surface area, the amounts of cement used in proportioning can be stated in terms of this value equally as well as in terms of the actual surface area.

It seems reasonable to assume that the actual surface area in a cubic foot of particles of any particular size coming from a certain source, is the same as another cubic foot of similar sized particles from the same source; it being very probable that there would be equal numbers of each of the many possible shapes of particles present in both cases, and the studies referred to herein have confirmed this assumption.

Another source of criticism has been the fact that the cement is itself made up of minute particles which do not form a continuous unbroken covering for the aggregate but, like the aggregate, simply make contact with these particles and with one another. Consideration of this point led to the conclusion that with a uniform distribution of cement the number of cement particles in contact with any particle of aggregate is a function of the area of its surface, and hence this criticism offers no serious objection to the method.

The studies described above appear to offer conclusive evidence that the surface area method of proportioning is correct in principle. However, it was considered essential that its application to concrete be studied experimentally, and this work is now under way in the laboratories of the Hydro-Electric Power Commission of Ontario, under the direction of the writer. It is not possible to give any account of these experiments at the present time except to say that the results so far obtained bear out these theoretical deductions fully, and although the experiments are not yet completed, the results have been so encouraging that the method is being tried out in a practical way on a considerable scale upon several of the construction jobs of the Commission.

Tests Do Not Bear Out Surface Area Method?

Six Criticisms of Capt. Edwards' Theories—Areas of Finest Particles Cannot be Satisfactorily Dealt With—Separate Treatment for Each Aggregate—Laborious Computations Necessary—Not Clear How Method Can be Applied to Simplest Problems

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IN designing concrete mixtures, three elements must be kept in mind: (1) Workability; (2) strength, or other desirable property; and (3) cost. In usual circumstances, each of these three factors is an absolute limitation on the makeup of the concrete. If cost were no item, concrete of any desired strength and workability could be secured by using rich mixtures. In order to reduce the cost to a minimum, we use as much aggregate as feasible. The degree of workability required depends on the nature of the work and the methods used in handling and placing. The workability of concrete is one of its prime advantages and a certain degree of workability is absolutely essential. In order to reduce to a minimum the cost of handling and placing, a satisfactory degree of workability may be secured by using a little more water than is necessary, and an aggregate of somewhat greater fineness than that known to produce maximum strength of concrete. In designing concrete mixtures, the engineer must work out a nice balance between the strength, cost and workability in order to secure an economical building material.

Twofold Function of Water

It has been pointed out that the function of water in concrete is twofold: (1) To hydrate the cement; (2) to form a plastic mass.

The quantity of water required to hydrate the cement has not been definitely determined; it is probable that not more than 25 to 40% of the water in ordinary concrete is necessary for this purpose.

Tests made in this laboratory have shown that with given materials and conditions of test the quantity of mixing water used determines the strength of the concrete so long as the following conditions are observed: (1) Concrete is plastic with the method of placing used; (2) aggregate not too coarse for quantity of cement used; (3) mixture not so wet that all water cannot be held by the concrete.

Regardless of the size or grading of the aggregate, the amount of cement or the consistency of the concrete, the "water-ratio" may be used as a measure of the strength of the concrete. In other words, it makes no difference *why* the water-ratio is changed; the fact that it *is* changed within the limits stated above produces a definite result. Other properties of concrete, such as wearing resistance, modulus of elasticity, etc., have been found to follow similar laws.

Captain Edwards has not given sufficient weight to the fundamental relation between the water content and the strength of concrete. He states in his original paper that "the surface-area method of proportioning concrete assumes as its basic principle that the physical properties are primarily dependent upon the relation of volume of cementing material to the surface areas of the aggregates." It seems to me that the tests reported fail to bear out this assumption. On the other hand, many different series of tests made in this laboratory have shown that the quantity of cement is *not* a criterion of the strength of the concrete unless at the same time we take into account the quantity of water used. A 1: 9 mix may be as strong as a 1: 2 mix. In other words, it is the *ratio of water to cement* that determines the strength of the concrete. Table III. shows one way in which the quantity of cement may be varied 400 to 600% without producing any appreciable effect on strength so long as the water-ratio is constant. Much greater variations in cement content could have been made had it seemed desirable.

The "water formula" for concrete cannot be reduced to the simple form given by Captain Edwards, if it is to be of general application. The water formula given in Bulletin No. 1 takes account of the following six factors: (1) Relative consistency of concrete (workability factor); (2) normal consistency of cement; (3) the mix (volume of cement); (4) size and grading of aggregate (measured by the fineness modulus); (5) absorption of aggregate; (6) moisture contained in aggregate.

Another term is necessary when an admixture is used. The items, with the exception of (1) and (4) can be readily determined for given materials. The amount of water required under (1) will depend on the nature of the work, the method of placing the concrete, etc. Any method which will give a *proper* distribution of the water due to the size and grading of the aggregate should give satisfactory results. This Captain Edwards has endeavored to accomplish by means of the surface-area factor, while we have used the fineness modulus of the aggregate.

Where the Methods Differ

The fineness modulus is the sum of the percentages in the sieve analysis of the aggregate, divided by 100. Sieves from the Tyler standard screen scale are used. The percentages are expressed in terms of the quantity of aggregate by weight or volume *coarser* than each of the sieves. For a particle of a given size the surface area and the fineness modulus bear a direct relation to each other, since they are