The next step in the laboratory investigation is to determine for these materials the relation between cement content at normal consistency, water-cement ratio and compressive strength.

Using the combination of fine and coarse aggregate giving the grading already determined as most suitable, a series of tests are made in which the cement is proportioned according to the surface area of the aggregate. Water is added to give mixtures of the same mobility. Concrete test specimens are made from these mixtures and tested in compression. These tests establish the relation between compressive strength and cement content at the normal or test consistency, and between compressive strength and water-cement ratio for all consistencies, inasmuch as the relation between water-cement ratio and strength is independent of the consistency, and if established for one consistency, holds equally for all others. Typical results of such tests are given in Table 2. Figs. 3 and 4 are plotted from these data and are representative of a large number of curves obtained in similar manner.

In proportioning cement by surface area, the unit of measurement used is the "pound per 100 sq. ft." The number of different proportions in a series of tests depends upon circumstances. Where the work for which the tests are being carried out involves only a few thousand cubic yards of concrete, four sets of five specimens are made, proportioned 1.5, 2.0, 2.5 and 3.0 lbs. of cement per 100 sq. ft. of area, and tested at 28 days. Where the yardage is considerable, six sets of ten specimens, with a range of cement from 0.75 to 4.0 lbs. per 100 sq. ft. of area, are tested at both 28 and 90 days. Where the yardage is very large, even more extensive investigations are warranted. In any case, less than four sets are inadvisable, and more are always to be recommended.

TABLE 1—SURFACE AREA PER 100 LBS. FOR DIFFERENT SIZES OF SEPARATION OF SAND, GRAVEL AND CRUSHED STONE

Pass.	Sieve No. retained.	Sand and gravel, sq. ft. per 100 lbs.	Crushed stone, sq. ft. per 100 lbs.
2½	1½	23.6	36
1½	¾	42.7	62
¾	½	74.6	124
½	¼	130	163
¼	No. 6	255	
No. 6	" 10	437	
" 10	" 20	875	
" 20	" 35	1,744	
" 35	" 65	3,490	
" 65	" 150	6,975	

In proportioning water, the simplest way is for the operator to add the water until in his judgment the mixture is of the required mobility. With an experienced operator, this method can be made to yield satisfactory results, even with a wide range of cement ratios and differently graded aggregates.

In the work of the Hydro-Electric Power Commission, a formula is used for determining the correct amount of water required to bring a mixture to the proper mobility. This formula is based on a theory as yet only partially established, and its discussion is without the scope of this article. It is not general in its application, and its constants have to be determined for each different class of material. They are derived from the tests made when studying the relative mobility of the different combinations of aggregates. With this formula, mixtures have been obtained the mobility of which were so nearly equal that no difference could be detected by any means at our disposal.

Our concrete specifications provides for four classes of concrete, designated A, B, C and D. Class A concrete is required to be of such quality as to show a minimum compressive strength of 2,500 lbs. per sq. in. at the age of 28 days when tested in accordance with the Commission's standard methods of testing. Classes B, C and D are required to have minimum compressive strengths of 2,000, 1,500 and 1,000 lbs. per sq. in., respectively, under the same conditions. This form of specification has been adopted because it is considered more logical to specify the desired property of concrete, than to give a formula for the mixing of its ingredients.

In designing concrete mixtures to fulfil these specifications, it is customary to allow a margin of from 300 to 500 lbs. per sq. in., to take care of field conditions. A 300-lb. margin should be ample, however, if the operations of proportioning and placing are subject to careful inspection. Allowing a 300-lb. margin of safety, the ratio of cement to surface area which corresponds to each of the above classes of concrete would, in the case of the materials used in the tests of Fig. 3, be those shown in Table 3. These, however, hold only for concretes of the same plasticity as that used in the tests. As before noted, compressive strength depends on the water-cement ratio of the paste. From Fig. 3, therefore, is obtained the range of water-cement ratio which corresponds to both the minimum compressive strength specified for each class, and to that minimum compressive strength plus its margin of safety. The former is the maximum water-cement ratio allowable, and must never be exceeded if concrete of the proper quality is to be obtained. The latter is the water-cement ratio normally worked for. These minimum and normal water-cement ratios are likewise given in Table 3.

TABLE 2—RELATION BETWEEN CEMENT CONTENT, WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH

Cement, lbs. per 100 sq. ft.	0.75	1.5	2.0	2.5	3.0	4.0	5.0
Water-cement ratio	1.994	1.118	0.915	0.780	0.697	0.590	0.526
Compressive strength, lbs. per sq. in.	548	1,337	1,791	2,290	2,851	3,426	4,158

By means of these tests and investigations, all the data required for proportioning concrete mixtures are obtained. The next step is to apply these data to setting proportions in the field.

In the field the first step is to obtain the surface area per batch in order to proportion the cement. This requires a mechanical analysis of the different aggregates used, and a determination of their weight per cubic foot and if possible of their moisture content and of the proportions in which the different aggregates are to be combined in the mix.

The proportions for the different aggregates are worked out using as a basis the data obtained by the laboratory in the preliminary studies of the most economical mixture. The aim is to get the leanest concrete which is workable, gives a good surface, has the requisite density, and at the same time fulfils the requirements for water-cement ratio, and hence for strength.

TABLE 3—CEMENT RATIO AT NORMAL CONSISTENCY AND WATER-CEMENT RATIO CORRESPONDING TO CLASSES OF CONCRETE IN SPECIFICATIONS

Class.	Minimum specified compressive strength, lbs. per sq in.	Cement, lbs. per 100 sq. ft. surface area, normal consistency.	Range of water-cement ratio. Min.	Max.
A	2,500	3.18	0.68	0.74
B	2,000	2.58	0.78	0.86
C	1,500	2.08	0.91	1.04
D	1,000	1.48	1.14	1.37

Although the laboratory's preliminary studies are of great value in obtaining this, the final proportions should actually be set in the field, because to some extent they depend on the type of structure being built (whether mass or reinforced), on the amount and spacing of the reinforcing, on whether the sections are thick or thin, on the maximum size of stone used and the quantity of this maximum