt	.0082
Total cost of bottom per square foot	$0.1303

711. *Forbes Hill.* — The Forbes Hill reservoir[1] forms a part of the distribution system of the Metropolitan Water Works of Boston and was built under the direction of Mr. Dexter Brackett, M. Am. Soc. C. E. The reservoir is two hundred eighty by one hundred feet, partly in embankment. The soil under the embankment was first stripped to a depth of two and one-half

[1] Described by Mr. C. M. Saville, M. Am. Soc. C. E., Division Engineer, before the N. E. Water Works Assn. Abstracted in *Engineering News*, March 13, 1902.

feet at the toe, increasing to five feet stripping at the inner edge of the slope. The material was hard pan, and the embankments were built in four inch layers, rolled with four thousand pound rollers, so made as to leave a slightly corrugated surface. The bank was extended one foot inside of the finished line to assure a compact face, and afterward trimmed to grade.

712. The bottom of the reservoir was covered first with a layer of concrete about four and one-half inches thick, composed of one part natural cement, two parts sand, and five parts stone. The sand was of good quality; the stone came from the excavation and was washed before crushing. This layer of natural cement concrete was covered by a layer of Portland cement mortar one-half inch thick, made of two parts sand to one cement, and finished with a richer mortar, one part sand to four of cement.

This half-inch layer was laid in strips four feet wide and finished like a cement sidewalk. Although this mortar coat was kept well moistened, some cracks developed which were filled with grout before applying the second layer of concrete. If no joints were used in the lower layer or base concrete, and joints in the coat of mortar were provided in one direction only, as appears to have been the case, the cracking should have been anticipated. At any rate, the value of the mortar coat between the two concrete layers was greatly impaired by this cracking, and the experience points to the advisability of placing the upper layer of concrete on the mortar before the latter has set, thus avoiding the expense of finishing the mortar layer.

The upper layer of concrete was composed of one part Portland cement, two and one-half parts sand and four parts broken stone, and was laid in blocks ten feet square. These blocks were laid alternately each way.

The slope was first lined with Portland concrete of 1 to 2½ to 6½, then one-half inch layer of mortar as for the bottom. The upper layer of concrete on slope was same as the upper layer of the bottom lining, but the blocks were eight by ten feet and finished with one inch of granolithic, in which stone dust and particles smaller than three-eighths inch were substituted for the one and one-half inch stone of the concrete.

713. Cost. — The cost of lower layer of concrete on bottom, natural 1 to 2 to 5, was as follows: —

1.25 bbl. natural cement, at $1.08	$1.350	
.34 cu. yd. sand, at $1.02	.347	
.86 cu. yd. stone, at $1.57	1.350	
Materials in concrete		$3.047
Forms, lumber, at $20.00 per M	$0.090	
Forms, labor	0.100	
Total forms		.190
General expenses	$0.08	
Mixing and placing	1.17	
		1.250
Total cost per cu. yd.		$4.487

Cost of lower layer on slopes, Portland 1 to 2½ to 6½, was as follows: —

1.08 bbls. Portland cement, at $1.53	$1.652	
.37 cu. yd. sand, at $1.02	.377	
.96 cu. yd. stone, at $1.57	1.507	
Materials in concrete		$3.536
Forms, lumber, at $20.00 per M	$0.016	
Forms, labor	0.121	
Total forms		.137
General expenses	$0.177	
Mixing and placing	1.213	
		1.390
Total cost per cubic yard		$5.063

The cost of the upper layer on bottom and slopes, including the finish on slopes, Portland 1 to 2½ to 4, was as follows: —

1.37 bbls. Portland cement, at $1.53	$2.09	
.47 cu. yd. sand, at $1.02	.48	
.745 cu. yd. stone, at $1.57	1.17	
Materials in concrete		$3.74
Forms, lumber, at $20.00 per M	$0.25	
Forms, labor	0.26	
Total forms		.51
General expenses	$0.15	
Mixing and placing	1.53	
		1.68
Total cost per cu. yd.		$5.93

The cost of the half-inch plaster coat between the layers of concrete was twenty cents per square yard.

714. *Rockford.* — A reservoir for the city of Rockford, Ill.,[1] was built almost entirely of concrete after plans prepared by the City Engineer, Mr. Chas. C. Stowell. The soil was a loose gravel, and after excavation was completed, parallel lines of drain tile were laid in trenches nine to ten feet centers and leading to a fifteen inch vertical sewer pipe carried to the surface of the street and capped. This sewer pipe served as a sump for a pump should it be found necessary at any time to repair the bottom. These trenches were filled with broken stone and the whole area of the foundation covered with three inches of clay. The concrete bottom was in two layers, eight inches and seven inches thick, respectively, and composed of two parts sand and five parts stone to one of Portland cement.

The walls were of similar concrete for the bottom twelve feet, natural cement being used in the upper eight feet of the walls. The thickness at the bottom was 4½ feet, walls being straight on outside with one to ten batter on inside. The entire inner surface of floor and walls was plastered with one-half inch of Portland mortar, one to one. The cost of concrete in the work averaged $6.50 for Portland and $4.00 for natural, and the finishing coat cost seventy-five cents a square yard.

715. The roof was of concrete, expanded metal lath, and steel rods, the finished thickness being but two inches. This was supported by ribs of concrete, each twelve inches thick at the crown and having a seven-inch channel on the under side. The springing line of the ribs was eight feet below the top of the walls, giving a good depth at the skew back. Ribs were spaced about seven feet centers. The span of the roof was about fifty-five feet, and rise about eleven feet. The cost of roof was less than twenty-five cents a square foot.

716. *Concord.* — The groined arch roof of the Concord, Mass.,[1] sewage storage well, designed by Mr. Leonard Metcalf, Assoc. M. Am. Soc. C. E., was fifty-seven feet diameter and contained about one hundred cubic yards of masonry. The cost of the roof per square foot of surface was as follows: —

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[1] Described in *Engineering News*, Feb. 22, 1894.

Centering	$0.18
Concrete materials	.15
Labor and supervision	.05
Total	$0.38

717. *Albany.* — The Albany filter plant roof,[1] designed by Mr. Allen Hazen, Assoc. M. Am. Soc. C. E., was also of the groined arch type, the arches having the same span and rise as the Wellesley reservoir. The cost of the roof per square foot of area was as follows: —

.029 cu. yd. concrete, at $6.30	$0.182
Piers	.054
Earth filling and seeding	.014
Manholes, entrances, etc.	.027
Total cost per sq. ft.	$0.277

For a list of reservoirs and filter beds, in the roofs of which groined arches have been used, giving in tabular form the general dimensions, the proportions used in the concrete, and in several cases the cost of the roof per square foot of reservoir, the reader is referred to *Engineering News* of December 24, 1903.

[1] Trans. A. S. C. E., June, 1900.

CHAPTER XXII

SPECIAL USES OF CONCRETE (CONTINUED)
BRIDGES, DAMS, LOCKS, AND BREAKWATERS

ART. 81. BRIDGE PIERS AND ABUTMENTS AND RETAINING WALLS

718. The use of concrete in large **bridge piers** was at first confined to the hearting or backing of stone masonry shells. It was soon found, however, that in many cases the concrete was able to withstand the effects of frost and ice better than was the variety of stone available for building the masonry shell, and many important bridges are now supported by piers built entirely of concrete.

As an example of this use may be mentioned the bridge across the Red River [1] in Louisiana, which has six concrete piers of heights from forty-four to fifty-three feet. The pivot pier is twenty-seven feet in diameter, with vertical sides. The draw rest piers are seven feet wide under the coping, nineteen feet between shoulders and twenty-six feet long over all. The sides have a batter of one-half inch to the foot. The coping is of limestone.

719. In the construction of the Arkansas River Bridge [2] of the K. C. P. & G. R. R., ten piers and two abutments were built of concrete. The piers varied in height from twenty to sixty-five feet, some of them containing over six hundred cubic yards of concrete. The entire work was completed in eleven months, although many difficulties were met. The concrete was composed of one part Portland cement, two and one-half parts coarse, sharp sand, and five parts of clean, broken stone.

The lagging for the forms was of two-inch yellow pine, surfaced one side and sized to one and three-quarters inches. On

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[1] George H. Pegram, Consulting Engineer. Walter H. Gahagan, Engineer for Contractors.

[2] *Engineering News*, Aug. 25, 1898.

the straight part of the pier this lagging was laid horizontal and supported by four by six vertical posts set four-feet centers, posts on opposite sides of the pier being tied together by three-quarter inch bolts passing through one and one-half inch gas pipes spaced five feet vertically. The gas pipe was allowed to remain in the finished pier, the bolts being withdrawn.

The lagging for the semicircular ends was of two by six with bevel joints, placed vertical, and supported at five-foot intervals by segmental ribs of double two by twelve planks. At the ends of the ribs were bolted short pieces of eight by eight inch angle irons with edge horizontal. These angle irons were, in turn, bolted to four by six verticals at the corners or shoulders of the pier.

720. The foundation piers of the Lonesome Valley Viaduct,[1] thirty-six piers and two abutments, are entirely of concrete. The piers are four feet square on top with batter of one inch to the foot, and are from five to sixteen feet in height. The total concrete laid was 926 cubic yards at a contract price of about $7.00 per cubic yard. The piers were finished on top with a steel plate, four feet square and one-half inch thick, taking the place of coping stones. Where rock foundations were not found, the lower portion of the pier was given an increased batter to secure such a cross-sectional area at the bottom that the unit pressure on the earth did not exceed one ton per square foot. The cost of the concrete for this work has already been given (§ 322).

721. Steel Cylinders. — Steel shells filled with concrete have been used to good advantage, especially for bridge approaches. Such shells are usually in pairs placed abreast, one under each truss of the bridge or viaduct. The two cylinders of a pair are usually connected by lateral bracing, and if desired in heavy work, this bracing may be inclosed in a concrete wall and thus protected from injury by running ice, etc. The thickness of metal in the shells need not be great, three-eighths of an inch usually being sufficient, though this depends on the height, the stresses, and the liability to injury. In soft ground requiring piles, most of the piles are sawn off below the limit of scour, or below the water line for land piers, but one or more may be

[1] Gustave R. Tuska, Trans. A. S. C. E., September, 1895.

allowed to project up into the cylinders and the concrete filled in around the heads, thus anchoring the pier. In foundations on rock if the cylinders require an anchorage, this may be provided with bolts fox-wedged or cemented in the rock and projecting into the cylinder. (For details of methods adopted in this class of construction, see "Bridge Substructure and Foundations in Nova Scotia," by Martin Murphy, Trans. A. S. C. E., September, 1893.)

722. Repair of Stone Piers. — Where masonry piers are being destroyed by the abrading or expansive action of ice, or by other causes, concrete is successfully used to arrest such action, the entire pier being incased in a layer, one to three feet thick, of Portland cement concrete of good quality.

The piers of the Avon River bridge,[1] originally built of ashlar masonry, failed entirely to withstand the deteriorating influences of an extreme range in tide coupled with the severe temperature of a Nova Scotia winter. Five of them were subsequently incased in concrete, as follows: A form was made of ten by ten inch spruce timber surrounding the ashlar masonry of the piers and forming a mold to receive the concrete and retain it in place until set. The thickness of the concrete casing was two and one-half feet at the bottom and one and one-third feet at the top, which was three feet above high water. The concrete was composed of one barrel Portland cement, one and one-half barrels clean sand, one barrel of clean gravel, and in it was placed by hand four parts of common field stone weighing from eight to twenty pounds each. This treatment was entirely successful in preventing further disintegration.

723. An efficient **cutwater** for bridge piers is made by placing old rails vertically on the upstream nose of the pier, anchoring them to the masonry and filling between with concrete, leaving only the wearing surface of the rail head exposed.

724. Pneumatic caissons are usually filled with concrete, the filling over the working chamber being carried up fast enough to keep the work above water as the caisson is sunk. The filling of the working chamber calls for special care in tamping under and around the longitudinal and cross-timber braces. A space of about three inches next the roof of the chamber is

[1] Trans. A. S. C. E., December, 1893.

filled with a rich concrete, containing no stone larger than one inch, mixed quite dry and solidly tamped with special edge rammers.

725. Retaining Walls and Abutments. — Concrete is used very largely for constructing retaining walls and bridge abutments. The foundations of a retaining wall should be of ample width, and if the wall is not founded on rock, some settlement and outward movement may be expected if the common formulas are used in computing the dimensions.

If this movement is not equal throughout the wall, cracking is likely to take place, and to confine these cracks to predetermined vertical planes, it is well to construct the wall, if a long one, with vertical joints at intervals of fifteen to thirty feet. Such a joint is made by building one section and following with another, without special precautions to make a bond between.

If there is an opportunity for water to accumulate, care should be taken to drain the earth back of the wall, either by drains leading around the ends, or by pipes passing through the wall. The latter may result in discoloration of the face.

726. Coping. — The face of a retaining wall or abutment is preferably given a batter, and a coping is provided to improve the appearance. The coping should have a slight inclination toward the back to prevent the discoloration of the face by dripping. It should be divided by vertical joints into blocks, not more than six to eight feet in length. The projection of the coping will depend upon the dimensions of the wall. Wing walls are preferably built with a sloping top or coping, but this should be made monolithic with the wall by special molds (§ 729).

727. Rules for Use of Concrete in Abutments. — In the use of concrete for abutments and piers, the practice of the Illinois Central Railroad, as set forth in their specifications, can hardly be improved upon. The engineer of bridges and buildings on this road, Mr. H. W. Parkhurst, M. Am. Soc. C. E., is one of those engineers who early recognized the value of concrete in bridge work, and as the result of his extensive experience along this line, he is widely known as an able and conservative authority.

These specifications are printed nearly in full in *Engineering*

News of July 18, 1901, from which the following extracts are made: —

728. *Natural and Portland Cement: Where used:* —

Natural cement concrete "may be used where foundations are entirely submerged below low-water mark, or where there is no risk of the same being exposed to the action of the weather by cutting away the surrounding earth. It, however, shall be used only where a firm and uniform foundation is found to exist after excavations are completed. In all cases where foundations are liable to be exposed to the action of the water, or where the material in the bottom of excavations is soft or of unequal firmness, Portland cement concrete must be employed for foundation work.

"The natūral cement concrete shall usually be made in the proportions (by measure) of one part of approved cement to two parts of sand and five parts of crushed stone, all of character as above specified. For Portland cement concrete foundations, one part of approved cement, three parts of sand and six parts of crushed stone may be used. Wherever in the judgment of the engineer or inspector in charge of the work, a stronger concrete is required than is above specified, the proportions of sand and crushed stone employed may be reduced, a natural cement concrete of 1, 2 and 4, and a Portland cement concrete of 1, 2 and 5 being substituted for those above specified.

"*Portland Cement Concrete:* — Concrete for the bodies of piers and abutments, for all wing-walls for same, and for the bench walls of arch culverts, shall generally be made in the proportions (by measure) of one part of cement, two and one-half parts of sand and six parts of crushed stone. Where special strength may be required for any of this work, concrete in the proportions of 1, 2 and 5 may be used; but all such cases shall be submitted to the judgment of the engineer of bridges, before any change from the usual specification is to be allowed.

"For arch rings of arch culverts and for parapet headwalls and copings to same, Portland cement concrete, in proportions of 1, 2 and 5, shall generally be used. Concrete of these proportions shall also generally be used for parapet walls behind bridge seats of piers or abutments, and for the finished copings (if used) on wing-walls of concrete abutments, also for arch work in combination with I-beams or in combination with iron-work for transverse loading.

"**Bridge seats** of piers and abutments and copings of concrete masonry which are to carry pedestals for girders or longer spans of ironwork, shall generally be made of crushed granite and Portland cement, in the proportion (by measure) of one part of approved cement, two parts of fine granite screenings, and three parts of coarser granite screenings, the larger of which shall not exceed three-quarters inch in greatest dimension."

729. After specifying the method of building molds, which is treated elsewhere (Art. 62), the specifications proceed: —

"The *planking* forming the lining of the molds shall invariably be fastened to the studding in perfectly horizontal lines; the ends of these planks shall be neatly butted against each other, and the inner surface of the mold shall be as nearly as possible perfectly smooth, without crevices or offsets between the sides or ends of adjacent planks. Where planks are used a second time, they shall be thoroughly cleaned, and, if necessary, the sides and ends shall be freshly jointed so as to make a perfectly smooth finish to the concrete.

"The molds for projecting copings, bridge seats, parapet walls, and all finished work shall be constructed in a first-class workmanlike manner, and shall be thoroughly braced and tied together, dressed surfaces only being exposed to the contact of concrete, and these surfaces shall be soaped or oiled if necessary, so as to make a smoothly finished piece of work. The top surfaces of all bridge seats, parapets, etc., shall be made perfectly level, unless otherwise provided in the plans, and shall be finished with long, straight edges, and all beveled surfaces or washes shall be constructed in a true and uniform manner. Special care shall be taken in the construction of the *vertical angles* of the masonry, and where I-beams or other ironwork are not used in the same, small wooden strips shall be set in the corners of the mold, so as to cut off the corners at an angle of 45°, leaving a beveled face about one and one-half to two inches wide, instead of a right-angled corner.

"Where **wing-walls** are called for, which have slopes corresponding to the angle of repose of earth embankments, these slopes shall be finished in straight lines and surfaces, the mold for such wing-walls and slopes being constructed with its top at the proper slope, so that the concrete work on the slope may be finished in short sections, say from three to four feet in length, and bonded into the concrete of the horizontal sections before the same shall be set, each short section of sloped surface being grooved with a cross-line separating it from adjacent sections. It will not be permitted to finish the top surface of such sloped wing-walls by plastering fresh concrete upon the top of concrete which has already set, but the finished work must be made each day as the horizontal layers are carried up, to accomplish which the mold must be constructed complete at the outset; or, if the wing-wall is very high, short sections of the mold, including the form for the slopes, must be completed as the horizontal planking is put in place."

730. This is followed by directions concerning foundation work; the following is given relative to **building steel into the masonry:** —

"Iron rails to be furnished by the railroad company shall be laid and imbedded in such manner as may be specified in such foundation concrete as in the opinion of the engineer of bridges needs such strengthening, and no extra charge, except the actual cost of handling the same, shall be made by the contractor for such work, but the volume of such iron shall be estimated as concrete.

"Where I-beams are to be placed in the angles of concrete piers as a protection against ice, drift, etc., these shall be set up and securely held in position so that they will extend one foot or more into the foundation concrete. The planking of molds shall be fitted carefully to the projecting angles of these I-beams, and small fillets of wood shall be fitted in between the inner faces of the mold and the rounded edges of the I-beam flanges, so that no sharp projecting angle of concrete will be formed as the work is constructed.

"These fillets may be made in short pieces and fastened neatly into the mold as the layers of concrete are carried up. Such I-beams will generally be furnished of sufficient length to extend at least six inches above the top of the battered masonry into the concrete coping, and special pains shall be taken to tamp the concrete thoroughly around the I-beams, and to finish the coping above and around the ends of the same, so as to make a compact and solid bearing against the ironwork.

"Where **anchor bolts** for bridge-seat castings are required, they shall be set in place and held firmly as to position and elevation, by templets, securely fastened to the mold and framing. Such I-beams and anchor bolts shall be imbedded in the concrete work without additional expense beyond the price to be paid per yard for the several classes of concrete in which such iron is placed, the volume of iron being estimated as concrete.

"After the work is finished and thoroughly set, all molds shall be removed by the contractor. They shall generally be allowed to stand not less than forty-eight hours after the last concrete work shall have been done. In cold weather, molds shall be allowed to stand a longer period before being removed, depending upon the degree of cold. No molds shall be removed in freezing weather, nor until after the concrete shall have had at least forty-eight hours, with the thermometer at or above 40° Fahr., in which to set."

731. After giving in detail the methods to be followed in placing and ramming concrete and the use of facing mortar, the following paragraph is especially applicable to the subject in hand:

"Layers of concrete shall be kept truly horizontal, and if, for any reason, it is necessary to stop work for an indefinite period, it shall be the duty of the inspector and of the contractor to see that the top surface of the concrete is properly finished, so that nothing but a horizontal line shall show on the face of the concrete, as the joint between portions of the work constructed before and after such period of delay. If for any reason it is impossible to complete an entire layer, the end of the layer shall be made square and true by the use of a temporary plank partition. No irregular, wavy or sloping lines shall be permitted to show on the face of the concrete work as the result of constructing different portions of the work at different periods, and none but horizontal or vertical lines shall be permitted in such cases."

ART. 82. CONCRETE PILES

732. Piles may be made of concrete either with or without steel reinforcement. In the former case they are built in place, but where steel is used the piles are usually driven after they have been prepared in suitable molds. Concrete is also employed to protect from decay, or from the ravages of the teredo, wooden piles already in service.

Concrete piles are much more durable than wooden piles, and may be used without reference to the water line. A saving may thus be made under certain conditions, as the use of concrete piles may obviate the necessity of excavating to the water line and building up with masonry resting on a wooden pile foundation. As the diameter of the pile is not limited, a much greater load per pile may be provided for. There are of course many places where piles of concrete are not as suitable as wooden piles; they are not as well adapted to withstand certain kinds of hard usage, such as violent shocks, and they are much less flexible.

733. Building in Place. — In certain kinds of soil, such as stiff clay, a wooden pile, or dummy, of the proper length may be driven and withdrawn, the hole left being at once filled with concrete. The application of this crude method is very limited, as it is seldom that the soil will stand until the hole is filled with concrete.

For the building of piles without reinforcement, Mr. A. A. Raymond[1] has patented a system by which a thin steel shell or casing is driven to the desired depth and then filled with concrete in place. A shell is first slipped over a steel pile core made to fit it, and the shell and core are driven by a pile driver in the ordinary manner. The core is then slightly shrunken in diameter, by a simple device, and withdrawn, leaving the shell in the ground. The core is hoisted in the pile driver leaders, another shell is lowered into the one just driven and then slipped up on the core, after which the driver is shifted to the next location, and this shell is driven in the same manner as the first. The filling of the shells with concrete is done as soon as convenient. While the shape of the shells may be varied to suit conditions, the ordinary size is about twenty inches diameter at the top and six inches at the bottom, and such a shell twenty feet long weighs about seventy pounds.

734. The same company has a system of sinking shells in sand by the water jet. For this purpose the shells are in

[1] Raymond Concrete Pile Co., Chicago, Ill.

conical telescopic sections about eight feet in length. A two and one-half inch pipe with three-quarter inch nozzle is attached to the center of a cast iron point fixed to the inner section. Water forced through the pipe causes the shell to settle, and as the inner shell descends, its upper end engages with the lower end of the second section, so that when fully lowered the sections form a continuous cone. The concrete is filled in simultaneously with the sinking, imbedding the two and one-half inch pipe which remains permanently in the center of the concrete pile.

735. Concrete-Steel Piles: Molding. — Piles of concrete-steel usually have three or more steel rods of about one square inch cross-section imbedded longitudinally in the pile, and connected by smaller rods or wires at intervals of six to ten inches. Molds are so made that they may readily be detached and used again. At least one side of the mold should also be in short sections that may be put in place as needed, in order to facilitate placing the concrete. The molds should be set up vertically with the longitudinal steel rods in position. Enough concrete is put in the molds to fill six to ten inches in length, when a set of transverse tie rods or wires is placed, then another layer of concrete, etc. The concrete, which is of Portland cement, should be mixed rather wet, as thorough tamping is difficult in the confined space. The piles should be provided with a cast iron shoe at the bottom, or a steel plate covering to protect the point. At the top, one of the main rods is bent over to form a ring to facilitate handling the piles.

736. Driving. — When the concrete has hardened sufficiently, say at the end of four to eight days, the mold should be removed, and the pile allowed to remain in its original position twenty to twenty-five days longer, sprinkling it occasionally. When thoroughly set, they may be driven with an ordinary pile driver, using a heavy hammer and short drop. A steam hammer is preferred, however, and a special cap must be used to prevent injury to the pile head. Such a special cap may well be made of cast steel, fitting over the head of the pile like a helmet. The space between the lower end of the cap and the side of the pile is calked with clay and rope yarn or other suitable material. Through a hole provided in the top of the helmet, the space between the pile and cap is then completely filled with dry sand. Such a cushion cap effectually protects the pile head, distributing the pressure to the entire head. Caps in the form of a steel ring filled with sawdust surmounted by a wooden block, and also caps made of alternate layers of lead, wood and iron plates have been successfully used.

Art. 83. Arches

737. The use of concrete in the construction of arch bridges is becoming so extended and diversified that it would require a volume by itself to adequately cover the subject, and such a treatment of it is well merited. All that can be attempted here is to describe briefly one or two examples of well proportioned arches, and to give a few hints on methods of design and construction.

738. DESIGN. — Concrete arches may be built with or without steel reinforcement, but for long spans concrete-steel is usually employed. The design of a concrete arch without steel is entirely similar to that of a stone masonry arch, except that planes of weakness corresponding to joints between voussoirs in a masonry arch, may be somewhat more arbitrarily arranged in the former.

In fixed concrete-steel arches, the arch ring is continuous, and is capable of resisting a bending moment. The computations are therefore somewhat more complicated, and until the action of concrete and steel in combination has been more carefully determined, it may be said, in the words of a prominent engineer, that "the development of the system of arches of concrete must necessarily be largely based upon empirical information coupled with sound judgment and work executed with great care."[1] Fortunately, the saving effected by this construction over a masonry arch is usually so great that it is possible to use a large factor of ignorance, and it is to be hoped that the use of concrete-steel for arches of long span will not be given a serious check by the failure, perhaps under unforeseen conditions, of some of the web-like structures that have been built of it.

739. Where the span and rise of the arch are not fixed by the local conditions, the comparative economy of different

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[1] L. L. Buck, Trans. A. S. C. E., April, 1894.

arrangements and the appearance of the completed structure must govern. Shortening the spans decreases the amount of concrete required in the arches, but increases the pier work, which is usually the most expensive part of the structure.

These points having been decided, the form to be given the arch ring is next to be considered. While it is desirable that the neutral axis of the arch ring should nearly correspond with the line of pressures for a full load, there is still considerable choice allowed the designer as to the actual form to be given the intrados without serious changes in the amount of material required. As the semicircular arch can usually be adopted for very short spans only, the choice must lie between the segmental, the elliptical, and the polycentered arch approaching more or less closely the ellipse, the parabola, or the transformed catenary.

The segmental arch, the parabola and the catenary do not give a pleasing effect at the junction of the arch ring and the abutment, and the curve is sometimes departed from near the springing to make the intrados tangent to the face of the abutment. The final choice will thus usually lie between a true ellipse and the basket-handled arch.

Mr. Edwin A. Thacher, M. Am. Soc. C. E., designer of the Topeka bridge, considers that "arches with solid spandrel filling should be flat at the center and sharper at the ends, approaching an ellipse; while arches with open spandrel spaces should be sharp at the center and flatter at the ends approaching a parabola, or, which is better, sharp at the ends and center and flat at the haunches." [1]

The form of the intrados having been fixed, the depth of keystone for an arch without reinforcement is derived, tentatively, from the rules of either Rankin or Trautwine, to be corrected later if necessary. The form of the extrados is then so chosen as to give the required depth of arch ring to confine the line of pressure within the middle third.

740. Concrete-steel Arch. — The computation of a concrete-steel arch is, as already stated, more involved. The graphical analysis is much the simplest method of deriving the bending moment, direct thrust and shear. The experience of Mr.

[1] *Engineering News*, Sept. 21, 1899.

Thacher has led him to endeavor to have the line of pressure lie within the middle third of the arch ring, although this is not absolutely necessary in reinforced concrete. The same authority considers it good practice to design the steel work to be capable of taking the entire bending moment with a unit stress of about one-half the elastic limit of the steel.

The thrusts, bending moments and shears at successive sections of the arch ring having been determined, both for full and half span loads, by the graphical methods explained in Greene's "Arches" or Cain's "Elastic Arches," or by the analysis given in Howe's "Treatise on Arches," the dimensions of the arch ring and the steel reinforcement are to be derived by the aid of such formulas as are given by Mr. Thacher[1] involving the allowable unit stresses in steel and concrete, and their respective moduli of elasticity.

741. General Considerations. — In short spans, parallel spandrel walls with earth filling between, may be used, but for long spans the spandrels are usually open, that is, built of vertical piers or walls running parallel to the axis of the soffit, and arched over at the top to support the pavement or ballast. This treatment has the following advantages: only vertical forces are transmitted to the arch ring; decreased loads on arch and abutments; increased waterway in case of unusual floods; and better architectural effects.

The beauty of the structure is an important consideration, inasmuch as the decision in favor of a concrete arch as against a steel bridge is usually affected quite as much by considerations of æsthetic effect as of cheapness and durability. In this connection it may be said that in concrete-steel construction there may be little difference in the thickness of arch ring required at the crown and near the springing, but the appearance of the structure will usually be improved by accentuating a little, if necessary, the increased thickness at the springing, except in the case of the semicircular arch in which the eye is accustomed to a nearly uniform thickness of the voussoirs. The appearance is also frequently improved by molding the concrete at the crown to represent a keystone, projecting a little beyond the face of the rest of the arch ring.

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[1] *Engineering News*, Sept. 21, 1899.

The beauty of a concrete arch may easily be marred by faulty design, and some very ugly, as well as some very beautiful, arches have been erected.

742. Stone Facing. — The practice which has been followed to some extent of facing the spandrel walls with cut stone masonry, is considered questionable. The cost of ashlar facing is likely to be so great as to discourage the use of headers of sufficient length to give a good bond with the concrete, and it is next to impossible to make this equal to monolithic concrete construction. Again, since concrete is frequently used to protect ashlar masonry that has started to disintegrate, it is rather a reversal of what has been found good practice to face concrete with a *thin* layer of cut stone. No criticism is intended of the method of building a pier of large dimension stone with concrete hearting, as this is a different matter. But a thin parapet or spandrel wall faced with a mere shell of cut stone, however beautiful it may be when built, is likely to take on a somewhat dilapidated appearance after ten years' service, especially if it is called upon to pass through one or two floods of unusual violence.

743. Quality of Concrete. — As already intimated, the cost of a concrete arch, especially where reinforcement is used, is, under ordinary circumstances, considerably less than a masonry arch of equal appearance and strength. The only exceptions to this rule are where the facilities for obtaining stone suitable for masonry are exceptional, and where the work is far removed from cement-producing regions and from the coast. The ability to employ common labor for much of the construction work in a concrete arch is an advantage only partially offset by the necessity of having somewhat more careful work done upon the arch centers and more careful supervision of construction.

The concrete of the arch ring should be of the best quality, especially if steel reinforcement is not used. For this purpose, the stone. broken to a size not exceeding two inches in any dimension, should be mixed with a quantity of mortar a little more than sufficient to fill the voids, and composed of one part Portland cement to two parts sand. Interiors of piers and abutments may be made of a poorer mixture, such as one Portland cement to three of sand and six of broken stone, or even in some cases where abutments are massive, one to four to eight concrete may be employed.

744. Centers. — Substantial centers must be provided for concrete arches, and the lagging should be sized, dressed on the upper side, and laid with radial joints parallel to the arch axis. Two inch plank sized to one and three-quarters inches is usually employed for lagging, and the supporting ribs should be from three to four feet centers. For spans up to forty feet a braced wooden rib with one center support and two end supports is used, but for longer spans a trussed center with supports ten to eighteen feet apart is employed. The centers should be made rigid and the camber need be very slight, say from $\frac{1}{1200}$ to $\frac{1}{600}$ of the radius at the crown. Not less than twenty-eight days should be allowed to elapse after building the arch before striking the centers.

745. Construction. — A method that has been largely employed in building the arch ring is to divide the arch into longitudinal rings by planes at right angles to the arch axis. It is believed to be better practice, however, to build the arch as a series of voussoir courses beginning with the spring course, but not necessarily proceeding in order from the springing to the crown. The advantages of this method of building the arch, in transverse courses parallel to the axis of the intrados, are that the planes of weakness may be made at right angles to the line of pressure; the unequal loading, and consequent settlement of the centers, has less tendency to crack the sections or to separate one section from another. In cases of failure of concrete arches under excessive floods, the tendency of the arch to separate along a longitudinal joint forming a plane of weakness has been clearly shown.

746. The tendency of the center to rise at the crown as the arch ring is built up on the haunches is sometimes overcome by temporarily loading the crown. In constructing the ring in voussoir courses, the order of the work may be so arranged as to distribute the loading on the centers in any manner desired. Such an expedient was adopted in the construction of the Illinois Central R. R. arch across Big Muddy River, where the arch ring was divided into nineteen voussoirs. The two springers were built first, then the fifth row of voussoirs towards the crown on each side, followed by the ninth row, the third and seventh. The intermediate blocks were then built in order toward the crown, the second, fourth, sixth and eighth, and finally the keystone. In this way the weight was well distributed on the centers, and the load on the two sides of the crown was kept symmetrical. The monolithic blocks forming the voussoirs that were built in molds had recesses on either side, which were made by securing planks to the interior of the mold. When the intermediate blocks were built, the concrete thus keyed into the blocks first made.

The division of the work into voussoir courses will usually admit of such size molds or blocks that two, one on either side of the center, may be completed in a day. If it becomes necessary to interrupt the laying of a block, however, a vertical bulkhead should be constructed in the mold, with key or dowel pins if desired, to assist in making a bond when the block is completed.

747. Finish and Drainage. — To provide a smooth face, a thin facing mortar of one part Portland to two parts sand is desirable, laid at the time of building the concrete in accordance with methods already described. A thicker layer of granolithic may be used on the soffit and will somewhat more effectually prevent the broken stone of the concrete settling on the lagging, which is always likely to occur to the detriment of the appearance of the finished work.

The division between adjacent voussoirs should be clearly marked on the face, and additional joints may be indicated if desired, by lines in a plane approximately perpendicular to the line of pressure. Such lines are obtained by securing triangular strips on the inner face of the molds. When spandrel walls are used, these may be similarly marked on the face by horizontal and vertical joints. On long spans the spandrels should have expansion joints, and the coping and parapet, when of concrete, should also have vertical joints to provide for changes in length due to loading or thermal variations.

The arches over the spandrels should be provided with a waterproof covering, either of Portland cement grout or an asphalt mixture to prevent the percolation of water to the arch ring. Pipe drains should be provided to carry the water to a point over the piers where it may be discharged. Care should be taken that such pipes have their outlets so located that the drip shall not disfigure the wall. Open spandrels may be drained by pipes built into the arch ring at suitable places.

748. Highway Arch without Reinforcement. — A good example of a highway bridge built of concrete without reinforcement is the monolithic arch spanning San Leandro creek, between Oakland and San Leandro, Cal.[1] This arch has a five centered, elliptical intrados, with span of 81¼ feet, rise of 26 feet and width of about 60 feet. At the crown the thickness of the arch ring is 3 feet, the radius of the intrados 61½ feet and of the extrados 88 feet.

As the arch rests directly on a bed of clay containing some gravel, the footings are made 30 feet wide, and they extend 5 feet below the creek bed. The lagging for the forms was of 2 by 6 inch scantling laid transverse to the axis of the structure or parallel to the axis of the intrados. The ribs of the centering were built of two 1 by 12 inch boards and the braces of 4 by 6 inch timbers, converged to three short 12 by 12 inch timbers supported by wedges bearing on 12 by 12 inch longitudinals.

749. The concrete was composed of one barrel Portland cement, two barrels sand to seven barrels of broken stone of varying sizes.

When the haunches had been built up about one-third the way, as flooding of the work was anticipated, an arch ring one foot thick was first completed, the remainder being placed as a second layer. There is a parapet wall three feet six inches high on either side of the bridge. The spandrel walls show a solid face, and are paneled to bring out the outlines of the extrados and parapet. The centers were struck ten days after the completion of the second arch ring, and the settlement at the crown was about one and one-half inches. The forms contained 90,000 feet, B. M., of lumber, and 3,384 cubic yards of concrete were used. The cost of the bridge was $25,840.00, or less than $8.00 per cubic yard of concrete. The contractors were the E. B. and A. L. Stone Co. of Oakland, Cal., and the plans were prepared by the County Surveyor's office of Alameda County, Cal.

750. A Three Span Arch. — The three span arch spanning a

[1] Described by Mr. William B. Barber, *Engineering News*, Aug. 27, 1903.

mill pond on Anthony Kill, near Mechanicsville, N. Y.,[1] is worthy of notice on account of some peculiarities in the centering and because of the location of the plant on a side hill, so that the concrete was delivered on the work with very little labor. Two of the arches were of 100 ft. span, with rise of 20 feet, and the remaining arch was of 50 ft. span. The width is but 17 feet, and the piers are founded on rock at a depth not exceeding 12 feet.

For the centering, piles were first driven, six feet centers, in bents ten feet apart, and the bents capped with ten by twelve inch timbers. Stringers of the same dimensions were then laid longitudinally, and eight by ten inch posts were erected on the longitudinals and spaced three feet centers. These posts, which were cut to proper length, so that their tops conformed to the curve of the intrados, were then capped with eight by ten inch timbers parallel to the axis of the intrados, and the lagging laid upon them transverse to this axis or parallel to the center line of the bridge. This lagging was of two thicknesses of one inch boards sprung into place and nailed, the upper layer being of dressed lumber to give a smooth surface to receive the concrete.

The concrete was of one part Portland cement, three parts sand, three parts gravel and three parts broken stone, except for the arch ring, in which but two and one-half parts each of gravel and stone were used. The concrete plant was so arranged that the stone could be passed from the crusher to the mixer by gravity. The concrete was delivered on the arch in cars of three feet gage drawn by cable. From fifty to sixty cubic yards of concrete were placed in ten hours with but nine laborers. 140,000 feet B. M. lumber was used in centers. The entire work consumed about 2,500 cubic yards of concrete.

751. Railroad Arch without Reinforcement. — The concrete bridge carrying the Illinois Central R. R. over the Big Muddy River furnishes an excellent example of a long span arch, built without reinforcement so far as the arch ring is concerned. The bridge is very fully described by Mr. H. W. Parkhurst, Engineer of Bridges and Buildings I. C. R. R., in *Engineering News* of Nov. 12, 1903. There are three spans, each 140 feet

[1] Described in *Engineering News*, Nov. 5, 1903.

in the clear, with 30 feet rise above springing lines. The arch ring proper is five feet thick at the crown, but as the spandrels, which are built open over the haunches, have near the crown only a false opening on the face, the actual thickness of concrete at the crown is seven feet.

The piers and abutments already in place for the three Pratt trusses formerly in use, were surrounded with new concrete masonry, making the piers 21 ft. 6 in. wide at the top. As rock was found only at considerable depth, the piers rested on piles. To relieve the load on foundations as much as possible, as well as to avoid cracking, which would be likely to occur in heavy longitudinal spandrel walls from temperature strains, transverse spandrel arches were adopted. Since in case of derailment of trains these spandrel arches would be subjected to shock, the concrete in this portion of the structure was reinforced by a self-supporting skeleton structure built of steel rails. Longitudinal rails were laid horizontally, three feet center to center, connected at frequent intervals by one inch rods and held in place by vertical posts, which in turn rested upon transverse horizontal rails laid in recesses left in the arch rib.

752. Expansion joints were provided in the spandrel arches at the ends, two at each pier and one at each abutment, to allow some movement due to changes in temperature. The expansion joints were made by placing in the joint several thicknesses of corrugated asbestos board protected by a $\frac{1}{8}$-inch lead plate folded into the joint, forming a trough at the top. The lead plate lies flat on top of the concrete for five inches from the joint, and about two inches at each end of the plate is bent down at right angles and set into the concrete. An asphaltic composition is then laid over the lead plate, entirely covering it and filling the trough.

The centering was erected on pile bents spaced about 14 feet centers, the calculated pressure on each pile being about eighteen to twenty tons. For the center span, five 60 foot deck plate girders resting on pile piers were used over the deepest portion of the channel to provide for possible floods bringing large amounts of drift.

753. The arch ring was laid in voussoir courses as described in § 746. Face joints were made by securing triangular shaped pieces to inner face of the molds in lines approximately at right angles to the line of pressure. All exposed work was faced with a layer of about 1½ inches of Portland cement mortar placed and rammed with the concrete. The surfaces were not given, in general, any further finish, no attempt being made to remove or conceal the usual marks left by the mold boards.

Portland cement was used throughout, the quality of the concrete being varied by the amount of cement used to given quantities of the aggregates. In the centers of large masses the poorer mixtures were employed, while the richer concretes were used in those places subjected to the most trying conditions.

In making the concrete the principle followed seems to have been to keep the mixer as near the work as practicable, moving the mixer and carrying materials to it, rather than to transport the mixed concrete from a certain fixed location of the mixing plant. Much of the concrete was handled in barrows, but derricks were also used in portions of the work. As traffic on the old bridge had to be maintained during the erection of the new structure, considerable extra handling of concrete was necessary and additional work was involved in ramming the concrete in places difficult of access. The concrete was mixed rather wet, so that but little tamping was required to make it quake.

754. Cost. — The total amount of concrete was over 12,000 cubic yards, which was placed at an average cost of $5.43 per cubic yard. In cofferdams and centers 400,000 feet B. M. of timber was used, and about 300,000 pounds of steel was employed in the skeleton structure of the spandrels. This steel cost 1.2 cents per pound, the punching, fitting and erecting costing but about 0.61 cent per pound. The total cost of the bridge is estimated to have been $125,000.00, or about the same as the estimated cost of a steel structure designed for the same duty.

755. The **Melan Arch Bridge** at Topeka, Kan., is one of the most important concrete-steel structures yet erected in the United States. It consists of one span of 125 feet, two of 110 feet each, and two of 97.5 feet each. The foundations for piers and abutments are piles in soft sand. The steel reinforcement is in the form of a latticed member. The bridge is fully described in *Engineering News* of April 2, 1896, and *Engineering Record*, April 16, 1898.

756. Concrete-Steel Viaduct. — A viaduct of ten concrete-steel arches, of about 65 foot span, carries a double track electric line across West Canada Creek near Herkimer, N. Y.[1] The piers rest on piles driven into hard blue clay, the surface of which is 6 to 12 feet below the creek bed. The segmental arches have a rise of 12 to 14 feet, with thickness of 21 inches at the crown and 4½ feet at the springing; the radius of intrados is about 46 feet, and of extrados about 57 feet. The stresses were computed for full load and for live load on half span, Prof. Cain's graphical method being employed. The maximum stresses allowed were six hundred pounds per square inch compression in concrete and ten thousand pounds per square inch tension in steel. The stresses caused by a variation of fifty degrees in temperature were allowed for. The tensile strength of the concrete was disregarded. Thacher bars, 1¼ inches diameter, were used for the reinforcement, being placed eleven inch centers near both intrados and extrados.

757. Expansion joints were provided in spandrel walls by nailing to the sides of the forms for arch pilasters a narrow strip of timber, thus forming a groove into which the spandrel wall is tongued. These joints show some motion and allow some water to leak through.

The **concrete** was mixed three parts sand and seven parts gravel to one volume packed cement for foundations and piers, and two and one-half parts sand and five of gravel to one cement for the arch rings and spandrel walls. All concrete was mixed wet and by hand. The work was faced with mortar composed of one part cement to two and one-half parts sand, and after the removal of forms the face was brushed with thin mortar wash and rubbed with sandstone blocks, giving a uniform color to the surface.

Art. 84. Dams

758. Concrete vs. Rubble. — Concrete has been employed to some extent in most of the important masonry dams of recent construction, and has formed the main portion of some of the largest dams yet built.

The relative value of concrete and uncoursed rubble masonry

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[1] *Engineering News*, Feb. 27, 1904.

laid in Portland cement mortar is perhaps still an open question, though it is believed that the former will eventually be preferred by engineers who are familiar with both. Concrete will require in general a larger proportion of cement than does the masonry, so that in localities difficult of access, the masonry may for this reason be cheaper. Usually, however, concrete will be the cheaper, and less skilled labor will be required in the building. With the same amount of inspection, concrete of good materials properly proportioned will form at least as impervious a wall as will rubble.

759. Quality of Concrete. — The up-stream face of the dam should be made as nearly water-tight as possible, and therefore a rich concrete employed in which the mortar is in excess of the voids in the stone, and the mortar itself contains about two parts sand to one cement. The body of the wall, however, may be made of a poorer mixture, one to three to six usually being sufficient. Bowlders may also be imbedded in the mass to cheapen the concrete without any serious detriment. Such bowlders should, of course, be sound and clean, and well wet before being placed. They should be kept well back from the face of the wall and should be separated one from another by at least six inches, to allow of thoroughly tamping the concrete between them.

760. Building in Sections. — In a wall of rubble the contraction and expansion are taken care of by minute cracks between the stone and mortar which frequently are not noticeable. In a concrete wall, unless provision is made for this, these signs of movement may be concentrated in cracks at intervals of thirty to sixty feet; these are always unsightly, and may in exceptional cases be a serious defect. The remedy evidently lies in so building the dam that if these cracks appear, they shall be confined to predetermined planes where they will not do any serious harm. Such contraction cracks will be very much less likely to occur in a dam arched in plan than in a straight dam, since in the former a slight movement of the masonry up or down stream changes the length of the wall and relieves the tension strains.

761. Joints. — The joints in a concrete dam should not be unbroken planes for any great distance. That is, the concrete should be so placed that the joints between work of different days are not planes extending through the wall. The wall may well be kept higher on the down-stream side and step down toward the up-stream side. The vertical joints should also be broken by right-angled off-sets, but the wisdom of using a dove-tail joint in such work is very questionable. The joining of one day's work to another necessarily forms a plane of weakness, and therefore the work should be carefully planned to the end that these planes shall be, in direction and location, where they will not unnecessarily weaken the structure or render it pervious to water.

762. Examples: *St. Croix Dam.* — A dam at St. Croix, Wis.,[1] was built of sandstone masonry of uncoursed rubble in one-to-three mortar, and faced with concrete of one Portland cement to three parts sand to four parts broken stone of 1 to 3½ inch size. The concrete was rammed in place between the stone-work and the concrete forms. The selection of the uncoursed rubble was probably made on account of the site being five miles from the railway and the consequent difficulty of getting cement. The dam was arched in plan, and in preparing the foundation, several grooves or trenches were cut in the rock in a longitudinal direction, to avoid, as usual, a through course at the bottom, and these trenches were also filled with concrete. Had the concrete for the facing contained five parts of broken stone having maximum size of 2 or 2½ inches, it would have been more nearly in conformity with the best practice.

763. *Massena Dam.* — In the construction of the dam at the forebay of the Massena Water Power Company, Massena, N.Y.,[2] it was sought to take up the tension stresses due to contraction by imbedding in a longitudinal direction in the concrete, T-rails two feet apart horizontally and four feet apart vertically.

764. *Butte Dam.* — The dam built in connection with the Butte, Montana, water system is 120 feet high, 350 feet long, 10 feet wide at the top and 83 feet wide at the 120 foot point. The bed rock was granite, which was first covered with four inches of concrete made with small sized stone. In the body of the dam, granite bowlders were thickly imbedded in the

[1] *Engineering News*, June 13, 1901.
[2] *Engineering News*, Feb. 21, 1901.

concrete, care being taken that each bowlder was entirely enveloped in concrete and that there were no horizontal or nearly horizontal courses either of concrete or bowlders.

765. *San Mateo Dam.* — The San Mateo Dam of California, one of the highest dams in existence, is built entirely of concrete, 170 feet high. It is 126 feet thick at the base and is arched upstream with a radius of 637 feet. The dam was constructed in blocks of 200 to 300 cubic yards each, of irregular heights, so as to bond the courses together and have no through joints. Concrete, one, two to six, was delivered in small push cars on a high trestle over the dam, and was dropped through iron pipes 16 inches in diameter to the place of deposition. In some cases this drop was 120 feet, and it is stated that the concrete appeared not to be injured by this method of handling.

766. *Barossa Dam.* — The Barossa Dam in South Australia[1] is of a bold arch design. The arch has a radius of 200 feet, and the chord is 370 feet subtending an angle of 135 degrees, 20 minutes, and the length of the arc 472 feet. The height of the dam is 94 feet above the ground line, yet the greatest thickness above the foundation is only 34 feet, with a top width of only 4½ feet.

Special care was taken in selecting the materials and fixing the proportions. The cement was aërated fourteen days before use. Test cubes of concrete two feet on a side were prepared with different proportions of materials and subjected to a hydrostatic pressure of two hundred feet before deciding upon the proportions to use in the concrete. As a result of these tests, the aggregate was made up of one part screenings ⅛ to ½ inch, two parts "nuts" ½ to 1¼ inch, and four and one-half parts "metal" 1¼ to 2 inch. This mixture contained about 35 per cent. voids. The mortar was made of one part Portland cement to one and one-half parts sand, and was from seven and one-half to fifteen per cent. in excess of voids in aggregate. Plumbs were used in the dam to within fifteen feet of the top, and above this level iron tram rails were placed in string courses. The success accompanying the use of concrete in structures of this magnitude is sufficient evidence of its value and adaptability.

[1] Mr. A. B. Moncrieff, Engineer in Chief, *Engineering News*, April 7, 1904.

Art. 85. Locks

767. The use of concrete in the construction of canal locks is comparatively recent, but it has met with much favor, and its use is extending. The requirements for a lock wall are that it shall be reasonably water-tight, that its strength shall be sufficient to withstand the thrust of the gates and support the earth filling behind it (or in a river wall, the difference in water pressure on the two sides), and that it shall withstand the impact and abrading action of boats using the canal. In all of these respects concrete is believed to be the equal of a good class of stone masonry. At St. Marys Falls Canal, portions of the lock walls which have been injured by boats and repaired with concrete have given entire satisfaction, although in such cases the concrete had to be patched on, and sometimes in places difficult of access for work of this character.

768. Methods of Building. — The present accepted method of concrete lock construction is to build the walls in alternate sections, filling in the intermediate sections after the others have set. It is sometimes thought necessary to make the work on a section continuous from time of starting the concreting to its completion. That the exterior appearance of the work may be somewhat better if such a course is followed, is true, but it is very questionable whether the attainment of this desirable result is worth the additional expense and the additional liability of having poor work done under the cover of darkness when work at night is necessitated by such a rule. With proper precautions, such as making steps in the top surface of work left for the night, as already detailed elsewhere, and being careful that the limit of work on exposed faces is bounded by true horizontal and vertical lines, the plane of weakness occasioned by a horizontal joint extending only partially through the work cannot be a serious defect in a concrete wall.

769. The **molds,** so far as the walls alone are concerned, are comparatively simple and have already been described under the head of forms (Art. 62). Cable passages, gate recesses, hollow quoins, culverts, etc., call for special carpentry work, sometimes of quite intricate character. While the efficiency of the machinery and the lock as a whole should not be sacrificed to obtain easy construction, yet sharp corners should always be avoided, and simplicity of outline should be the constant aim. Linings of hollow quoins (when steel quoins are considered necessary), gate anchorages, cable sheaves and other parts built into the masonry, are in general placed with greater difficulty in concrete forms than in stone masonry. Aside from such special constructions, the walls may be built up much more rapidly of concrete than of stonework.

As to the **proportions** to be used in concrete for locks there is no rule of thumb. As a guide, the stresses in each part of the structure should be determined as well as the knowledge of the forces will permit, but the proportions will depend on the question of water-tightness and freedom from deterioration quite as much as upon required strength. It may be said, however, that in a considerable portion of the cross-section of the walls, weight is the main consideration and the concrete need not be very rich. The concrete surrounding the culvert, however, should be of good quality, as the stresses which may be developed here do not admit of close analysis.

770. The **walls** should be faced with mortar made of one and one-half or two parts sand, or, better, two parts of granite screenings one-half inch and smaller, to one part of the same kind of cement used in the body of the concrete. This facing need not be more than three inches thick, and if made of sand and cement, it will probably be better if not more than one inch thick, though this may depend on the materials and local conditions. In any case this facing should be laid with the concrete by means of a removable steel plate similar to that described in § 528. The top of the wall should be finished with mortar or granolithic similar to a concrete walk or driveway. While the walls should in general have a vertical face, a slight batter is allowable at the top, starting at about upper pool level, to protect the concrete from being chipped by the impact of boats, and for a similar purpose the outer corner of the wall should be rounded with six to twelve inch radius.

Special care must be taken in lining the **culverts,** particularly in silt-bearing streams, and in such places as a change is made in the direction of the flowing water. For high heads it may be necessary to line the culverts with cast iron for a portion of their length. Granite and hard burned bricks have also been used for this purpose, but in locks of moderate lift, granolithic lining will usually be found sufficiently resistant.

All necessary irons and bolts should be built into the masonry as the work progresses, as they will be much more secure than if set later in recesses left for them.

771. Cascades Lock. — The large lock in the canal at the Cascades of the Columbia was one of the first in the United States to be designed of concrete in this country. In this lock the walls, wells, copings and portions of culverts were faced with stone. The foundation rock was covered with eight inches of rich concrete, one part Portland cement, two parts sand to four parts gravel. Fourteen feet of the chamber walls and ten feet of gate abutments or wide walls were of concrete, one to three to six, while balance of masonry was of one to four to eight concrete.

The molds were of four by six posts four feet apart, and lagging of two-inch lumber, dressed to size for exposed faces. The work was carried up in horizontal layers, not more than two feet being placed in one day. The set concrete was picked and washed when fresh concrete was to be laid upon it so as to get as good a bond as possible. The inlet pipes to the turbines to operate the machinery were built in the lock walls, and as it was not desirable to place an iron pipe in this location, the pipe was molded of concrete and afterwards laid in the wall. The pipe was thirty-nine inches diameter, walls six inches thick and contained about 0.22 cubic yard of concrete per foot. It was made in three foot lengths in vertical molds, and the cost of about six hundred feet of it was at the rate of $3.56 per foot, or $16.19 per cubic yard.

772. Hennepin Canal. — In the locks for the Illinois and Mississippi Canal the walls are entirely of concrete, and were built in alternate sections about thirty feet long. Work on a given section once commenced was continued to completion without intermission. The top was finished without any plaster or wet coat, the excess concrete being simply cut off with a straight edge and rubbed smooth and hard with a float. Vertical wells one foot square were left in the walls at intervals, and these were kept filled with water for about three weeks after the completion of the section, and then filled with concrete. To avoid weak places due to single batches made from cement of poor quality which might have passed inspection, the cement was mixed in lots of five to ten barrels before being used in the concrete.

The quoins of these locks were of cast iron. The foundations and the spaces in rear of lock walls are cut off from upper pool by cross-walls, and are underdrained to the lower pool to prevent the action of water pressure due to the upper pool level tending to force up the foundation. Ten inch and twelve inch tile drains were used for this purpose.

The proportions used in general were one part Portland cement, three to three and one-third parts gravel, and four parts broken stone, the concrete containing about one and four-tenths barrels of cement per yard. The average cost of concrete in quantities of two thousand to four thousand yards was from $8.50 to $9.15 per cubic yard, distributed approximately as follows: —

Materials	$5.00 to $6.00
Molds	.82 to 1.42
Mixing and placing	1.64 to 1.82
Miscellaneous	.12 to .47

773. Herr Island. — In the Herr Island Locks, Alleghany River, the failure of the cofferdam to exclude water from the lock pit on account of porosity of the river bed, led to the adoption of a concrete foundation, laid under water, of sufficient weight to balance the hydrostatic pressure. After this foundation was in place, the cofferdam was pumped out and the concrete side walls built in the dry.

The concrete was placed in one foot courses covering the entire area of the wall, the forms being made of one course of two by twelve inch plank set on edge and halved at the ends to form two inch lap splices. Iron rods one-quarter inch diameter were placed six feet eight inches apart to tie face and back plank together. A two by twelve inch cross-plank was placed on edge beside each tie rod, dividing the work into short sections. After completing the concreting to the top of the forms throughout, the cross-planks were removed and the space filled with concrete, thus making a vertical joint. The forms for the next course were then put in place in a similar manner. The size of stone used as aggregate was first two inches in one dimension, but this size was afterward reduced to one and one-half inches, and finally to one inch, the smaller size stone being preferred.

774. Mississippi River. — The lock in the Mississippi River between Minneapolis and St. Paul was founded on a soft sandstone rock having many water-bearing seams. The lock was surrounded on three sides by a cut-off wall. A trench two inches wide and ten feet deep was cut in the soft rock by jetting a series of holes in close juxtaposition and then breaking out the intervening wall with a drill and saw of special construction. In this trench was first laid a double thickness of three-quarter inch boards and the remaining space was grouted full. Sections of this wall afterward uncovered, showed the method to have been very effective. Similar methods of sealing open seams in rock by the use of grout under pressures have been used elsewhere.

The forms for the construction of this lock were of excellent design[1] and have been described under the head of "forms" (§ 514). The walls were built in alternate blocks, twelve feet long. At the ends of the blocks are left vertical spaces five by seven inches, to be filled with mortar and other water-tight composition. The forms are lined with sheet iron, and to obtain a smooth face the concrete is thrown against the lining, the stones rebound, leaving only mortar on the face. The face is rammed with tampers of special form, wedge shaped, and measuring ¾ inch by 5 inches on the lower edge. This is followed by a flat rammer. The finish is said to be excellent.

775. Sand-cement was used quite largely in the lock construction. It was prepared at the site of the work, of equal parts Portland cement and siliceous sand ground together in a tube mill.

Proportions in the concrete were varied somewhat from time to time, though in general it was mixed one part silica cement, two and one-third parts sand and six and two-thirds parts of crushed stone without screening. Tests showed that about ten per cent. of this crusher product was fine enough to be considered sand, and account of this fact was taken in fixing the proportions as above. The cost of the concrete, over 11,000 yards, was as follows: —

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[1] Mr. A. O. Powell, Asst. Engr., *Report Chief of Engrs.*, 1900, p. 2778.

Cement		$2.76	
Stone	$1.29		
Breaking stone for crusher	.38		
Crushing stone	.82		
Total stone		$2.49	
Sand		.52	
Total materials			$5.77
Forms			1.21
Mixing and placing concrete			1.44
Total cost per cubic yard concrete			$8.42

Art. 86. Breakwaters

776. The use of concrete in the construction of breakwaters in the United States was suggested as early as 1845. In recent years it has been employed quite extensively, especially for harbor improvements on the Great Lakes, where it has withstood the rigorous winters, the severe storms, the attrition of ice, and the impact of boats, in a highly satisfactory manner. Its use has been confined largely to the construction of a superstructure on timber cribs, the concrete work being in the form of blocks set with derricks, or of monolithic blocks molded in place, or more frequently composed of a combination of these two forms.

Since in breakwater construction weight is of prime importance, it is not necessary, in general, to use an exceptionally strong concrete, as the increased expense had better be incurred in increasing the cross-section.

777. Buffalo Breakwater. — In the construction of the extensive breakwaters at Buffalo,[1] concrete has been used in large quantities and according to various plans. In 1887 the superstructure of some 750 feet of timber-crib breakwater was renewed, mainly with natural cement concrete. 250 feet of this superstructure was built with a facing of Portland cement concrete, while 500 feet of it was faced with stone masonry. The concrete started two feet below mean lake level. The cross-section of the superstructure was about 350 square feet, and the cost of concrete, exclusive of materials, was about $2.36 per cubic yard.

[1] Described by Mr. Emile Low, U. S. Asst. Engr. Trans. Am. Soc. C. E., December, 1903.

During the following year concrete footing blocks were used on both the lake and harbor faces, since it was found that the cement was washed out of the concrete laid in place below water. The blocks contained about 3¼ cubic yards and cost on the average a little more than $30.00 each, or $37.35 each including the setting, or at the rate of $11.29 per cubic yard. The molds or forms, which were used repeatedly, cost about $40.00 each.

778. Another style of concrete superstructure developed at Buffalo is that recommended by Major F. W. Symons. It consists of three longitudinal walls, connected at intervals by cross-walls, filled between with rubble stone and provided with heavy parapet and banquette decks. The longitudinal wall on the lake side is founded on heavy concrete blocks 5 feet high, 8 feet thick at the base and 7.2 feet long; the two minor walls are formed by smaller blocks, 4 feet by 4.5 feet by 12 feet. The total width at base is 36 feet. The space between lake face blocks and center row is 14 feet, and between center row and harbor face blocks is about 5 feet. The cross-wall blocks are 7 by 6 by 4 feet under the parapet, and 4 by 3 by 4 feet under the banquette, all spaced 36 feet centers. All concrete blocks have their bases set two feet below mean lake level and have panels in their upper surfaces to provide a bond with the concrete laid in place.

The lake wall above the concrete block is 8 to 4 feet thick, with batter on face, and the decks are 3 to 4 feet thick, built of concrete in place. The forms for the harbor face wall and cross-walls were of ⅞ inch matched pine, with vertical posts two to three feet centers tied through the wall with one-half inch tie rods.

The concrete was composed of the following volumes: one part Portland cement, one part screened gravel (about ⅜ inch), two parts sand grit (nearly half of which was ⅛ inch to ¼ inch gravel), and four parts unscreened broken limestone (about 11 per cent. dust). The cost of the concrete in blocks was $10.00 per cubic yard, and that in place cost $9.40 per cubic yard.

779. Cleveland Breakwater. — Several forms of concrete superstructure have been employed in the work at the Cleveland breakwater. One section on a thirty-two foot crib has three rows of concrete blocks, one each on lake and harbor sides and one in center of the crib, extending three feet below mean lake level. The concrete in place is started at mean lake level and is composed of a base five feet thick, with vertical faces over the entire crib, and surmounted on the lake side by a parapet five feet high and about twelve feet wide. The stone filling of the cribs was covered with a cheap decking of wood before laying the concrete in place.

780. Marquette Breakwater. — In the construction of the superstructure of the breakwater at Marquette, Mich., the conditions were peculiar in that it was desirable to provide a passageway within the superstructure through which the lighthouse on the outer end might be reached in stormy weather. This was accomplished by leaving near the harbor face a conduit, 6 feet 3 inches high and 2 feet 10 inches wide, the entire length of the structure.

The old timber structure having been removed to about one foot below mean lake level, a foundation course two feet thick of Portland cement concrete was laid on a burlap carpet placed over the stone filling of the crib. Upon this the monolithic blocks were built in place, substantial molds being set up for alternate blocks ten feet apart. After these had set, the molds were removed and other molds set up to form the two faces of the intervening blocks, the ends of the blocks already completed taking the place of end molds. The monolithic blocks were of natural cement concrete in proportions of 489 pounds of cement to one-half cubic yard of sand and one cubic yard of broken stone. About twenty per cent. of these monoliths was composed of rubble stone ranging in size from one-half to three cubic feet, care being taken that no rubble should be placed nearer than one foot to any outside surface. The standard block was twenty-three feet wide on the base, which was one foot above mean lake level. The lower five feet of the face had a 45° slope. There was then a nearly level berm, 7.5 feet wide, forming the banquette deck; from the back of this deck the face sloped at an angle of 45° to the parapet deck, which was 6 ft. 4 inches wide. The harbor side of the block was vertical, 9.4 feet high. Since the structure proved very stable and free from vibrations in heavy seas, the horizontal dimensions of the block were reduced as the shore was approached.

781. The method of placing the Portland cement concrete foundation was modified as described under the head of the block and bag systems of concrete constructions (Art. 64).

The **cost** of the monolithic blocks of natural cement concrete was as follows: —

490 lbs. cement, $1.04 per bbl.	$1.815	
.5 cu. yd. sand, $0.50 per cu. yd.	.25	
1.0 cu. yd. stone, $1.58 " " "	1.58	
Materials in one cubic yard concrete	$3.645	
80 per cent. concrete in the finished block, .80 of $3.645		$2.91
Loading materials		.33
Mixing concrete		.52
Depositing concrete		.41
Handling rubble		.09
Finishing blocks		.09
Moving and setting forms		.25
Timber waling, anchor bolts, etc.		.13
Total cost in place per cu. yd.		$4.73

Very interesting and detailed accounts of the construction of this breakwater, which was carried out with special care as to all details, were made by Mr. Clarence Coleman, Asst. Engr., and may be found in the reports of Major Clinton B. Sears, Reports Chief of Engineers, U. S. A., 1896 and 1897.

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