CHAPTER IX

STRENGTH AND COMPOSITION OF CEMENT MORTARS

The following are the important conclusions in this chapter:

(1) The strength of a mortar depends primarily upon (*a*) percentage of cement in a unit volume, and (*b*) density. (See p. 133.)

(2) The strongest mortar for any given proportions, by weight, of cement to dry sand, is obtained from sand which with the given cement produces the smallest volume of plastic mortar. (See p. 148.)

(3) The best sand is in general that which will produce the smallest volume of mortar of standard consistency when mixed with the given cement in the required proportions. (See pp. 133 and 149.)

(4) The density of a mortar is determined by calculating the absolute volumes of its ingredients. (See p. 138.)

(5) The qualities of different sands may be studied by screening each into three sizes and comparing their granulometric compositions with Feret's curves. (See p. 142.)

(6) Sharpness of the sand grains is of slight importance. (See p. 154a.)

(7) Coarse sand produces stronger mortar than fine sand. (See p. 146.)

(8) Fine sand requires more water than coarse sand to produce a mortar of like consistency, and consequently its mortar is less dense. (See p. 145.)

(9) Mixed sand, *i. e.*, sand containing fine and coarse grains, in mortars leaner than 1:2, usually produces stronger and more impervious mortars than coarse sand. (See p. 146.)

(10) Screenings from broken stone usually produce stronger mortars than sand because of their greater density. The relative value of screenings and sand may often be determined by comparing their densities or the densities of mortar made from them. (See pp. 150 and 153.)

(11) Mixtures of fine and coarse sand or of sand and screenings often produce better mortar than either material alone. (See p. 149.)

(12) The variation of the sand in different portions of the same bank may be utilized by requiring the contractor to mix two sizes without exact measurement, so that the material as delivered shall contain not less than a definite percentage of sand coarse enough to be retained on a certain sieve. (See p. 149.)

(13) Mineral impurities in sand, such as clay, in small quantities, may strengthen a lean mortar, and weaken a rich mortar. (See p. 154b.)

(13a) Organic impurities in sand, such as vegetable loam, even in minute quantities may destroy the strength of the mortar or concrete. (See p. 154b.)

(14) Gaging with sea water does not affect the ultimate strength of mortars. (See p. 159b.)

(15) The unit fiber stress in a cement or mortar beam is about the same for a prism 4 cm. (1.6 in.) on edge as for one 2 cm. (0.8 in.) on edge. (See p. 134.)

(16) The unit fiber stress in bending is about 1.89 times the unit tensile strength of briquettes of 5 sq. cm. (See p. 134.)

(17) The unit tensile strength of specimens decreases as the breaking area is enlarged. (See p. 134.)

(18) The unit compressive strength of similar specimens of cement or mortar is not greatly affected by their size. (See p. 134.)

Laws of Strength. There are two fundamental laws of strength which apply to mortars composed of the same cement with different proportions and sizes of sand.

(1) With the same aggregate,* the strongest and most impermeable mortar is that containing the largest percentage of cement in a given volume of the mortar.

(2) With the same percentage of cement in a given volume of mortar, the strongest, and usually the most impermeable, mortar is that which has the greatest density,† that is, which in a unit volume has the largest percentage of solid materials.

The first of these rules is understood by ordinary users of cement, but the second rule states a fact which is appreciated only by experts.

The value of a first-class cement is universally recognized, the effects of impurities have been studied in various ways, and the variations in strength of mortars made from different sands or broken stone screenings have been recorded, but the fundamental law of the relation of the density of a mortar to its strength, — a function nearly as important as the quality of the cement itself and explaining many of the seemingly paradoxical results of tests with different aggregates and different proportions of water, — is but vaguely comprehended by the majority of experimenters and most of the users of cement.

The importance of this subject claims for it a full investigation, and its study is taken up on page 134. The application of these laws to concrete is discussed in Chapter XX.

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*The word *aggregate* is defined on page 1.

†The meaning of *density* may be understood by referring to the figures on pp. 172 and 173.

STRENGTH OF SIMILAR MORTARS SUBJECTED TO DIFFERENT TESTS*

Mr. René Feret, Chief of the Laboratory of Bridges and Roads at Boulogne-sur-Mer, France, has made very extended tests of strength of mortars, studying his results scientifically, and in many cases formulating laws and formulas applicable to different conditions. The tests of one series in particular are of so wide a range in character and in proportions used that the authors have converted the values into English units, and reproduce the table in full on pages 136 and 137.

After plotting the strengths in various ways, Mr. Feret reaches conclusions which may be summed up as follows:

(*a*) The unit fiber stress for prisms 4 centimeters (1.6 in.) on an edge is about the same as for prisms 2 centimeters (0.8 in.) on edge.

(*b*) The tensile strength per square centimeter of prisms having a breaking area of 16 square centimeters (the strength of which he found to be similar to that of briquettes of the same section) is about two-thirds the strength per square centimeter of the normal briquettes which have an area of 5 square centimeters. This difference is attributed partly to the lack of homogeneity of the specimens, especially on their surfaces, but principally to the unequal distribution of the stress on the area of the section.

(*c*) Resistance to flexion, that is, the unit fiber stress in bending, is about 1.89 times the tensile strength per unit of area of briquettes of 5 square centimeters.

(*d*) The form and dimensions of the specimen do not greatly influence the strength per unit of area in compression when the height and width of the block are approximately equal.

(*e*) Resistances to flexion and tension are proportional to each other, and resistances to compression, shearing, and punching are proportional to one another, but there is no constant relation between the resistance to compression and the resistance to tension or flexion.

THE RELATION OF DENSITY TO STRENGTH

In the same paper from which we have quoted, Mr. Feret treats of the density and elementary volumetric composition of mortars, using in his studies the results given in the table just described. He calls particular attention to the fact that the properties of hydraulic mortar, such as durability, permeability, porosity, and ability to resist the decomposing action of sea water, depend not only upon the quality of the cement, but "in a measure greater than is generally believed, upon the granular physical

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*A valuable series of tests has also been made by Messrs. Humphrey and Jordan at the U. S. Government Testing Laboratory at St. Louis, see Bulletin No. 331 U. S. Geological Survey, 1908.

composition of the mortars, that is to say, upon the dimensions and relative positions of the different elements entering into their composition."

The density (*compacité*) of a mortar is represented by the total volume of the solid particles, — exclusive of the water and the voids, — entering into a unit volume of mortar.*

The "elementary volumes" in a unit volume of fresh mortar consist of the absolute volumes of the cement, sand, water, and voids, each expressed in the form of a decimal. To illustrate, the "elementary volumetric composition" of the mortar in Item 8 of the table on page 136, which is mixed in proportions by weight of one part cement to $1\frac{4}{5}$ parts of natural sand, is:

Cement $(c) = 0.226$
Sand $(s) = 0.499$
Water $(w) = 0.234$
Air voids $(v) = 0.041$
Total volume $= 1.000$

Expressing this in more familiar terms, 22.6% of the unit volume of the given mortar consists of solid particles of cement, 49.9% of particles of sand, 23.4% of water, and the remaining 4.1% of air voids.

The porosity, represented by the sum of the water and air voids, is 27.5%. The term *voids* is often employed to represent the porosity, that is, the sum of the air and water.

It is obvious that

$$c + s + w + v = 1;$$

also that

$$v = 1 - (c + s + w),$$

which is equivalent to the statement that the entrained air in any volume of fresh mortar is equal to the measured volume of the mortar minus the space occupied by the cement, sand, and water.

The density of the mortar considered above is $c + s$, or, $0.226 + 0.499 = 0.725$ as given in column (11) of the table on pages 136 and 137.

A thorough understanding of the use of these symbols is essential to the study of strength of concrete and mortar, for, as will be shown further on, practical tests of strength are of small value unless the density and exact mechanical composition of the specimens are clearly defined

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*If the word density is applied to sand alone, it means the proportion of the measured volume of the sand, which is occupied by the solid sand grains; a sand, for example, having under certain conditions 40% voids, would have a density of $1.00 - 0.40 = 0.60$.

Strength and Composition of Portland Cement Mortars.

BY R. FERET. (*See p.* 134.)

(Bulletin de la Société d'Encouragement pour l'Industrie Nationale, 1897, Vol. II, p. 1593.)

SAND.*	ITEM	Approximate Proportions by Weight		COMPOSITION OF MORTAR BY WEIGHT			Price of a cu. yd. of mortar	ELEMENTARY VOLUMETRIC COMPOSITION				Density $c+s$	$\left(\frac{c}{1-s}\right)^2$	STRENGTH PER SQ. IN. AFTER 5 MONTHS IN FRESH WATER							AVERAGE STRENGTH		
														Flexion		Tension		Compression					
		Cement	Sand	Cement in 1,000 grams dry mixture ($c+s$)	Water per 1000 grams dry mixture	Weight of a cu. yd. of fresh mortar		Cement c	Sand s	Water w	Air voids v			F_{16}	F_4	T_{16}	T_5	P_{50}	P_{16}	P_4	Shearing C_4	Tension and flexion T	Compression P
		(1)	(2)	(3) gr.	(4) gr.	(5) lb.	(6) $	(7)	(8)	(9)	(10)	(11)	(12)	(13) lb.	(14) lb.	(15) lb.	(16) lb.	(17) lb.	(18) lb.	(19) lb.	(20) lb.	(21) lb.	(22) lb.
G	(1)	1	18.6	51	62.5	3296	2.37	0.030	0.670	0.115	0.185	0.700	0.0083	134	134		65	210	340	160	170	69	240
	(2)	1	9.9	92	70	3426	2.95	0.055	0.663	0.132	0.150	0.718	0.0266	287	256	58	152	840	980	800	570	146	870
	(3)	1	6.9	126	76	3539	3.46	0.078	0.655	0.148	0.119	0.733	0.0511	418	370	129	220	1340	1690	1580	1070	212	1540
	(4)	1	5.2	160	81.5	3654	4.00	0.102	0.648	0.163	0.087	0.750	0.0841	509	461	144	260	2060	2620	2360	1440	258	2350
	(5)	1	4.1	196	88	3750	4.56	0.127	0.631	0.180	0.062	0.758	0.1190	597	568	206	326	2840	3680	3440	2000	314	3320
	(6)	1	3.2	237	95	3814	5.17	0.155	0.605	0.196	0.044	0.760	0.1537	693	687	245	371	3750	4510	4250	2560	367	4170
	(7)	1	2.5	287	104.5	3810	5.82	0.186	0.559	0.214	0.041	0.745	0.1772	804	807	277	407	4690	5430	5500	2790	421	5210
	(8)	1	1.8	355	116	3792	6.64	0.226	0.499	0.234	0.041	0.725	0.2034	935	939	299	451	5720	5870	6320	3580	480	5970
	(9)	1	1.2	449	133	3755	7.74	0.280	0.415	0.262	0.043	0.695	0.2304	1040	1060	356	502	6400	6500	7110	3930	537	6670
	(10)	1	0.7	602	163	3694	9.35	0.359	0.287	0.306	0.048	0.646	0.2530	1070	1120	395	532	7050	6270	>7110	3640	563	>6810
S	(11)	1	12.9	72	90	3111	1.96	0.039	0.592	0.152	0.217	0.631	0.0092	141	158		85	270	360	310	256	81	310
	(12)	1	7.0	125	96.5	3290	2.70	0.070	0.587	0.171	0.172	0.657	0.0289	330	341	54	192	970	970	940	669	182	950
	(13)	1	5.0	167	101.5	3409	3.29	0.097	0.576	0.186	0.141	0.673	0.0524	451	438	141	249	1380	1640	1490	1040	240	1510
	(14)	1	4.1	196	105	3485	3.74	0.116	0.569	0.196	0.119	0.685	0.0724	516	526	152	282	1780	2120	2080	1350	278	1990
	(15)	1	3.1	241	111	3622	4.45	0.148	0.555	0.215	0.082	0.703	0.1109	612	572	212	333	2460	2870	2820	1810	320	2720
	(16)	1	2.5	283	117.5	3645	5.02	0.173	0.525	0.227	0.075	0.698	0.1325	694	684	222	374	3130	3560	3600	2250	368	3430
	(17)	1	2.0	333	125	3674	5.71	0.204	0.486	0.242	0.068	0.690	0.1576	821	768	246	405	4010	4440	4680	2650	415	4380
	(18)	1	1.4	412	138	3701	6.76	0.252	0.428	0.265	0.055	0.680	0.1945	994	953	326	458	5230	5350	5730	2750	521	5440
	(19)	1	0.9	518	157	3659	7.99	0.309	0.340	0.294	0.057	0.649	0.2190	1080	1070	307	489	5830	5920	6560	3580	541	6100
	(20)	1	0.5	648	180	3630	9.44	0.376	0.241	0.329	0.054	0.617	0.2460	1180	1200	378	543	6600	6510	7050	3540	602	6720
D	(21)	1	12.3	75	167	3178	1.49	0.038	0.564	0.269	0.129	0.602	0.0076	114	141		65	160	200	130	156	67	160
	(22)	1	5.8	148	168.5	3230	2.38	0.077	0.528	0.276	0.119	0.605	0.0269	247	238	60	122	600	550	480	370	126	540
	(23)	1	3.5	225	170	3262	3.32	0.118	0.485	0.281	0.116	0.603	0.0529	408	415	119	208	1080	1290	1320	768	214	1230
	(24)	1	2.4	299	172	3318	4.26	0.159	0.444	0.289	0.108	0.603	0.0818	576	576	196	296	1790	1910	2120	1410	302	1940
	(25)	1	1.8	363	175	3367	5.09	0.195	0.409	0.298	0.098	0.604	0.1082	703	693	233	354	2380	2970	3170	2130	364	2840
	(26)	1	1.3	429	179	3412	5.98	0.234	0.370	0.307	0.089	0.604	0.1376	814	828	233	439	3470	3570	4100	2570	436	3710
	(27)	1	1.0	500	183.5	3458	6.92	0.274	0.331	0.318	0.077	0.605	0.1681	980	963	302	502	4750	4410	5830	2750	510	5000
	(28)	1	0.7	573	190	3510	7.90	0.320	0.282	0.333	0.065	0.602	0.1998	1100	1120	373	549	5750	5450	6070	3070	574	5760
	(29)	1	0.5	659	197	3495	8.92	0.361	0.223	0.341	0.075	0.584	0.2171	1210	1280	371	623	6630	5970	6900	3570	647	6500
	(30)	1	0.3	771	208	3545	10.39	0.426	0.151	0.361	0.062	0.577	0.2530	1280	1370	401	671	7400	6830	7110	(4120)	691	>7110
M′	(31)	1	5.0	167	123	3650		0.102	0.607	0.237	0.054	0.709	0.0676	613	623	239	330	2120	2350	2570	1720	328	2350
	(32)	1	3.0	250	136	3642		0.150	0.539	0.259	0.052	0.689	0.1056	842	808	304	475	3640	3870	4510	3100	450	4010
	(33)	1	2.0	333	148	3645		0.199	0.474	0.278	0.049	0.673	0.1429	990	981	336	513	4640	4860	4920	3070	518	4810
N′	(34)	1	3.0	250	91	3620		0.156	0.557	0.179	0.108	0.713	0.1246	862		293	455	3600	3670			456	3640
C	(35)	1	0	1000	245	3552		0.534	0.000	0.414	0.052	0.534	0.2851	1280	1510	385	624	8720	7350	>7110	3680	698	8040

NOTE.—All are plastic mortars except N′.

**Description of Sands.*

SAND	Nature of sand	Form of grains	Granulometric Composition† Coarse grains G	Medium grains M	Fine grains F	Approximate weights per cu. yd. lb.	Approximate price per cu. yd. $
G Sand from Gattemarre near Cherbourg	Granitic	Large and rounded	0.73	0.25	0.02	2815	1.18
S Sand from Saint-Malo	Very shelly	Varied	0.17	0.70	0.13	2537	0.59
D Sand from the dunes	Strongly siliceous	Fine and rounded	0.00	0.01	0.99	2461	0.15
M′ Ground quartzite sifted and remixed in equal parts	Quartz	Angular	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$		

N′ Ground quartzite passing a sieve of 64 meshes, and retained on one of 144 meshes per sq. cm. (20 and 31 meshes per linear inch).

C Neat Portland Cement.

†Granulometric composition is defined on p. 142.

EXPLANATION OF COLUMNS.

Col. (6) based on price and weight of given sand, on cement at 50 francs per "tonne" ($1.66 per bbl.), and on labor at 3 francs per cubic meter (44 cts. per cu. yd.) of mortar.

Cols. (7) to (12) are discussed on page 135.

Col.	Number of specimens of each mortar.	Size of specimens, centimeters.	Remarks.
(13)	15 prisms	4 x 4 x 16	Supports 10 cm. apart
(14)	15 "	2 x 2 x 13	" 10 " "
(15)	15 "	4 x 4 x 8±	Halves of broken prisms
(16)	25 briquettes	5 sq. cm. section	French standard briquettes
(17)	5 cubes	50 sq. cm. face	
(18)	15 prisms	4 x 4 x 8±	Halves of broken prisms
(19)	30 "	2 x 2 x 3±	Quarters of " "
(20)	15 "	2 x 2 x 6±	Halves " " "

(21) Average of cols. (14), (15) and (17) by formula

$$T=\frac{\left(\frac{F_{16}+F_4}{2}\right)+T_5}{1.89+1}$$

(22) Average of cols. (18), (19), (20).

In practice density of volumetric tests are of great value for comparing the relative values of different aggregates, and for determining the proportions for the most economical concrete. They are also useful for studying the effect of varying quantities of water. As is shown in the following pages, the density of mortars or concretes made from similar materials bears a definite relation to the strength, so that it is frequently possible to determine the best mixture as soon as the density tests are completed, instead of waiting for the tests of tensile or compressive strength. The test has been used by the authors in a practical way for comparing sands and for grading sands in special work, and also for concrete to fix on the best proportions when using merely one fine and one coarse aggregate, and in other cases to determine the proper proportions for a scientifically graded mix.*

Density of Mortars and Concrete. The density of fresh mortars of ordinary proportions, as shown by tests of the authors, averages about 0.70 (corresponding to 30% air plus water voids). Mortars of fine sands may run as low as 0.60 (40% air plus water voids), while by special grading or the use of an exceptionally good coarse sand the density may be as high as 0.75 (25% voids). The density of neat cement usually ranges between 0.50 and 0.55. The density of concrete ranges† from 0.76 to 0.88, depending upon the grading of the aggregates and the cement.

The values apply to the materials freshly mixed before setting. The chemical combination of the cement and water reduces the porosity further.

Density or Volumetric Tests of Mortar.‡ To obtain accurate results, considerable care is necessary in making the experiments. An approximate method suited to rough comparisons will be given first and this will be followed by more accurate methods advised for laboratory work.

The rough volumetric test may be made in almost any vessel or mold so long as the capacity is readily computed and its dimensions such that the depth of mortar or concrete can be measured exactly. A deep mold is more accurate than a shallow one. The volume of mortar and concrete of dry consistency will measure the same after setting as when green, but wet mixtures must be measured before setting, and again after they have become sufficiently hard to expel the surplus water. The measurement before setting is necessary in order to calculate the volume of air bubbles entrained in the wet mortar or concrete. The volume after setting, or partially setting, however, is the only one of real importance for studying the characteristics of strength, permeability, and cost. The sand is dried, or its moisture is determined by weighing and drying a sample of it. If stone of a porous nature is used the pores of its particles should be filled with water, but there should be no perceptible moisture on their surfaces. The quantities of dry materials for a single tube or mold are weighed in the required proportions, mixed with a known weight of water, and placed compactly in the mold, whose lateral dimensions have been exactly measured so that the volume of mortar in it may be obtained by measuring down from the top. The exact space occupied by the particles of each of the solid materials and by the water is calculated, if the metric system is employed, by dividing their total weight by the specific gravity of each, or, if English units are used, by dividing the weight times 1728 (the number of cubic inches in a cubic foot) by the specific gravity multiplied by the weight of a cubic foot of water. After partially setting, the exact depth of the mortar in the mold is measured and its volume calculated. The percentage of each of the dry materials, which really determines the density,—which is represented by the sum of the absolute volumes of the dry material,—is found by dividing the absolute volume of each material by the total volume of the set mortar or concrete.

The specific gravity of cement which has been stored for a short time may be taken at 3.10 and the specific gravity of dry sand at 2.65.

The following example from the authors' note book illustrates the method of finding the density when the measurements are in English weights and measures:

Example:—Find density of a mortar composed of Newburyport sand and Portland cement in proportions 1 : 2 by weight.

Solution:—For the mold used, it was estimated that 8 lb. cement and 16 lb. dry sand would be required. Gaging these with 3 lb., 12.6 oz. (3.79 lb.) of water, the quantity necessary for the desired consistency, the volume of the mortar was found by measurement to be 348 cu. in. when green, and 336 cu. in. after setting and pouring off the surplus

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* See Chapter XI, p. 183.

† From the "Laws of Proportioning Concrete," by Wm. B. Fuller and Sanford E. Thompson, Transactions American Society Civil Engineers, Vol. LIX, 1907, p. 67.

‡ The French Commission determine the "yield" of a mortar (see p. 129) by measuring its volume green, that is, just after introduction into the molds, when an excess of water may affect the volume, and thus give misleading results with very wet mixtures.

In his Report to the French Commission, 1895, Vol. IV, p. 243, Mr. Feret also measures the mortar wet, but he employs a vessel of known capacity,—a cylindrical measure whose height and interior diameter are each about 8 centimeters,—and uses only a portion of the mortar which he mixes, calculating his percentages by ratio of the weight of mortar made to the weight of mortar introduced into the measure to fill it exactly. This method eliminates inaccuracies in measuring the level of the surface.

water. The absolute volumes are expressed below, first in cubic inches and finally in terms of the density $(c + s)$, of the set mortar.

$$\text{Cement} = \frac{8 \times 1728}{3.1 \times 62.3} = 71.6 \text{ cu. in.}$$

$$\text{Sand} = \frac{16 \times 1728}{2.65 \times 62.3} = 167.4 \text{ cu. in.}$$

$$\text{Water} = \frac{3.79 \times 1728}{62.3} = 105.1 \text{ cu. in.}$$

Absolute volume cement, sand and water,	344 cu. in.
Measured volume green mortar,	348 cu. in.
Volume of entrained air,	4 cu. in.
Percentage of entrained air,	1.2%

$$\text{Density of set mortar, } c + s = \frac{71.6}{336} + \frac{167.4}{336} = 0.213 + 0.498 = 0.711$$

Volumetric Tests of Mortar at Jerome Park Reservoir. The methods used by Messrs. Fuller and Thompson at Jerome Park Reservoir in tests for the New York Aqueduct Commission in 1906* have since been adopted, with slight variations, in the authors' laboratory. The procedure is indicated in the blank form used in the tests, a copy of which filled out is here reproduced on page 139. While somewhat lengthy in appearance, it is arranged to correct almost automatically for the unavoidable losses due to free water and mortar sticking to the tools. The chief object of the test is to find the density of a fresh mortar, that is, the ratio of solid material in it to the total volume, and also to determine the elementary volumes of each ingredient. In the test illustrated, for example, the density is 0.696 and the air plus water voids are therefore 30.4%.

The apparatus used for density tests of mortar are a shallow pan about 9 inches diameter, a small pointing trowel, scales to weigh to one-tenth gram, measuring glass or graduate about 1½ inches diameter and 250 cubic centimeters capacity, one or two beakers, and a stick for tamping the mortar in the glass. 300 or 400 grams of mixed cement and aggregate may be used in the tests.

It has been found that the material which sticks to the tools is either cement or similarly fine aggregate, so that the weight of the aggregate which passes a No. 100 sieve should be recorded for use in the computations.

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* See paper by Messrs. Fuller and Thompson, Transactions American Society Civil Engineers, Vol. LIX, p. 67.

Volumetric test for *Reservoir* .... File *W. R.*
Cement *B* Aggregates *Clean Sand*.......................... Date 4-26-06.
Computed by *Brown* .... Checked by *T.*

(1) Experiment No.	152		
(2) Nominal proportions by volume	1 : 2		
(3) Proportions by weight	1 : 1.78		
(4) Description of aggregate	Sand		
(5) Wt. of cement	150.0		
(6) Total weight of aggregate	267.0		
(7) Wt. of the aggregate passing a No. 100 sieve	53.4		
(8) Wt. of vessel and water (before using)	287.7		
(9) " " " " " (after using)	228.7		
(10) " " water used = (8) — (9)	59.0		
(11) Percentage of water = $\frac{(10)}{(5)+(6)}$	14.2		
(12) Consistency	Soft		
(13) Temperature water	65°F.		
(14) Total weight mixed = (5) + (6) + (10)	476.0		
(15) Weight tray and tools (after using)	325.8		
(16) " " " " (before using)	322.2		
(17) Weight mix adhering = (15)—(16)	3.6		
(18) Weight measuring glass or graduate	295.4		
(19) Weight glass + mix	767.9		
(20) Weight glass + mix − free water	767.9		
(21) " free water = (19 − 20)	0.0		
(22) " mix set = (14) − (17) − (21)	472.4		
(23) " " " = (20) − (18)	472.5		
(24) Discrepancy = (23) − (22)	.1		
(25) Time mixing completed	10.15 a.m.		
(26) Volume of mix, in cu. cm	210.0		
(27) Time settling	2 hrs.		
(28) Final volume of mix in cu. cm	209.5		
(29) Water left on tray = $(10) \times \frac{(17)}{(5) + (7) + (10)}$	9.8		
(30) Cement left on tray = $(5) \times \frac{(17)}{(5) + (7) + (10)}$	2.1		
(31) Aggregate left on tray = $(7) \times \frac{(17)}{(5) + (7) + 10)}$	0.7		
(32) Wt. water in set mortar = (10) − (21) − (29)	58.2		
(33) Wt. cement in set mortar = (5) − (30)	147.9		
(34) Wt. aggregate in set mortar = (6) − (31)	266.3		
(35) Specific gravity cement	3.11		
(36) " " aggregate	2.71		
(37) Absolute volume water = $\frac{(32)}{(28)}$	.278		
(38) " " cement = $\frac{(33)}{(28)} + (35)$	.227		
(39) " " aggregate = $\frac{(34)}{(28)} \times (36)$	.469		
(40) Total absolute volume = (37) + (38) + (39)	.974		
(41) Density = (38) + (39)	.696		
Remarks: Fine Material on Surface	3 cc.		

NOTE: Weights are in grams; volumes in cubic centimeters.

The materials are carefully weighed, and enough water added,—the quantity varying with the fineness of the sand,—to produce a mortar softer than standard consistency which will scarcely hold its shape in the mixing pan. An examination of the various items in the table will show the purpose of each, the object being to correct for all losses and obtain a resulting volume corresponding to that of the mortar after setting. The figures following many of the items refer to the numbers of the other items, the fraction following item (29), for example, representing the water of the mix which adheres to the tray and tools. The weight of the water in this mortar which adheres is found from the proportion,—Mix adhering: total fine mortar = water in mix adhering : total water. Expressed in item numbers this becomes

$$\text{Item (29)} = \frac{\text{Item (17)}}{\text{Items (5)} + (7) + (10)} \times \text{Item (10)}.$$

The cement and aggregate left on tray, items (30) and (31), are similarly computed, and from these the weight of each of the materials in the set mortar is found. The absolute volumes, items (37) to (39), are then readily computed and the density determined.

Volumetric Tests of Concrete. For volumetric or density tests of concrete, molds at least 8 inches in diameter are necessary, but the process throughout is similar to that already described for the volumetric tests of mortar and a similar blank form may be readily made for records.

The density tests as made at Jerome Park Reservoir are fully described in the paper by Messrs. Fuller and Thompson already referred to† and results of the tests are there given.

Feret's Formula for Strength. For studying the relation of absolute volumes to strength, let

P = compressive strength of the mortar.
K = a constant which differs for different cements and at different ages of the same mortar.
c = absolute volume of cement.
s = absolute volume of sand.
w = absolute volume of water voids.
v = absolute volume of air voids.

The value of determining the density of mortars is made evident by the following law of Mr. Feret:*

"For any series of plastic mortars made with the same binding material and inert sands, the resistance to compression after the same length of set, under identical conditions, is solely a function of the ratio $\frac{c}{w+v}$ or $\frac{c}{1-(c+s)}$, whatever be the nature and size of the sand and the proportions of the elements, — cement, inert sand and water, — of which each is composed."

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*Bulletin de la Société d'Encouragement pour l'Industrie Nationale, 1897, Vol. II, p. 1604.
†See also Chapter XI of this Treatise.

It follows from this law, as Mr. Feret says, that the strength of any mortar increases with the absolute volume of the cement (c) in a unit volume of fresh mortar, and also with the density ($c + s$), whatever may be the relative volumes filled with water and air.

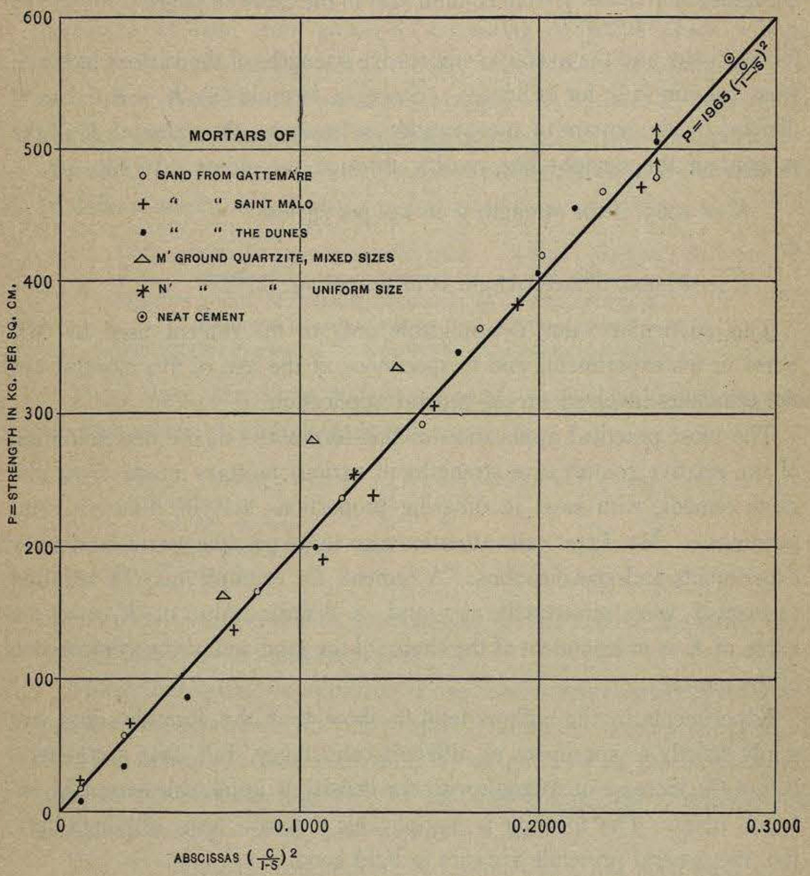

FIG. 49.—Derivation of Feret's Formula for Strength. (*See p.* 142.)
(Bulletin de la Société d'Encouragement pour l'Industrie Nationale—1897.)