cubes of 1 : 1 : 3 concrete made with uniform stone of different sizes. The weights of the specimens indicate that the increase of strength is due primarily to the density. The higher the limit of size the greater the variation in the sizes of material and therefore the greater the density of the mixture.

John Kyle* nearly doubled the strength of 1 : 2 : 6 concrete made with 1½-inch stone by substituting 4 parts of 3½-inch stone for a like portion of the 1½-inch.

Tests by Messrs. Fuller and Thompson† showing the effect of aggregates of different maximum size are illustrated in the curves in Fig. 127.

From these tests the following conclusions were drawn:

1.—Stone of the largest size makes the strongest concrete under both compression and transverse loading, i.e., a graded aggregate in which the maximum size of the stone is 2¼ in. in diameter gives stronger concrete than a graded aggregate with 1-in. maximum size, and the 1-in. stone gives a stronger concrete than ½-in. stone. A concrete in which the graded aggregate runs to 1 in. in maximum size will require for equal strength about one-sixth more cement, and with an aggreate running to ½-in. maximum size, about one-third more cement than concrete with an aggregate in which the maximum size is 2¼ in.

2.—The largest stone makes the densest concrete. Concrete made with graded stone having a maximum diameter of 2¼ in. is noticeably denser than that with 1-in. stone, and this is denser than that with ½-in. stone.

EFFECT OF THE QUALITY OF THE STONE UPON THE STRENGTH OF CONCRETE

The ultimate strength of concrete is often limited by the texture or strength of the coarse aggregate. This is evidently the case with cinder concrete. Experiments by Mr. Geo. W. Rafter‡ gave the strength of concrete made with hard broken sandstone and various proportions of mortar from 1.5 to 2.4 times the strength of similar mixtures of broken shale and mortar, and this discovery led to the rejection of the latter as a material for concrete.

Tests of the authors upon 12-inch cubes broken at the Watertown Arsenal lead them to believe that at least in certain cases the ultimate strength of a concrete is actually fixed by the shearing strength of the particles of stone which make up the aggregate. Cubes in proportions 1 : 2⅓ : 4⅔,—based on a cement barrel of 3.8 cubic feet,—attained an ultimate strength of 5000 to 5500 pounds per square inch. On account of

* Proceedings Institution of Civil Engineers, Vol. LXXXVII, p. 88.
† Transactions American Society of Civil Engineers, Vol. LIX, p. 67, 1907.
‡ Second Report on the Genesee River Storage Project, New York, 1894.

differences in the methods of mixing and ramming, some of the specimens reached this limit at the age of two months while others did not attain it for six months; but it was noticeable that at whatever period the ultimate strength was reached the planes of fracture were smooth, breaking through each piece of stone, whereas before the ultimate strength was reached many of the stones pulled out from the concrete, leaving jagged instead of smooth surfaces on the pyramids remaining after the cubes were broken to destruction. The stone employed for these specimens was a hard, dense trap. If a weaker stone had been used, it is probable that the pieces would have sheared at a much earlier period and the ultimate strength would have been lower.

Tests at the United States Government Laboratories at St. Louis§ upon 6-inch cubes of exceptionally good 1 : 2 : 4 concrete 26 weeks old, made with different coarse aggregates, show the following average ultimate strengths:

Granite concrete, 4750 pounds per square inch.

Gravel concrete (quartz pebbles), 3810 pounds per square inch.

Limestone concrete, 3460 pounds per square inch.

Cinder concrete, 2320 pounds per square inch.

If concrete is mixed in such proportions or by such methods that the ultimate strength is reached before the stones shear, the strength of the particles of stone is a much smaller factor in the result.

Tests of crushing strength of building stone made by Mr. Richard L. Humphrey* give the relative strength of specimens of several kinds of stone:

The average of a large number of tests of 2-inch cubes, part on edge and part on bed, by Gen. Q. A. Gillmore, and quoted in Burr's "Materials of Engineering,"† shows average results for granite and sandstone almost identical with the average of Humphrey's tests on these materials, while the average strength of specimens of limestone and marble was about 13 000 lb. per square inch. Tests at the Watertown Arsenal‡ give the crushing strength of 4-inch cubes of sound trap rock as 33 300 lb. per square inch, and of seamy trap as 19 400 lb.

The table giving results of Mr. Humphrey's test is especially interesting as showing in a general way that the heaviest rock is apt to have the highest strength. Of the 8-inch cubes tested on their bed, so as partially to eliminate the effect of cleavage planes, the specimen of quartzite is the only one which does not follow this rule. In Gillmore's tests mentioned above, the

§ U. S. Geological Survey Bulletin, No. 344, 1908.
* As tabulated by Edwin C. Eckel in *Engineering and Mining Journal*, June 20, 1903, p. 931.
† Edition of 1903, p. 433.
‡ Tests of Metals, U. S. A., 1898, p. 577.

variation in the same kind of stone from different localities is large, but in each kind the heavier rocks usually give the higher resistances. We may state, therefore, as a general rule in comparing rocks of the same kind, that those of the highest specific gravity are apt to be the strongest, and this rule may be extended in many cases to the comparison of different kinds of rock.

Crushing Tests of Cubes of Stone.

BY RICHARD L. HUMPHREY. (*See p.* 391.)

Location.	Kind of Stone.	Weight per cubic foot. lb.	Specific Gravity.	Absorption.	Average Crushing Strength. 2-inch cube. Bed. lb. per sq. in.	2-inch cube. Edge. lb. per sq. in.	8-inch cube. Bed. lb. per sq. in.	8-inch cube. Edge. lb. per sq. in.
Chester, Pa..........	Gneiss	165.71	2.69	0.385	6 097	5 446	9 505	6 426
Germantown, Pa.....	Gneiss	176.23	2.825	0.135	19 891	15 555	11 636	13 984
French Creek, Pa.....	Granite	190.46	3.085	0.155	19 997	14 348	17 274	7 910
Conshohocken, Pa....	Mica schist	177.76	2.91	0.155	20 038	15 680	10 417	7 532
Curwensville, Pa......	Sandstone	146.00	2.40	2.335	10 218	8 013	7 513	4 463
Lumberville, Pa......	Quartzite	158.19	2.63	0.998	no test	no test	14 841	8 637

EFFECT OF PERCENTAGE OF CEMENT UPON THE STRENGTH OF CONCRETE.

The strength of concretes of the same density made with similar materials varies approximately with the percentage of cement, so that the comparative strength of concrete in different proportions sometimes may be estimated sufficiently close for practical purposes. The following table gives the results of certain of the Jerome Park tests* by Messrs. Fuller and Thompson, where the density of the concrete was maintained nearly constant.

DESTRUCTIVE AGENCIES

The effect of sea water, frost, fire, and rust, are treated in Chapters XVI, XVII and XVIII.

Effects of Acids. Experience shows that after concrete has thoroughly hardened, it resists the attack of diluted acids, such as are found in sewage, and that it is only seriously affected by strong acids which injure nearly all other materials. Concrete has proved to be the most successful lining for digesters in pulp mills, where sulphurous acid is present under high heat pressure.

* Transactions American Society of Civil Engineers, Vol. LIX, p. 67, 1907.

Effect of Manure. Concrete of good quality after hardening is not affected by manure, although it may be injurious to green concrete.*

Effect of Oils. Tests† indicate that mineral oils do not injure concrete even if applied to it when only a week or two old. Animal fat and vegetable oils tend to disintegrate it if applied when the concrete is green, but these appear to be successfully resisted if the concrete has thoroughly hardened. Hardened concrete may be affected by the vapor from the melting of animal fat, probably because of the acid which it contains. Mr. Toch‡ states that

Comparative Density and Strength of Similar Concrete with Different Percentages of Cement and 2¼-inch Stone Graded as an Elli, se and Straight Line.

BY FULLER AND THOMPSON. (*See p.* 392.)

MATERIALS.		DENSITY WITH DIFFERENT PERCENTAGES OF CEMENT*				MODULUS OF RUPTURE AT 90 DAYS, DIFFERENT PERCENTAGES OF CEMENT.*				COMPRESSIVE STRENGTH AT 140 DAYS, DIFFERENT PERCENTAGES OF CEMENT.			
Stone.	Sand.	8%	10%	12½%	15%	8%	10%	12½	15%	8%	10%	12½%	15%
Crushed	Screenings	0.829	......	......	......	188	....	....	....	980	......	......	......
"	"	......	0.846	......	......	....	250	....	....	....	1 129	......	......
"	"	......	......	0.832	......	....	....	245	....	....	......	1 418	......
"	"	......	......	......	0.839	....	....	....	326	....	......	......	1 634
"	"	0.871	......	......	......	163	....	....	....	990	......	......	......
Gravel	Sand	......	0.855	......	......	....	245	....	....	....	1 715	......	......
"	"	......	......	0.865	......	....	....	307	....	....	......	1 890	......
"	"	......	......	......	0.867	....	....	....	339	....	......	......	2 040
Averages		0.850	0.850	0.848	0.853	176	248	276	332	985	1 428	1 654	1 837
Strength computed as proportional to the percentage of cement, based on strength with 8% cement....................						176	220	275	330	985	12 30	1 540	1 850

* In gravel and sand mixtures the percentage by weight of cement was increased in each case to balance the difference in specific gravity between this and the crushed material.

the action of fat or vegetable oil is due to expansion caused by the formation of crystals of stearate and oleate of lime. Light oils, like kerosene or naphtha, penetrate any substance very readily, so that if concrete tanks are used for their storage, special precautions must be taken in their construction.

Effect of Electrolytic Action. Tests§ and experience indicate that concrete is injured by electrolysis. However, there is less danger for plain concrete or for reinforced concrete than for structural steel even if the latter is incased in concrete or other masonry.

* See "Investigation of Collapse of Filter Roof during Construction at Lawrence, Mass.," by Sanford E. Thompson, Journal New England Water Works Association, Vol. XXII, No. 2.

† James C. Hain in Engineering News, Apr. 20, 1905, p. 279.

‡ Engineering News, Apr. 20, 1905, p. 419.

§ By A. A. Knudsen, American Institute Electrical Engineers, Vol. 26, p. 133, by Maximilian Toch, Engineering Record, June 30, 1906, p. 794, and by N. J. Nicholas, Engineering News, Dec. 14, 1908, p. 710.

STRENGTH AND ELASTICITY OF CINDER CONCRETE

Tests at the Watertown Arsenal* on 12-inch cubes of cinder concrete mixed in different proportions gives results arranged in the following tables:

Compressive Strength of 12-inch cubes of Cinder Concrete.
Watertown Arsenal. (*See p.* 394.)

Cement.	Proportions Cement.	Sand.	Cinder.	Age, 1 month. Mean weight lb. per cu. ft.	Compressive strength lb. per sq. in.	Age, 3 months. Mean weight lb. per cu. ft.	Compressive strength lb. per sq. in.
German Portland.............	1	1	3	112.1	1 466	110.4	2 001
	1	2	3	115.2	1 098	112.8	1 634
	1	2	4	111.2	904	107.9	1 325
	1	2	5	108.8	769	105.3	1 084
	1	3	6	107.6	529	103.5	788
American Portland............	1	1	3	117.2	1 965	115.2	2 624
	1	2	5	111.3	818	110.0	1 412

Note: Each value for German cement is an average of three 12-inch cubes. Each value for American cement is an average of six 12-inch cubes made from two brands of first-class Portland cement. The exact age of the German cement specimens was 38 and 99 days, and of the American cement specimens 31 and 90 days.

Elastic Properties of Cinder Concrete, 12-inch cubes at three months.
Watertown Arsenal. (*See p.* 394.)

American Portland Cement.	Proportions. Cement.	Sand.	Cinder.	Age when Tested.	Modulus of Elasticity between loads per sq. in. 100 and 600 lb.	100 and 1000 lb.	1000 and 2000 lb.	Permanent sets after loads per sq. in. of 600 lb.	1000 lb.	2000 lb.	Compressive strength lb. per sq. in.
	1	1	3	90	2 500 000	2 500 000	1 429 000	0.	.0001	.0006	2 780
A	1	2	5	90	1 087 000	957 000		.0008	.0028		1 402
	1	2	5	90	1 471 000	1 286 000		.0002	.0010		1 715
	1	1	3	90	4 167 000	3 214 000	1 190 000	0.	.0001	.0014	2 368
B	1	1	3	90	2 083 000	1 875 000	1 351 000	.0001	.0002	.0017	2 580
	1	2	5	90	1 190 000	849 000		.0009	.0066		1 200
	1	2	5	90	1 087 000	865 000		.0024	.0089		1 263

*Tests of Metals, U. S. A., 1898, pp. 561 and 573.

MAKING CONCRETE SPECIMENS FOR TESTING

Complete and careful records must be made of the methods employed and the materials used in making concrete specimens for testing, in order to reach results of value for comparison with those of other experimenters. The lack of this care and accuracy has rendered the larger number of tests on concrete of only local significance.

The practical relation of the density of a concrete to its strength, as discussed in the preceding pages, indicates that it is not merely necessary to measure roughly the materials entering into the composition, but that the exact amount of solid matter, the coarseness of the particles, the character of the surfaces of the grains, the moisture in the materials, and the additional quantities of water used, must be very carefully recorded.

The cost of making and testing concrete specimens is so great, that the additional time required for entering notes full enough to produce results of scientific value is insignificant. The blank form with the values in an actual test filled out is presented on page 396 for recording data relating to the making of concrete specimens. On the same form may be added places for recording the results of the tests. In most cases it is advisable for greater exactness to make separate batches for each specimen.

In addition to the information outlined, mechanical analyses should be made of the aggregates as a part of the permanent records, and for the computations in the form, it is also necessary to determine the specific gravities of the materials.

The specific gravity of Portland cement in most cases may be assumed as 3.1, and, in fact, the specific gravity of the sand may also be assumed without appreciable error as 2.65. For the specific gravity of other aggregates special tests are necessary.

Concrete for experimental specimens should be mixed by experienced men. There is a certain knack in properly turning the materials so as to mix them thoroughly which can be acquired only by practice, and the amount and manner of ramming or puddling is so important that specimens may be rendered worthless by improper manipulation.

The molds for specimens should be made of metal or of good quality lumber, preferably white pine, so that it will not twist or get out of shape, and the surface next to the concrete should be planed, and all joints made water-tight. The mold should be wet or greased before placing the concrete. If metal, the grease or oil must cover every part of the surface. A wooden mold for two cubes is shown in Fig. 128.

Dimensions of Specimens. Compression specimens are limited in size

Expt. No.___________
File *Waltham Reservoir.*
Date *2/9/06.*

Form for Recording Data on Concrete Specimens

(Figures in ( ) refer to Item Numbers.)

ITEM.

1. Nominal Proportions .... *1 : 1.8 : 4.1*
2. Car No. *00*
3. Kind of Cement .... *Atlas*
4. Kind of Sand .... *¾u.c. ¼G*
5. Analysis No. .... *420 and 421*
6. Kind of Coarse Aggregate .... *W. Gravel*
7. Analysis No. *422*
8. Weight of Cement Used *3.12*
9. Weight of Sand Used *5.72*
10. Weight of Coarse Aggregate Used *12.85*
11. Weight of Water Used *1.77*
12. Per Cent Water to Weight of Cement plus Sand *20%*
13. Temperature of Water .... *60° F.*
14. Temperature of Laboratory .... *70° F.*
15. Total Weight of Material (8) + (9) + (10) + (11) *23.46*
16. Weight of Mold Empty *3.00*
17. Weight of Mold Filled *26.30*
18. Weight of Concrete Net *23.30*
19. Weight of Concrete Left Over *0.00*
20. Weight Unaccounted for—Assumed as Solid Material* *0.16*
21. Weight Unaccounted for—Assumed as Water *0.00*
22. Volume of Fresh Specimen (cu. ft.) *0.1527*
23. Weight of Specimen—Mold Removed *22.7*
24. Method of Storage .... *Air*
25. Weight of Specimen Before Testing *22.5*
26. Measurements of Specimen Before Testing .... *7.99″ × 8.02″ × 4.12″*
27. Date and Hour Specimen Made .... *2/9–3 p.m.*
28. Date Tested .... *3/9–10 a.m.*
29. Specific Gravity Cement .... *3.15* 30. Sand .... *2.65* 31. Stone *2.75*
32. Weight of Cement in Fresh Concrete $(8) \times \frac{(18)}{(18) + (19) + (20)}$ *3.09*
33. Weight of Sand in Fresh Concrete $(9) \times \frac{(18)}{(18) + (19) + (20)}$ *5.68*
34. Weight of Coarse Aggregate in Fresh Concrete $(10) \times \frac{(18)}{(18) + (19) + (20)}$ *12.76*
35. Weight of Water in Fresh Concrete $(11) \times \frac{(18)}{(18) + (19) + (20)}$ *1.76*
36. Absolute Volume Cement in Fresh Concrete (assume 1 cu.ft.water, 62.4 lb.) $\frac{(32)}{(22) \times 62.4 \times (29)}$ *0.103*
37. Absolute Volume Sand in Fresh Concrete $\frac{(33)}{(22) \times 62.4 \times (30)}$ *0.225*
38. Absolute Volume Coarse Aggregate in Fresh Concrete $\frac{(34)}{(22) \times 62.4 \times (31)}$ *0.487*
39. Absolute Volume Water in Fresh Concrete $\frac{(35)}{(22) \times (62.4)}$ *0.184*
40. Total Absolute Volume Materials (36) + (37) + (38) + (39) *0.999*
41. Density (36) + (37) + (38) *0.815*
42. Remarks ....

Computed by *G. B.*
Checked by *S. E. T.*

* Adhering to Tools and Trays. Divide the Total Loss, (15) − [(18) + (19)], by Estimation into Items (20) and (21).

by the capacity of the testing machine. The Emery Machine at the Watertown Arsenal, one of the largest in the world, has a capacity of 800 000 pounds, and the authors have had 12-inch concrete cubes tested there which reached this limit, so that 12 inches on a side may be fixed in general as the maximum size for specimens. For a lower limit it is doubtful if specimens less than 6 inches square can be made to give accurate results. A series of comparative tests by the authors upon 8-inch and 12-inch cubes gave much higher breaking strength per square inch for the larger size

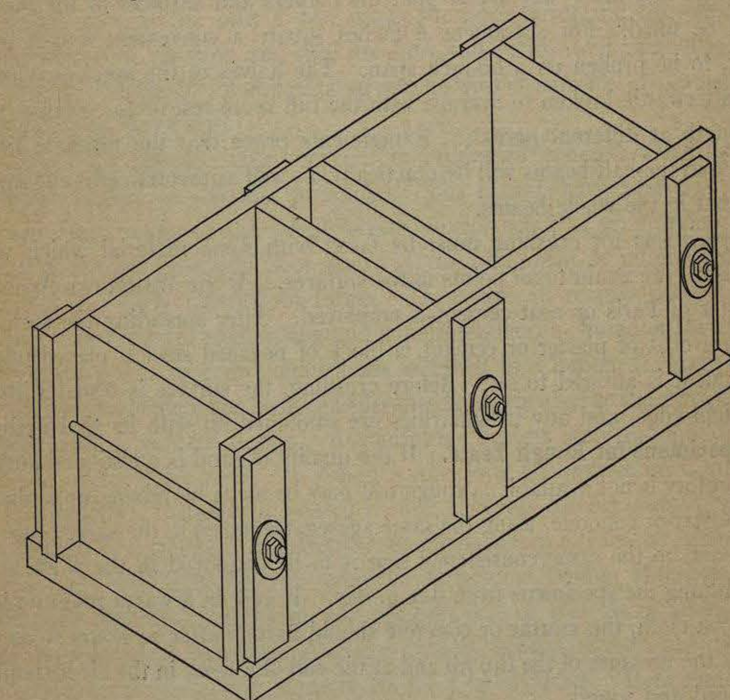

FIG. 128.–Mold for Concrete Cubes. (*See p.* 395.)

specimens. It was evident from the lower unit weight of the smaller specimens, that the difference was due, at least in part, to variation in homogeneity.

Cubes have been the common form of compression specimens and are suitable for comparative tests of ultimate breaking strength, but for studying the real value of concrete in compression, or for determination of elastic properties, long prisms are preferable.

For column tests, the length of a specimen should be at least five times the largest lateral dimension. Both theory and practice show that beyond this point there is but little variation in the strength per square inch, providing the loading is central. See p. 369.

The specimen recommended for crushing tests by the Joint Committee on Concrete and Reinforced Concrete, and used at the U. S. Government Laboratories at St. Louis, is a cylinder 8 inches diameter by 16 inches long.

For reinforced concrete beams the Committee recommended 8 by 11 inches by 13 feet long, testing this on a 12-foot span.

Beams for testing the transverse strength of concrete are usually made from 6 to 12 inches square. The smaller size is satisfactory provided the mixture is a fairly wet one so that the corners and surfaces of the molds can be filled. For specimens 6 inches square a convenient length is 6 feet, to be broken on a 60-inch span. The halves of the specimens may be afterwards broken to average with the full beam test or to compare the strength at different periods. Experiments prove that the ultimate fiber stress in the half beams will be practically, as well as theoretically, the same as that in the whole beams.

Specimens for crushing must be faced with some material which will transmit the strain to all points in the surfaces. At the Watertown Arsenal plaster of Paris or neat cement is employed. After spreading the surface with a coat of plaster or cement, a block of polished steel is placed upon it, and it is allowed to set. Before crushing, the surface is tested with a straight-edge, and any irregularlties are smoothed off with its sharp edge.

Specimens for Rough Tests. If the quality of sand is questioned and a laboratory is not available, a rough test may be made by mixing up a block of mortar or concrete, using the same aggregates mixed in the same proportion and to the same consistency that is to be employed in the work and examining the specimens from day to day. If kept in a warm room under a moist cloth, the mortar or concrete should harden after 24 hours so as to resist the pressure of the thumb and at the end of a week in the air it should be hard and sound.

Method of Quartering. To obtain an average sample from a pile of sand, gravel, or stone, the method of quartering is useful. Shovelfuls of the material are taken from the various parts of the pile, mixed together and spread in a circle. The circle is quartered, as one would quarter a pie, two of the opposite quarters are shoveled away from the rest, thoroughly mixed, spread, and quartered as before. The operation is repeated until the quantity is reduced to that required for the sample.

CHAPTER XXI

REINFORCED CONCRETE DESIGN

Reinforced concrete is concrete in which steel or other metal is imbedded to increase its strength. Although it has been employed generally as a building material for only a few years, the laws governing the effective combination of concrete and steel are now sufficiently well established to enable the engineer to design a structure with assurance of permanent strength and durability.

Occasional failures have occurred in reinforced concrete construction through neglect of essential principles. The causes have been (1) poor design, particularly in the details which do not occur in steel design; (2) poor materials, especially poor sand; (3) misplacement of reinforcement; and (4) too early removal of forms. These are all readily preventable causes under careful engineering and superintendence. Some of the more important points to guard against are outlined in Chapter II, page 28a.

Until recently there has been considerable divergence in the theory of beam design and of column design. Authoritative reports were brought out in Europe in 1907 and 1908. In America, the Joint Committee on Concrete and Reinforced Concrete presented its first Progress Report early in 1909. This Joint Committee is composed of members selected from the American Society of Civil Engineers, the American Society for Testing Materials, the American Railway Engineering and Maintenance of Way Association, and the Association of American Portland Cement Manufacturers, and therefore represents the highest authority in the United States. Its recommendations have tended to standardize general practice.

In this chapter the recommendations on design of this American Joint Committee have been followed, not only because of their general acceptance as a standard, but because they agree with the views of the authors and represent the most satisfactory rules thus far formulated. This has necessitated no changes in the methods of analysis given in the first edition, since the theory of stress there presented has since been generally adopted.

Results of recent tests have made possible a more complete treatment of the details of design, and extensive study and investigation have led to the addition of simple working formulas and practical recommendations.

In general, only brief discussions together with the rules and principal formulas for design are given in the text, the analytical treatment of each