time to time on the basis of experience. The above formula is No. 11. It is based on the experience of many thousand tests. I do not mean to be understood as believing that this formula is exact and will require no further modification. On the other hand, subsequent experience may dictate certain changes.

The formula has been subjected to many severe tests by applying it to aggregates of the most diverse character. A recent series of tests using four different coarse aggregates (graded No. 4 sieve to 1½ in.) and the same sand gave the following results (Table II.) for 1:4 mixes:—

TABLE II.—STRENGTH OF CONCRETE FROM FOUR AGGREGATES

Coarse Aggregate.	Compressive Strength (Pounds per Square Inch.)
Pebbles	3,620
Crushed limestone	3,830
Crushed slag	3,750
Crushed granite	3,850

Tests were made on 6 by 12-in. cylinders at the age of three months. Twenty-one different gradings were used for each coarse aggregate. Specimens were stored under two conditions. Each value given above is the average of 105 tests. The water for these concretes was proportioned by the formula given above. The fact that with similar gradings and water properly controlled we secure uniform plasticity and strength is a severe test of the formula, when it is considered that we are comparing spherical and crushed materials of widely different characteristics. The absorption of the aggregate was also different in each case. Many serious errors have been made by experimenters in comparing the concrete-making qualities of different aggregates. The wide variations reported in the strength of the concrete made from different materials can almost invariably be traced to failure to take account of differences in size or grading, and to neglect of the absorption of aggregates.

Due to Different Cause

The sand-mortar tests in Captain Edwards' paper, which were mixed with 1 volume of cement for each 13 sq. ins. of calculated surface area of the sand, gave mortars of fairly uniform strengths at three different ages. These tests are interpreted as proving that the surface area of the aggregate is a proper basis for proportioning mortar and concrete mixtures. It is the writer's view that the uniformity in strength is due to an entirely different cause. Since both the water and cement were proportioned on the basis of the surface area of the aggregates, he obtained a uniform water-ratio, which is solely responsible for the uniform strength. This is the result to be expected so long as all of the mixtures were plastic and none of the aggregate gradings was too coarse for the quantity of cement used.

Tests Do Not Check

It is unfortunate that it was not feasible to include in our Bulletin No. 1 all of the data on which the conclusions were based. It is the writer's belief, however, that the tests given in Table 2 of the bulletin bring out a fatal limitation of the surface-area method of dealing with proportioning of aggregates. Twenty-seven different gradings of the same aggregate were used. The gradings were made to vary over a wide range, but had one property in common; that is, the fineness modulus was uniform. They were mixed with the same proportions of cement and water. The strengths for two different consistencies showed a mean variation from the average of about 3%, and a maximum variation from the average of about 10%. The corresponding values for surface areas are 43% and 110% respectively. If the water proportioning of these tests had been based on Captain Edwards' formula the water-ratios of the concrete would range from 0.39 to 0.57, an extreme variation of 69%, and would have made a great difference in the plasticity of the concrete. It is true that these tests were made with a view to determining whether or not a uniform strength of concrete was obtained with such wide variations in the sieve analysis of the aggregates. However, the plasticity or workability of the concrete did not differ materially.

The surface-area values in our table were calculated from the diagrams given in Captain Edwards' paper. It was necessary to estimate the areas of the sand particles below the 100-mesh sieve, and wide variations may be due to this cause. In certain of the tests as much as 10% of the aggregate was sand finer than the 100-mesh sieve. The surface area of this portion which we must estimate or neglect entirely is probably considerably greater than the entire surface area of many other gradings in the same group. The quantities of water given by Captain Edwards' formula are only 60 to 70% of those required for the materials used in this laboratory. It was impossible to mix concrete using the water given by his formula.

Some Recent Tests

Table III. herewith gives the results from a portion of some recent tests in this laboratory. Two leaner and two richer groups of mixtures are omitted. The quantity of materials required for each specimen, beginning with the 0-1½ in. aggregate and a mix of 1:2½:5, 1:2:4, 1:1½:3, etc., was calculated. The coarser sizes of aggregate were dropped in turn, but we retained exactly the same quantity of cement and water. The final mixes in terms of volume of cement and total aggregate are given in Col. 2 of the table. It is obvious that the richer mixes in each group are much more plastic than the leaner ones, and that equal workability was not secured. As in all other tests in these investigations the concrete for each cylinder was mixed separately by hand. Each value is the average of five tests made on various days. The second series of tests is not yet completed; however, the tests which have been made show a greater uniformity in strength than those in Table III., due to slight readjustments of certain constants in the water formula. These tests confirm the conclusion based on many other series: Namely, that *the widest variations may be made in the mix, consistency, and size of aggregate without any change in strength so long as the water-ratio is unchanged* and the above limitations are not violated.

Which is Simpler, Sounder?

It seems to the writer that any comparison of the surface-area and fineness-modulus methods must be reduced to the following two factors: (1) Which rests on the more sound experimental basis? (2) Which is the more simple to apply?

As stated above, the whole question of the comparison between the two methods resolves itself into that of determining which will give the better distribution of water in a mix, so far as the size and grading of the aggregates are concerned. Both of these methods make use of the sieve analysis of the aggregate. However, it seems to the writer that there is more variation in the underlying principles than is suggested by Captain Edwards.

Surface Area Method's Disadvantages

It appears to the writer that the following disadvantages accompany the use of the surface-area method: (1) Areas of the finest particles of sand cannot be computed; (2) crushed aggregate requires a greater quantity of water for the same grading than pebbles of a spherical form; (3) if the surface-area method were strictly interpreted it would require separate treatment for practically each kind of aggregate; (4) the method requires laborious computation, with the resulting chance of error; (5) it is not clear how the method can be applied to the simplest problems which arise in the course of designing concrete mixtures; for instance, to determine the best proportions of given fine and coarse aggregates for a concrete mixture; (6) it has not been shown that there is any theoretical reason why the surface-area method gives more nearly correct results than other methods which have been proposed.

Applies to Limited Range

If the surface-area method is correct, it would seem to be a serious fault that the areas of the finest particles cannot be satisfactorily dealt with. It seems probable that in extreme cases the areas of the particles finer than the 100-mesh sieve would be in excess of the combined areas of