illustrated in Figs. 59, 60, and 61, and is important in its application to the selection of materials for concrete.

(4) The fact that an aggregate consisting of a mixture of stones and sand has greater density, that is, contains fewer voids than the sand alone,

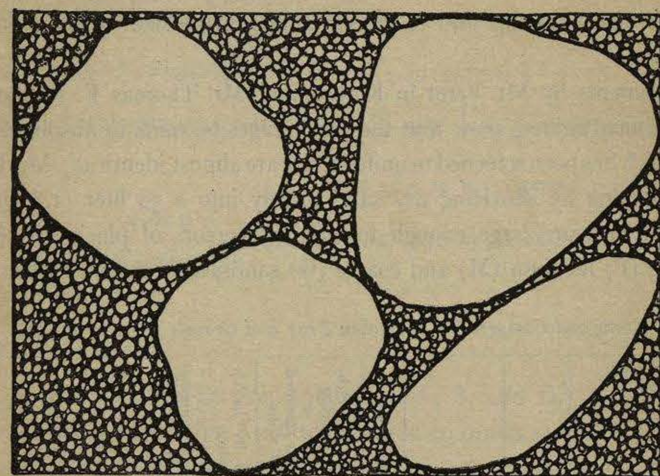

FIG. 59.—Large Stones with Voids filled with Sand. (*See p.* 172.)

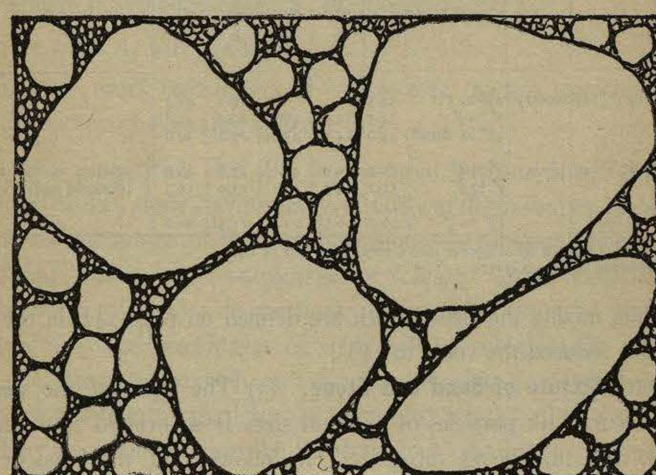

FIG. 60.—Large Stones with Voids filled with small Stones and Sand. (*See p.* 172.)

is illustrated by comparison of Figs. 59 and 61. The voids of the large stone in Fig. 59 are filled with sand, while the voids in the same large stone in Fig. 61 are filled with mixed sand and stone, and the mass of the mixture is evidently denser, that is, it contains more solid material. This

law relates directly to the difference between mortar and concrete. The substitution of stones for small masses of sand reduces the voids and consequently the quantity of cement required. Extending the principle to the fixing of proportions of sand and stone, it is evident that for maximum

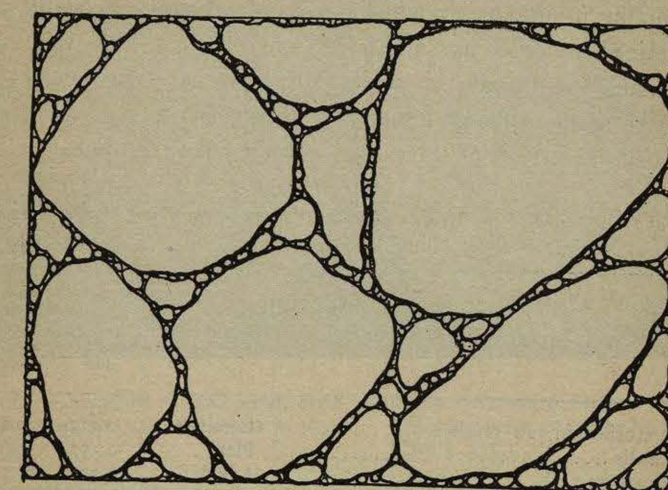

FIG. 61.—Large Stones, with Voids filled with medium sized Stones surrounded by smaller Stones and Sand so as to give Graded Mixture. (*See p.* 172.)

economy and equal strength there should be used the largest possible quantity of stone in proportion to the sand, the strength of concrete being often actually increased simply by substituting more stone for a portion of the sand. In the following table this is illustrated by tests selected from Mr. Fuller's 6-inch beam experiments, which are given in full on page 376.

Relation of Strength of Concrete to Relative Proportions of Sand and Stone. (*See p.* 173.)

Proportions by weight of cement to total aggregate.	Proportions by weight of cement to sand and broken stone.	Modulus of Rupture lb. per sq. in.
1 : 6	1 : 1 : 5	504
1 : 6	1 : 2 : 4	439
1 : 6	1 : 3 : 3	355
1 : 6	1 : 4 : 2	210
1 : 6	1 : 6 : 0	93

The total amount of aggregate in each case is the same, namely, one part cement to 6 parts sand and stone, but the strength varies with the relative proportions of each, from 93 lb. to 504 lb.

(5) The discussion of Fuller's experiments on the relation of the best

practical mixture of sizes to a parabolic curve is given in Chapter XI, page 201.

Effect of Shape of Grain. (6) The fact that round grains, such as gravel, contain fewer voids than material with angular grains, such as broken stone, even if the particles in both are the same size, is proved from experiments in America and France. Mr. Allen Hazen states* that round grained water-worn sands have from 2% to 5% less voids than corresponding sharp grains of sand. Mr. Feret† also has studied the effect of the shape of the grain upon the density of sand, using in each case an artificial mixture of three sizes, with the following results:

Effect of Character of Sand Grains upon the Volume of the Sand. (*See p.* 174.)
BY R. FERET.

Nature of Sand	Shape of Grains	Actual solid volume per liter of sand: Not shaken, liter	Actual solid volume per liter of sand: Shaken to refusal, liter
Quartzite crushed in jaw crusher	Laminated	0.525	0.654
Crushed shells	Flat	0.557	0.682
Ground quartzite	Angular	0.579	0.726
Natural granitic sand	Rounded	0.651	0.744

The voids in each case are the complements of the figures given.

The conclusion to be drawn is that the real volume increases (and therefore the voids decrease) as the sand approaches the round form.

When experimenting upon gravels and broken stone Mr. Feret‡ separated each into three sizes which he called respectively:

G (coarse) passing holes of 6 cm. (2.36 in.) diameter and retained by holes of 4 cm. (1.57 in.) diameter;
M (medium) passing holes of 4 cm. (1.57 in.) diameter and retained by holes of 2 cm. (0.79 in.) diameter;
F (fine) passing holes of 2 cm. (0.79 in.) diameter and retained by holes of 1 cm. (0.39 in.) diameter.

Each size of broken stone loosely measured gave about 52% voids, and each size of gravel about 40% voids. The voids in the broken stone were reduced to 47%, the lowest result obtainable, by mixing G and F in about

*Twenty-fourth Annual Report, Massachusetts State Board of Health, 1892.
†Annales des Ponts et Chaussées, 1892, II, p. 32.
‡Annales des Ponts et Chaussées, 1892, II, p. 153.

equal parts with no M, and in the gravel to 34% with about $3\frac{1}{2}$ parts of G to one part of F. These figures are of course directly applicable only

FIG. 62.—Standard Ottawa Sand, dry.* No. 20 to No. 30 Sieves. (*See p.* 175.)

FIG. 63.—Standard Ottawa Sand with 6% moisture.* No. 20 to No. 30 Sieves. (*See p.* 175.)

FIG. 64.—Natural Bank Sand.* No. 20 to No. 30 Sieves. (*See p.* 175)

FIG. 65.—Crushed Quartz.* No. 20 to No. 30 Sieves. (*See p.* 175.)

to the special materials which he studied, and do not apply to gravel or stone containing sand or dust.

Photographs of Sand. Photographs of three types of sand are shown in Figs. 62 to 65. Figures 62 and 63 are photographs of the Ottawa,

*Each sand has passed a No. 20 and been retained on a No. 30 sieve. Magnified $10\frac{1}{2}$ diameters.

Illinois, bank sand screened to the size selected for the standard sand by the Committee of the American Society of Civil Engineers. They illustrate the effect of moisture upon the arrangement of the sand grains, which is more fully described below. Fig. 64 is an ordinary bank sand from Eastern Massachusetts which has passed through and been retained by the same screens as the Ottawa sand. Fig. 65 is a sample of crushed quartz sand, formerly the standard in the United States. The sands are all reduced by the same number of diameters. The Ottawa sand, Figs. 62 and 63, is apparently of finer grain than either the bank sand or the crushed quartz, but close inspection will show that its grains, very uniform in size, are of about the same diameter as the smallest grains in the other sands. In other words, all the grains correspond very closely to a No. 30 sieve, the lot of sand from which it was screened containing no larger particles.

Effect of Moisture on Sand and Screenings. (7) Moist sand occupies more space and weighs less per cubic foot than dry sand. This is directly contrary to what one would naturally suppose. Indeed, it is almost incredible that the addition of water can reduce the weight of any material. The statement is readily proved, however, by shoveling a small quantity of natural sand as it comes from the bank with, say, 3% or 4% of moisture into a measure and drying it. The sand will settle, leaving the surface much below the level of the top of the measure. The explanation of this apparent anomaly lies in the fact that a film of water coats each particle of sand and separates it by surface tension from the grains surrounding it. This is illustrated in Figs. 62 and 63, page 175, the grains of the moist sand being separated from each other by the film of water. Fine sand, having a larger number of grains, and consequently more surface area, is more increased in bulk by the addition of water than coarse sand. The volume of coarse broken stone and gravel is but slightly, if at all, changed by moisture, while small broken stone composed largely of particles of less than ¼-inch diameter is affected like sand.

If a small quantity of water is poured into a vessel containing dry sand, the bulk is not increased because of the inertia of the particles, but if the sand after moistening is dumped out and then turned back into the vessel with a shovel or trowel, its bulk will be increased. On the same principle, a sand bank does not swell in bulk during a shower, but the effect of the moisture is shown in the excavated material as soon as it is loosened with the shovel, and therefore its loose measurement for concrete or mortar is effected.

The diagram in Fig. 66, plotted by Mr. Fuller* from experiments upon a single sample of natural sand mixed by weight with varying percentages of water, illustrates the effects of moisture upon the actual percentages of voids in sands loose and tamped. The volumes produced by varying degrees of compacting are located between the two curves. It is noticeable that both the loose and tamped sand increase in volume with the addition of water and reach a maximum with about 6% of water, then decrease, and finally, when saturated, return to slightly less than their original dry bulk. The same sand, it is seen, may contain from 27% to 44% of absolute voids, according to the percentage of water and the degree of compacting.

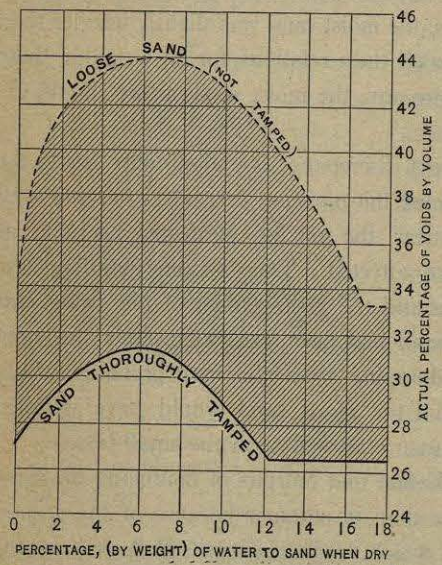

FIG. 66. — Percentage of Absolute Voids in a Natural Bank Sand containing Varying Percentages of Moisture. (*See p.* 177.)

The percentage of water by weight which will give the greatest bulk, — corresponding, of course, to the largest percentage of absolute voids, — varies with different sands from 5% to 8%.

The actual variation on different days in the percentage of moisture in a natural bank sand was found by the authors, in a series of experiments, to range from 1½% to 5¼% of the total weight, or from 2½% to 7¼% of the bulk of the moist sand. The sand, screened from a gravel bank in Eastern Massachusetts, ranged in coarseness from very fine to that which would pass a ⅜-inch mesh screen. The moist sample was taken from the pile the day after a shower, and weighed 84½ lb. per cubic foot, while the dryer sample, taken after a period of dry weather, weighed 107 lb. per cubic foot.

A sample of very fine sand which had been standing in a pile through the same shower contained 9½% of moisture by weight, corresponding to 13% by volume. Ordinary gravel, on the other hand, from which the sand had been screened, was found after a heavy rain to contain only 1.8% of moisture by weight, this being apparently the maximum quantity which it would hold.

*Engineering News, July 31, 1902, p. 81.

The maker of concrete is especially interested in the influence of moisture upon the bulk of sand and upon its voids (1) because of its effect upon the actual measurement of sand used in construction work, and (2) because of its effect upon his experimental determinations of proportions.

Rather incomplete experiments of the authors tend to show that the actual effect of moisture upon the volume of sand used in concrete and mortar may often be less than would naturally be inferred from the various experiments cited, and depends largely upon the processes of handling the sand. For example, fairly dry sand (3% moisture) shoveled by laborers from the pile into the regular sand-measuring box weighed 454 lb., while after a rain, the sand (with 5% moisture) shoveled from the pile into the same box weighed 464 lb., that is, the moist sand was slightly heavier than the dry. Further handling reversed these relations, for on weighing these two sands in a half cubic foot measure, the moist sand, as we should expect, was lighter than the dry.

The explanation of this apparent discrepancy is undoubtedly due to the fact that as the rain which affected the moisture occurred after the sand had been excavated and piled near the mixing platform, its bulk, as suggested on page 176, was not affected. The laborers handling the moist sand took large shovelfuls and the arrangement of the grains was not greatly disturbed. If the sand had been excavated after the rain, the handling with shovels and dumping from the cart probably would have rearranged the grains so that the moist sand would have weighed less than the dry in the large measure as well as in the small box.

Mr. Feret* calls attention to the fact that mortars of nominally the same proportions are richer in winter than in summer because of the greater amount of moisture in the sand, which, by increasing its bulk, reduces the absolute volume of the grains in a unit of measure. On the other hand, mortars are leaner in dry than in damp weather because the sand has greater density when dry.

In the experimental study of sand for determining the proportions of cement to be used, the effect of moisture is exceedingly important. The voids in absolutely dry sand are certainly no criterion of its qualities for mortar, while a moist sand will give entirely different results on different days. The best that can be done, if the study can be pursued no further than void determination, is to select conditions as near as possible to the average, and after determining the voids, considered as air alone and also as space occupied by the air and moisture, to use the results as a basis for judgment, bearing in mind that the volume of paste made from 100 lb.

*Annales des Ponts et Chaussées, 1892, II, p. 26.

of neat Portland cement, while varying largely with different brands, averages about 0.86 cubic feet, and that the volume of the additional water required for the sand (see pages 146 and 221) actually occupies space in the resulting mortar.

The most important conclusion to be drawn from the extreme variation in the same sand under different conditions is the impossibility of attaining results by the usual void experiments upon sand alone, which will be of accurate value in the consideration of mortar and concrete, and the practical necessity of employing methods such as are described by the authors in Chapter IX, page 138, or by Mr. Fuller in Chapter XI.

In the preceding paragraphs we have referred chiefly to the variation in the condition of the same sand. The importance of studying mortars rather than the sand alone is still further emphasized by the varying effect of moisture upon sands of different sizes. This is brought out very clearly in Mr. Feret's paper.* In studying the normal consistency of mortars he finds that not only every cement but also every sand has a definite percentage of water necessary to bring it to what may be called normal consistency. This he illustrates in the triangle shown in Fig. 67 (constructed as described on page 143), giving the "proportions of water (by weight) required for ground quartz sands of all granulometric composition." It is evident from the diagram that coarse sands,† G, require 3% by weight of water, medium sands, M, 9%, and fine sands, F, 23%, while mixtures of the three sizes require intermediate percentages.

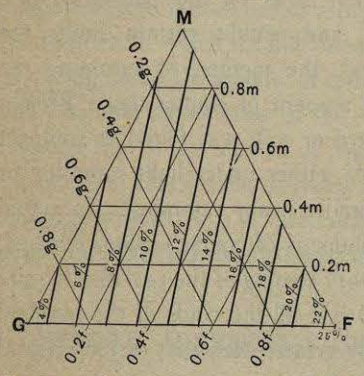

FIG. 67.—Percentages of Water Required to Gage Ground Quartz Sand of all Granulometric Compositions. (*See p.* 179.)

Compacting of Broken Stone and Gravel. Since concrete is usually compacted by ramming or lubrication of semi-liquid mortar, the density or the percentage of voids in compacted material is an important function. The statement has been made frequently that the aggregate compacts more when rammed in concrete than when rammed dry or merely moistened with water, because the mortar acts as a lubricant. Experiments by the authors indicate that broken stone under the same ram-

*Annales des Ponts et Chaussées, 1892, II.

†The sizes of screens defining coarse, medium, and fine sands are given on page 142.

ming will compress on the average 1% more when it is moistened than when dry, and that an amount of mortar sufficient to lubricate without filling the voids produces no further reduction in volume. For example, a volume of broken stone mixed with 20% of mortar and rammed in 6-inch layers produced a volume exactly equal to that of the rammed broken stone which had been merely moistened.

Further experiments, partially outlined in the table on page 171, upon gravel and also upon varying sizes and mixtures of trap rock from two quarries, the one producing a soft and the other an exceedingly hard stone, lead to the conclusion that with stones of the same general structure, the percentage of reduction in volume by similar ramming in 6-inch layers is quite uniform, irrespective of the actual sizes of the particles, their relative sizes, the percentage of voids, and, within certain limits, the degree of hardness. On the other hand, the method of ramming the same stone will very largely affect the amount of compacting. Broken stone of the nature of trap, whether hard or soft, was found to compact when spread in 6-inch layers about 14% either under light ramming or shaking the measure, and about 21% under heavy ramming. In actual concrete work this large reduction of volume is of course seldom reached, because imperfect mixing and the necessary coating of the particles require a larger percentage of mortar than will just fill the voids of the rammed stone, and the bulk of concrete is usually greater than that of the original stone.

Screened gravel spread in 6-inch layers and unconfined, compacted about 12% under either light or heavy ramming.

These percentages of compacting are based upon the loose measurement of the material as thrown by a laborer into a barrel or box measure. Rehandling a material like broken stone as it comes from the crusher tends to mix particles of unequal size and therefore to compact it very slightly. In one case a screened stone fresh from the crusher compacted 1% when rehandled once, and an additional 1% when rehandled the second time.

It is interesting to note that the method of shoveling broken stone into a measure has but slight effect upon its shrinkage; for example, a lot of stone thrown with force into an inclined barrel occupied a space scarcely appreciably less than when very carefully and lightly placed. On the other hand, dropping from a considerable height does affect the volume, for Mr. Desmond Fitzgerald* states that broken stone dropped 12 feet into a car shrank to a volume 7% less than when it was measured in a box.

*Transactions American Society of Civil Engineers, Vol. XXXI, p. 303.

Sand, unlike stone, is largely affected by the manner of shoveling and the size of the receptacle.

Compacting of Sand. The degree of compacting of sand is largely dependent upon the percentage of moisture which it contains. The dry sand shown in diagram in Fig. 66, page 177, when thoroughly tamped compacted from 34% to 27% voids or 9.6% in volume,* the sand with 6% moisture from 44% to 31% voids or 18.8% in volume, and the saturated sand from 33% to 26½% voids or 8.8% in volume.

Attention is called by Mr. Feret to the fact that the measurement of the weight of a given sand depends not only upon the quantity of moisture in it, but also upon the depth of the box which is used for the measure, the quantity of sand introduced at a time, — that is, the size of a shovelful, — the height from which it falls, the amount of shaking, if any, given to the box during filling, the amount of compacting given to the mass when leveling it off, and the smoothness of the surface left. As an illustration of the difference due to the method of placing in the measure, the authors found that a certain coarse sand shoveled into a pail about as a laborer would fill a measure weighed 88.9 lb. per cubic foot, while the same sand carefully poured into the pail weighed 83.3 lb. per cubic foot.

DEFINING COARSENESS OF SAND BY ITS UNIFORMITY COEFFICIENT

The size of a sand may be indicated by what is termed its uniformity coefficient. This gives an idea of the actual variation in the size of the particles, and thus affords a means for comparing sands in different localities. A sand which is termed *coarse* in one section of the country is often considered *fine* in another.

To find the uniformity coefficient of a sand, screen it into at least five sizes, determine the percentage by weight of each size, and plot the mechanical analysis curve as described on page 196, and illustrated in Fig. 72, page 200. Then divide the diameter of the particles represented by the point at which the curve of the sand crosses the 60% horizontal line by the diameter of the particles where the curve crosses the 10% line. The quotient is the uniformity coefficient.

As an illustration of the value of the uniformity coefficient (u. c.) for different sands, reference may be made to the three mechanical analysis curves in Fig. 72, page 200. The curve of the coarse sand crosses the

*Ratio of compacting $= \frac{0.34-0.27}{1.00-0.27} = 0.096$

horizontal 60% line at the ordinate corresponding to a diameter of 0.117 inch, and the 10% horizontal line at ordinate 0.023 inch. Its uniformity coefficient and similarly the uniformity coefficients of the other sands are as follows:

			Uniformity Coefficient
Coarse sand	$\frac{0.117}{0.023}$	=	5.1
Medium sand	$\frac{0.038}{0.009}$	=	4.2
Fine sand	$\frac{0.018}{0.008}$	=	2.2

In general, it may be said that a sand with a uniformity coefficient above 4.5 is a good coarse sand for concrete work, and in comparing different natural sands the one having the highest uniformity coefficient may be considered the best.

As in ordinary bank sands the size of the particles at the 10% line (which is termed the effective size,* e. s.) does not greatly vary, the diameter at the 60% line alone is a very good indication of the coarseness of the sand. A knowledge of the effective size and the uniformity coefficient of any sand enables one accustomed to mechanical analysis diagrams to form a picture of its character.

Mr. Allen Hazen,† who first used these terms in the examination of filter sand, states with reference to the percentage of voids or "open space" in compacted sand corresponding to different coefficients:

> A rough estimate of the open space can be made from the uniformity coefficient. Sharp-grained materials having uniformity coefficients below 2 have nearly 45 per cent. open space as ordinarily packed; and sands having coefficients below 3, as they occur in the banks or artificially settled in water, will usually have 40 per cent. open space. With more mixed materials the closeness of packing increases, until, with a uniformity coefficient of 6 to 8, only 30 per cent. open space is obtained, and with extremely high coefficients almost no open space is left.

For loose sand at least 10 should be added to these percentage values.

*The effective size itself is of considerable value for comparison of sand for filters, but not for concrete.

†Twenty-fourth Annual Report of State Board of Health of Massachusetts for 1892.

CHAPTER XI

PROPORTIONING CONCRETE

BY WILLIAM B. FULLER*

IMPORTANCE OF PROPER PROPORTIONING

The proper proportioning of concrete materials increases the strength obtainable from any given amount of cement, and also the water-tightness. Conversely, it permits, for a given requirement of strength and water-tightness, a reduction in the amount of cement, thereby reducing the cost.

Upon large or important structures it pays from an economic standpoint to make very thorough studies of the materials of the aggregates and their relative proportions. This fact has been seriously overlooked in the past, and thousands of dollars have sometimes been wasted on single jobs by neglecting laboratory studies or by errors in theory. Since cement is always the most expensive ingredient, the reduction of its quantity, which may very frequently be made by adjusting the proportions of the aggregate so as to use less cement and yet produce a concrete with the same density, strength and impermeability, is of the utmost importance.

As an example of such saving, the ordinary mixture for water-tight concrete is about 1 : 2 : 4, which requires 1.57 barrels of cement per cubic yard of concrete. By carefully grading the materials by methods of mechanical analysis the writer has obtained water-tight work with a mixture of about 1 : 3 : 7, thus using only 1.01 barrels of cement per cubic yard of concrete. This saving of 0.56 barrels is equivalent, with Portland cement at $1.60 per barrel, to $0.89 per cubic yard of concrete. The added cost of labor for proportioning and mixing the concrete because of the use of five grades of aggregate instead of two was about $0.15 per cubic yard, thus effecting a net saving of $0.74 per cubic yard. On a piece of work involving, say, 20 000 cubic yards of concrete such a saving would amount to $14 800.00, an amount well worth considerable study and effort on the part of those in responsible charge.

Proper proportioning is also important for reinforced concrete so as to give the uniformity and homogeneity which cannot be obtained without careful attention to the proportions and grading of the aggregates.

*The authors are indebted to Mr. Fuller for the material for this chapter.