CHAPTER XII

TABLES OF QUANTITIES OF MATERIALS FOR CONCRETE AND MORTAR

This chapter presents tables, curves, and formulas (pp. 221 to 235), by which the volumes of materials required for a known volume of concrete may be estimated, and emphasizes the importance of distinctly stating the proportions (p. 217).

The volume of concrete, even when made from materials in the same proportions, varies largely with the character of the materials and the methods of placing it. A mixed aggregate like gravel contains fewer voids and with the same proportions by volume of the same cement and sand produces a larger quantity of concrete than a screened broken stone. The fineness of the sand also largely affects the volume of the concrete and mortar, a fine sand requiring more water, and therefore producing a larger volume of mortar than coarse sand in the same proportions by volume. If the sand is dry, a slightly larger bulk of mortar is produced than with the same sand when containing a larger percentage of moisture, because the latter is less compact (see p. 176). Some cements require more water in gaging than others, and produce a larger amount of paste, which increases the volume of the concrete or mortar. The method of mixing and placing the concrete also affects the resulting volume, since an imperfectly mixed or poorly compacted mass contains voids which increase the volume. An excess of water in mixing affects the resulting volume of the set concrete or mortar to a slight extent, although most of the surplus water is expelled during setting.

It is possible to provide for all these variations, except those relating to improper mixing and placing, in rational formulas from which the resulting volumes may be accurately estimated if the characteristics of all the materials are known. For most practical purposes, however, average values, such as are presented in the tables and curves, are sufficiently accurate for estimating quantities. These average values are based upon a large number of tests in the United States, France, and Germany.

The theory of a concrete mixture is discussed, and formulas for volumes and quantities are given on pages 220 to 227 preceding the tables.

EXPRESSING THE PROPORTIONS

In framing concrete specifications, the proportions of the constituents should be stated so distinctly that there can be no misunderstanding between the engineer and the contractor as to the quantities which will be required for the work. The quantity of cement should invariably be regulated by its weight; if the proportions are stated by volume a definite weight or number of packages of cement must be assumed to the unit volume. For reasons discussed in Chapter XI, it is also more accurate and scientific to measure the aggregates by weight than by volume, and since with a properly constructed plant using materials of several sizes, the cost need be no more than volume measure, the authors believe this will eventually become common practice in the case of important construction.

With our present system of weights and measures, it is advisable either to specify the number of cubic feet (or pounds) of sand and gravel, stone, or mixed material to a definite weight of cement, or else to stipulate a definite weight of cement to a cubic yard of concrete tamped in place, with an aggregate of clearly described material proportioned as the engineer may direct.

In stating the proportions for both mortar and concrete, it is now customary in the United States to separate the materials by colons, the first figure always representing the cement, followed by the aggregates in the order of the size of their grains. For example, 1:3:6 means 1 part cement (the unit of measurement should be stated), 3 parts sand, and 6 parts coarse material; or 1:8 means 1 part cement (of defined weight) to 8 parts of graded aggregate. Mortar in proportion 1:2 signifies one part cement to two parts sand by either weight or volume as specified.

In France, proportions are stated as one or more volumes of mortar to a definite number of volumes of stone, — "un volume de mortier pour deux volumes de cailloux."

Unit for Proportioning. If the proportions must be stated in parts, it is recommended that the weight of cement be assumed as 100 lb. per cubic foot, and the corresponding volume of a barrel as 3.8 cu. ft. By this system of units, proportions 1:3:6 would represent 100 lb. cement to 3 cu. ft. of sand to 6 cu. ft. of gravel or stone; or, 1 bbl. cement (*i.e.*, 4 bags or 376 lb.) to 11.4 cu. ft. sand to 22.8 cu. ft. gravel or stone.

The authors offer these recommendations after correspondence or personal interview with some fifty authorities* (members of the American

*See Preface.

Society of Civil Engineers) on concrete construction, representing all sections of the United States.

With reference to the unit which should be selected for the volume of a cement barrel (corresponding to 376 lb. Portland cement) the opinions were varied, but nearly every authority advocated specifying a definite weight of cement instead of measuring it loosely by volume. The units which met with the most favor were 3.5, 3.6, 3.8 and 4.0 cu. ft. The advocates of the first two values based their figures upon the measured volume of a cement barrel, while those selecting the last two did so on the presumption that the unit is an arbitrary one in any case, and 100 lb. per cubic foot, or 95 lb. per cubic foot (the latter equivalent to 1 cu. ft. to the bag), is convenient for calculation. An approximate average of all the figures suggested was 3.8 cu. ft. to the barrel, corresponding to 100 lb. per cubic foot, the advocates of this value being, among others, Messrs. Charles E. Fowler, William B. Fuller, Peter C. Hains, Allen Hazen, Rudolph Hering, George A. Kimball, Leonard Metcalf, J. Waldo Smith, and J. H. Wallace. Accordingly, in cases where it is advisable to specify the proportions by parts, the authors have adopted this unit as their standard.

When stating the proportions by volume, too much stress cannot be laid upon the necessity for the adoption of a standard unit, such as a barrel of 3.8 cu. ft. or the equivalent assumption that a cubic foot of cement weighs 100 lb., and upon distinctly specifying this standard, as otherwise an unscrupulous contractor may adopt for his unit the volume of cement very loosely measured, and thus produce too lean a concrete. Moreover, without a standard there is no means of comparing the concrete in different structures or the results of different experiments. It is even inaccurate to state that proportions shall be based on packed or on loose measurement of cement, for either of these terms is very elastic. The authors have personally known engineers to place the volume of a barrel of packed cement all the way from 3.1 to 3.8 cu. ft., corresponding to a variation in weight of from 123 to 100 lb. per cubic foot, while loose measurement, on the other hand, is variously fixed at from 3.8 to 4.5* cu. ft. to the barrel, or 100 to 84½ lb. per cubic foot. The extreme actual variation is therefore from 3.1 to 4.5 cu. ft. per barrel, or 123 to 84½ lb. per cubic foot. Proportions 1:3:6 in the first case would require 1 bbl. or 376 lb. cement to 9.3 cu. ft. of sand and 18.6 cu. ft. of gravel; in the last case, proportions 1:3:6 would stand for 1 bbl. or 376 lb. cement to 13.5 cu. ft. of sand and 27 cu. ft.

*This value is given by one engineer in Proceedings Association of Railway Superintendents of Bridges and Buildings, 1900, p. 212.

of gravel. In other words, concrete mixed 1:3:6 by one man may be called 1:4¼:8½ by another.*

It may be contended that this variation is of little moment provided the unit is distinctly stated. The fact is, however, that it is customary in discussing a piece of work to give the proportions of materials without stating the unit selected, and many records giving tests of strength of concrete do not even specify the units used in proportioning the ingredients. It is especially confusing also, to a contractor who is not very careful in

Tests of Capacity of Portland Cement Barrels and Weight of Contents.

(Tabulated by the authors from measurements of Boston Transit Commission, 1896, Howard A. Carson, Chief Engineer.) (*See p.* 219.)

No. of barrels tested results averaged	Brand	Height between heads	Average diameter of barrel	Average horizontal area	Capacity of barrel between heads	Depression of cement below head	Volume of depression	Volume of cement per barrel			Net weight of cement per barrel		Weight per cubic foot				Weight of barrel
								Packed	Loose	Shaken*	Before dumping	After dumping	Packed	Loose	Shaken	Sifted	
		ft.	ft.	sq.ft.	cu.ft.	ft.	cu.ft.	cu. ft.	cu. ft.	cu. ft.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
5	A	2.12	1.437	1.622	3.446	0.17	0.235	3.21	3.75	3.432	377.4	376.9	117.5	100.5	109.4	90.6	21.1
6	B	2.19	1.430	1.605	3.495	0.12	0.171	3.35	4.17		381.0		113.8	91.4			29.0
3	C	2.07	1.412	1.571	3.249	0.07	0.096	3.15	4.05		387.0		112.8	94.2			22.7
5	D	2.01	1.407	1.554	3.123	0.07	0.093	3.03	3.99	3.522	373.2	371.4	123.2	93.2	105.5		25.6
6	E	2.08	1.403	1.546	3.219	0.04	0.059	3.16	4.19		374.2		118.4	89.2			24.3
1	F	2.13	1.38	1.496	3.186	0.03	0.039	3.15	4.27	3.695	378.0	378.0	120.1	88.5	102.3		22.0
5	G	2.01	1.46	1.662	3.327	0.10	0.148	3.21	4.06	3.598	370.7	370.2	115.7	91.4	102.9	80.3	23.3
Final Averages		2.09	1.42	1.579	3.292	0.09	0.120	3.18	4.07	3.562†	377.4	374.1†	118.8	92.6	105.1†	85.4†	24.0

NOTE.—A and B are American Cements; C. D E and F are German Cements; G is a Danish Cement; Paper weighs about 1 lb.
*Box rocked over bar.
†Partial averages, to be compared only with like brands.

reading specifications, to find that, say, 25% or 30% more cement than he had figured is required to a cubic yard of concrete. When considering this question, the authors were surprised to find that the sidewalk and paving specifications of fifteen of the largest cities in the United States failed to state the proportions by definite weight or volume, but gave the quantities simply in "parts," a few of them adding that the parts shall be "by measure" or "by exact measure."

Weight of Cement. Experiments by Mr. Howard A. Carson, for Boston Transit Commission, upon 31 barrels of Portland cement of

*For further data, see letter of Sanford E. Thompson to *Engineering News*, Nov. 12, 1903, p. 434.

American and foreign brands, furnish an interesting illustration of the difference in weight of the same cement in different stages of compactness. The results,* a summary of which is presented in the table on page 219, show a variation from 86 to 118 lb. in the average weights of the same cement, according as it was weighed sifted, or packed in a barrel, while the actual weight of one brand, the average of 5 barrels, was as high as 123 lb. per cubic foot as it came from Germany packed in a barrel.

From the experiments just described, the ratios of volume and weight of the same cements in different degrees of compactness are calculated by the authors as follows:

Ratio of volume of packed cement to capacity of barrel between heads	0.97
Ratio of volume packed to volume loose	0.78
Ratio of volume packed to volume shaken	0.88
Ratio of volume loose to volume shaken	1.13
Ratio of weight packed to weight loose	1.28
Ratio of weight packed to weight shaken	1.13
Ratio of weight packed to weight sifted	1.37

From the table it is evident that the selection of the volume of a barrel is arbitrary. The adopted volume of 3.8 cu. ft. is convenient for calculation because it assumes a cubic foot of cement to weigh approximately 100 lb.

THEORY OF A CONCRETE MIXTURE

The discussion and the formulas which follow relate to plastic mortars and plastic or medium concrete. While a small amount of water in mixing may result, with heavy ramming, in a concrete or mortar of less than average volume, in practice the volume is more apt to be increased by lack of water because of the less perfect mixture and the visible voids. The volume of set concrete or mortar produced by a very wet mixture is approximately the same as that of a plastic mixture, because nearly all of the surplus water is thrown to the surface and expelled by the settling of the solid materials. This the authors have repeatedly proved by experiment.

The frequently repeated assertion that a very wet mixture contains visible air voids because of the drying out of the water is incorrect. This may be proved by carefully pouring neat cement grout into a rectangular mold, one of whose sides is formed by a piece of glass. The surplus water is expelled, and the specimen after setting is dense and glassy with no visible voids. The large visible voids which sometimes occur in very wet

*Tabulated by Sanford E. Thompson in *Engineering News*, Oct. 4, 1900, p. 229.

concrete, similar in appearance to visible voids in dry concrete, are due to the grout running away from the stones, or to too violent agitation in placing.

The volume of fresh concrete or mortar produced by any mixture of cement and aggregate or aggregates is equal to the sum of the volumes of the *separate particles* of the cement, the sand, and the other dry materials, the water contained in the aggregate and added in mixing, and the small volume of air entrained between the particles. The volume of set mortar or concrete is not appreciably different from its compacted volume when fresh or green, except in very wet mixtures, which expel a portion of the water. The volumes of the *particles* of dry materials are termed *absolute volumes*, and it is important to note the distinction between the absolute volumes and the apparent volumes determined by measuring the materials. Absolute volumes are discussed on pages 135 to 139.

The fact that water actually occupies space in a mass of fresh concrete or mortar has been entirely ignored by many writers on the subject of concrete mixtures. As stated on page 216, the fineness of the sand and the moisture contained in it affect the volume of the resulting concrete or mortar. Mr. Feret has proved by experiments (cited on page 179) that fine sands require more water for gaging than coarse. This extra volume of water produces a mortar of less density and consequently less strength; even stones such as are found in gravel or coarse broken stone require a very small percentage of water.

FORMULAS FOR QUANTITIES OF MATERIALS AND VOLUMES

A concrete is therefore made up of solid grains of cement plus water required for the cement, plus solid grains of sand plus water required for the sand, plus solid stone particles plus water required for the stone, plus air voids. The last term, the *air voids*, represents the voids entrained by the sand, which may be considered as a function or percentage of the sand, and the voids due to imperfect mixing of the concrete materials, which may be considered a function or percentage of the stone. Accordingly the volume of a concrete mixture may be expressed as a rational formula, which is applicable to all concrete and mortar mixtures in which the voids of the coarse stone are filled with mortar. The formula (1) which follows is presented to illustrate the theory, but because of the variation in the coefficient with different sands and different proportions, formula (2), page 222, and formulas (3) to (8), which are based on average conditions, are suggested for practical use as sufficiently accurate for most purposes.

Let

c = absolute volume* of cement.

s = absolute volume* of sand.

g = absolute volume* of stone.

m = ratio of the absolute volume of the water plus air voids of the cement, to the absolute volume of cement.

n = ratio of the absolute volume of the water coating the grains of sand plus the air entrained in gaging it, to the absolute volume of sand.

p = ratio of the absolute volume of the water coating the stone particles plus the air voids due to imperfect mixing, to the absolute volume of stone.

W = volume of concrete produced.

In other words, these ratios, m, n, and p, represent the sum of the volumes occupied by the water required for the material in mixing plus the air, in terms of the respective volumes of cement, sand, and stone.

Then

$$W = c + mc + s + ns + g + pg$$

or

$$W = (1 + m)\ c + (1 + n)\ s + (1 + p)\ g \tag{1}$$

The coefficient n is really composed of two variables, one depending upon the coarseness of the sand, and the other upon the ratio of cement to sand, since a lean mortar contains more air voids. It is possible to express this coefficient as a more complex term with this ratio as a factor, but by what appears to be a peculiar coincidence, experiments show that for ordinary bank sand the variation in voids caused by different proportions may be provided for by taking the cement and sand together; in other words, for different proportions of the same cement and sand, the sum of the water and the air voids in the mortar is approximately a constant. Where there is no sand, or where the stone and sand are mixed, formula (1) must be employed.

The more practical formula may be expressed as follows, employing similar notation to that given above, and letting

r = ratio of the absolute volume of the water plus the air entrained in gaging, to the absolute volume of cement plus sand,

then

$$W_1 = c + s + r\,(c + s) + g + pg$$

or

$$W_1 = (1 + r)\ (c + s) + (1 + p)g \tag{2}$$

*Absolute volumes are defined on p. 135.

Substituting average values for r and p, which the authors have selected by analyzing the results of a number of exact records in the United States and Europe of the volumes of concrete and mortar, the formula becomes

$$W_1 = 1.34\ (c + s) + 1.08\ g \tag{3}$$

The comparison of this formula with actual experiments is shown on page 227. The formula may be readily reduced to practical working form if the characteristics of the cement, sand, and stone are known. The cement may be expressed in pounds by substituting for the absolute volume, c, the number of pounds of cement divided by its specific gravity (which may be taken as 3.1) times the weight of a cubic foot of water (62.3 lb.). It may also be expressed in barrels by substituting for the absolute volume, c, the number of barrels, B, multiplied by the net weight per barrel, 376 pounds, and divided, as above, by the specific gravity times the weight of a cubic foot of water [see formula (4)]. The terms relating to sand and stone may be expressed in pounds in a way similar to that just shown for cement, or they may be expressed in measured volume by substituting for the absolute volume, s or g, the measured volume, S or C, multiplied by the proportion of solid material contained in it. Expressing this algebraically, if

Q = quantity of concrete made with B barrels cement,

Q_1 = quantity of concrete made with one barrel cement,

B = number barrels cement,

B_1 = number barrels cement per cubic yard of concrete,

S = volume of loose sand in cubic feet,

S_1 = volume of loose sand in cubic yards per cubic yard of concrete,

G = volume of broken stone or gravel or cinders in cubic feet,

v = absolute voids in sand determined by weight method (p. 166),

v' = absolute voids in stone determined by weight method (p. 167),

then from formula (3), since $c = B\dfrac{376}{3.1 \times 62.3}$

$$Q = \frac{1.34 \times 376}{62.3 \times 3.1}B + 1.34\ (1 - v)\ S + 1.08\ (1 - v')G$$

$$Q = 2.61\ B + 1.34\ (1 - v)\ S + 1.08\ (1 - v')\ G \tag{4}$$

The volume of concrete in cubic feet made by one barrel of cement, assuming that a cubic foot of average loose, moist sand contains 89 pounds of dry sand, and that its specific gravity dry is 2.65, is,

$$Q_1 = 2.61 + 0.723\ S + 1.08\ (1 - v')\ G \tag{5}$$

This formula is applicable to average concrete made with Portland cement of good quality, coarse bank sand measured loose and containing ordinary moisture, and any broken stone or gravel of known voids. Formula (5) has been used in compiling tables on pages 233 to 235, except in the first twelve proportions, which contain no sand.

If the volume of concrete made from a barrel of cement plus the sand and other aggregate which accompanies it is known, the number of barrels of cement per cubic yard is readily calculated. In formula (5), Q_1 represents the number of cubic feet of concrete made with one barrel cement, hence the number of barrels cement per cubic yard of concrete is 27 divided by Q_1

$$B_1 = \frac{27}{Q_1} \tag{6}$$

Assuming a cubic foot of average sand to contain 89 pounds of dry sand produces the formula employed in calculating tables on pages 230 to 232, and substituting in formula (6) the value of Q_1 from formula (5),

$$B_1 = \frac{27}{2.61 + 0.723\,S + 1.08\,(1 - v')\,G} \tag{7}$$

The formulas may be expressed in parts by volume (such as 1:2:4) by multiplying the coefficient of S and G by the assumed volume of a barrel, say by 3.8.

Knowing the number of barrels of cement, B_1, per cubic yard of concrete, the number of cubic yards of sand per cubic yard of concrete, S_1, is evidently

$$S_1 = \frac{B_1 \times \text{quantity sand in cubic feet per barrel of cement}}{27} \tag{8}$$

The quantity of stone is similarly obtained.

If two or more coarse materials, such as broken stone and gravel, are used, they must be mixed in the selected proportions, before weighing, to determine their voids.

In mortars of extremely fine sands the density $(c + s)$ is apt to be about 0.60 (see Feret's table, sand C, p. 136) and the coefficient of first term of formula (3) becomes $\frac{1.00}{0.60} = 1.67$ instead of 1.34. In plastic mortars of standard Ottawa sand the density $(c + s)$, by tests of the authors, averages about 0.71, hence the coefficient becomes $\frac{1.00}{0.71} = 1.41$ instead of 1.34. Substituting these values, or any others which may be obtained by experiment, in formula (2), the working formulas which follow it may be readily deduced. It is evident from the variation in the coefficient with different sands, that the variation in volume of mortar and concrete obtained by different experimenters is due chiefly to the difference in the materials employed.

The coefficient of $(c + s)$ is also affected, though to a less degree, by the character of the cement, some cements requiring more water than others and therefore producing a greater bulk of paste for a given weight of cement.

In concrete mixtures of cement and coarse stone, with no sand or screenings, formulas (2) to (8) are inapplicable because apparently the air voids do not increase with the leanness of the mixture until the point is reached at which the paste fails to fill the voids in the stone. It is therefore necessary to go back to formula (1), page 222. Since s is zero, the formula becomes

$$W_2 = (1 + m)\,c + (1 + p)\,g \tag{9}$$

An average value of $(1 + m)$ for a first-class American Portland cement has been found by experiment to be 1.65. It varies with the quantity of water required to gage the cement to such a consistency that the voids will be filled, but no free water will exist upon the surface. The selected value, assuming 1% voids in the paste, corresponds to 20% of water by weight. The value of $(1 - p)$ is usually 1.04 to 1.08. An average formula for a concrete of cement and coarse stone may thus be taken as

$$W_2 = 1.65c + 1.08g \tag{10}$$

which is readily reduced to practical forms by the method adopted in evolving formulas (4) to (8) from formula (3).

If the stone is a mixture of sand and gravel, or broken stone and screenings, the coefficient of g must be increased and a figure selected whose value depends upon the relative proportion of fine and coarse material.

TABLES AND CURVES OF QUANTITIES OF MATERIALS AND VOLUMES

Tables on pages 229 to 235 are calculated from formulas (5), (6), (8), and (9). These formulas are used not merely because of their theoretical worth, but because, as stated on pages 216 and 227, the results from them agree with actual experiment.

The values are average values of sufficient exactness for practical use, although, as suggested on pages 222 and 224, variations in the quality of the materials largely affect the resulting volumes, especially of the mortar.

The tables on pages 231 and 234 are recommended for general use in determining the quantities of materials for concrete, or the volume of concrete made with known materials, and where the percentage of voids in the coarse aggregate is unknown the 45% columns should be adopted. The curves on page 228 are also in convenient form for practical use.

All except the first item in the table on page 229 and the first 12 items in tables on pages 230 to 235 are calculated from formulas (5), (6), and (8), page 223, with the assumption there outlined. The broken stone in the first twelve items in the concrete tables, pages 230 to 235, except where the voids are 40% or over, is assumed to contain fine material, and the coefficient selected for g, formula (9), varies from 1.08 for 50%, 45%, and 40% voids to 1.14 for 20% voids.

Use of Curves. The use of the curves on page 228 is best illustrated by the following examples:

Example 1. — Find quantities of materials required for 1 000 cubic yards 1:2½:5 concrete.

Solution. — Intersection of dotted horizontal line corresponding to 2½ barrels sand with dotted vertical line corresponding to 5 barrels stone falls on diagonal curve 1.30; hence, 1.30 barrels cement are required per cubic yard, or 1 300 barrels cement for 1 000 cubic yards concrete. From Note 4 of diagram $1\,300 \times 0.141 \times 2\frac{1}{2} = 460$ cubic yards sand will be required, and $1\,300 \times 0.141 \times 5 = 920$ cubic yards stone required.

Example 2. — Find number of barrels cement required for 1 000 cubic yards concrete in proportions one barrel cement to 9 cubic feet sand to 18 cubic feet stone.

Solution. — Intersection of full cross section horizontal line corresponding to 9 cubic feet sand with vertical line for 18 cubic feet stone gives 1.37 barrels cement per cubic yard or 1 370 barrels for 1 000 cubic yards concrete.

Example 3. — Find volume of concrete of Example 1 made from one barrel of cement.

Solution. — By Note 5 of diagram volume of concrete per barrel cement is 27 divided by the quantity of cement per cubic yard of concrete, or $\frac{27}{1.30} = 20.8$ cubic feet.

Comparison of Table Values with Actual Experiments. Comparatively few experimenters have recorded complete data with reference to the materials entering into their specimens of concrete and mortar. The most comprehensive records of this nature that have come to the knowledge of the authors are those by Mr. William B. Fuller,* which are tabulated in full on page 258, his proportions ranging from 1:0 to 1:6:10. The actual volumes obtained by him, having been found to agree closely with other carefully made experiments, are used in the determination of the constants employed in the above formulas and in compiling the tables and curves on pages 228 to 235. Volumes calculated from the formulas employing these constants agree with Mr. Fuller's tests with an average variation of 0.2 of 1% and a maximum variation of 6%.

Other records which have been compared with results calculated by our formulas, and with which they usually agree within less than 5% after making allowance for different materials and units, are those by Messrs. George W. Rafter,† Edwin Thacher,‡ J. E. Howard,§ E. Candlot,‖ and E. S. Wheeler,¶ C. A. Matcham,** E. S. Larned†† and Leonard Metcalf.††

Experiments by Mr. Edwin Thacher show the rammed volume of dry facing mortar (that is mortar mixed with a small proportion of water) to be about 12% less than the volume of slush mortar made from the same materials, and the quantity of cement per cubic yard to be correspondingly greater for the dry mortar.

The volume of mortar or concrete is affected by the character of the cement as well as by the sand and method of mixing, since some cements require more water and will make more paste to a unit weight of cement than others even of the same class. In one series of experiments, for example, 85 pounds of a certain first-class American Portland cement were required to make one cubic foot of paste, while for another standard American Portland cement of a different brand 107 pounds were required. Average values for wet or plastic mortars are given in the table on page 229.

*See page 261.
†Transactions American Society of Civil Engineers, Vol. XLII, p. 104.
‡Johnson's "The Materials of Construction," 1903, p. 610a.
§Tests of Metals, U. S. A., 1899, p. 786.
‖Ciments et Chaux Hydrauliques, 1898, p. 446.
¶Report Chief of Engineers, U. S. A., 1895, pp. 2922 to 2931.
**Engineering Record, April 15, 1905, p. 434.
††Personal Correspondence.