both simple functions of the diameter. The surface area varies as the square of the diameter, while the fineness modulus is a logarithmic function of the diameter. The relation is not so simple when we come to deal with graded aggregates. The discrepancy in this case becomes so great that both of these methods cannot be correct for a wide range of conditions.

The "Slump" Test

A further discussion of the quantity of water required on the basis of the grading of aggregate may be of interest. The plasticity or workability of the finished concrete is the only criterion which can be used in comparing the water requirements of different mixes, gradings, etc. We have used the "slump" test for this purpose. This consists of moulding the 6 by 12-in. cylinder in a smooth steel form by puddling the concrete in 4-in. layers with a ¾-in. steel bar, leveling off with a bricklayer's trowel, then immediately removing the form, without opening it, by a steady, upward pull. The shortening of fresh concrete from its original length, measured in inches, is the "slump."

The water which must be added, due to the presence of the aggregate, aside from that absorbed, may be divided into two portions: (1) To form a surface film on aggregate; (2) to make a thin cement paste which will produce a plastic mix with the aggregate. The total quantity of water required for this purpose can be determined experimentally by measuring the additional water necessary to produce a given plasticity in a concrete mixture as compared with that required for neat cement. By using different quantities of aggregate and different sizes and grading we arrived at the term, $0.30/1.26^m$, in our water formula which takes account of this factor. (It will be noted that this term gives a relation between water and fineness modulus similar to the water-strength curve in Fig. 1 of Bulletin No. 1.) The total quantity of water required for this term in an ordinary concrete mixture is about 8% by volume of concrete, or 40 to 50% of the total. This quantity is known to give satisfactory results. There is no reason why the water necessary to thin the cement paste should not be charged to the cement instead of the aggregate; however, the latter method seems more logical, since it is the presence of the aggregate and its size and grading that necessitate the addition of water to produce a mix of the same plasticity.

Quantity of Water Required

Let us see how much the quantity of water which must be charged to the aggregate (aside from that absorbed) is dependent upon surface area. Earl Pettijohn has shown (*Journ. Am. Chem. Soc.*, April, 1919) that the thickness of the surface film of standard Ottawa sand is 0.00003 in. at the point when free water begins to form. This means that 18 cc. (about 1/20 pint) of water would be required to produce the surface film on a cubic foot of standard sand and a much smaller quantity for ordinary concrete aggregates. The water required for this purpose is negligible. In other words, practically the entire quantity of water necessary on account of size and grading of aggregates must be charged to thinning the cement paste.

Ordinary mixes require water-ratios of 0.75 to 1.00; the value for neat cement with a normal consistency of 23% by weight is 0.35. In other words, the cement in concrete contains two to three times as much water as that required for normal consistency. It is the dispersion of the cement particles which results from the addition of water that is responsible for the rapid reduction in strength found in the wetter mixes.

How must the thinness of this paste be varied in order to produce a plastic mix with aggregate of different size and grading? Upon thinning the paste by adding water, we observe the following phenomena: (1) Increased plasticity; (2) change in volume.

The increased plasticity arising from adding water needs no demonstration. The volume of paste is first reduced, then increased as water is added to cement. Table I. herewith shows the effect with a standard cement weighing 94 lbs. per cu. ft.

That the *volume* of paste is an important factor in producing plasticity of mix can readily be seen from the fact that plasticity can be increased by increasing the quantity of cement and using relatively less water; in other words, a given degree of plasticity is produced by a low water-ratio or a rich mix and a high water-ratio with a lean mix. Just what effect the actual quantities of paste have on workability under the extreme conditions of mix, etc., has not been determined.

TABLE I.—VOLUME OF CEMENT PASTE

Water Added to One Volume of Dry Cement.		
Water-Ratio.	In Terms of Normal Consistency.	Volume of Cement Paste.
0.35	1.00	0.87
0.40	1.14	0.89
0.50	1.43	0.98
0.60	1.71	1.06
0.75	2.14	1.20
1.00	2.90	1.42
1.50	4.3	1.93
2.00	5.7	2.40
3.00	8.6	3.20

Current Theories Declared Wrong

Current theories of concrete are generally based on the idea that the quantity of paste is dictated by the voids in the aggregate, with a certain surplus. Four weaknesses in this theory may be mentioned: (1) The voids in the aggregate can be varied widely without producing any change in the quality of concrete; (2) the grading of aggregate which gives greatest strength in concrete gives higher voids than are found in other gradings of lower strengths; (3) concrete of highest strength may contain visible voids; (4) the strength and other desirable properties of the concrete depend on the *quality* of the paste and is little affected by the *quantity*, so long as we have sufficient to produce a workable mix.

The influence of the cement-water mixture on the plasticity of concrete is, then, a function jointly of the plasticity and volume of the paste. We have seen that the strength is a function of the water-ratio (volume of water to volume of cement) and that the strength of concrete decreases as the water-ratio increases; hence, in order to secure the highest grade of concrete at the lowest cost it is necessary to secure a given condition of plasticity with a minimum water-ratio. What condition with reference to the size and grading of the aggregate will give the desired result? It is obvious that this is a most complex relation if we consider the almost infinite variety of sizes and gradings which may be made from a single aggregate. Captain Edwards has used the surface areas as a satisfactory measure. It seems to the writer that the radius of curvature of the particles and the number of points of contact (or near contact) between adjacent particles are the factors which are primarily responsible for the additional water which is necessary, due to the presence of the aggregate. Both of these factors are functions of the diameter; the radius of curvature is one-half the diameter if we assume that aggregate of spherical form is being used. Since particles of all sizes are mixed at random, and there is no systematic arrangement, it is impossible to analyze the problem in a way that will enable us to compute the number of points of contact. The only practical method, then, is to determine the relation by trial. The fineness-modulus method was arrived at in this way. It was discovered from a study of mortar strength tests of about 1,000 different sands mixed to a uniform plasticity, and stored and tested under uniform conditions.

The water formula given in our Bulletin No. 1 is of a rational form and can be applied to any combination of concrete materials. Its development was an evolution extending over several years. These formulas were numbered in the order of their derivation as they were modified from