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Lawrence C. Maugh

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A COMPARATIVE STUDY OF METHODS
OF
PROPORTIONING CONCRETE

A Thesis Submitted in Partial
Fulfilment of the Requirements for the
Master of Science Degree

^{Lawrence}
L.C. Maugh (B.S.)

May 1923

Introduction

A continual increase in the use of concrete as a building material has greatly increased the demand for more definite knowledge of the factors that are conducive to strength and economy of construction. It has been found necessary to acquire this knowledge largely through definite and extensive experimental work under conditions that can be carefully controlled and regulated. Although a considerable amount of experimental work upon the properties and proportioning of concrete has been performed in the last decade, the conflicting statements that have been made clearly indicate that this field of research and investigation is by no means complete. This condition is particularly true of the present methods of proportioning and placing concrete in the large structures that are now being built of reinforced-concrete instead of wood or steel. Many results have been obtained, however, that are worthy of more investigation and that deserve more careful study. It is these general and sometimes indefinite conclusions that have been taken as a basis for further study.

The investigation has been conducted in two main parts:

A. Study of Aggregates.

1. Volume of Combined Aggregate.
2. Use of Colorimetric Test.
3. Sieve Analysis and Calculation of Surface Area.

4. Determination of the amount of voids and variation in the amount of sand in bank run gravel.

5. Fineness Modulus.

B. Methods of Proportioning.

1. Void Measurement.

2. Maximum Density or Ideal Curve.

3. Surface Area.

4. Fineness Modulus.

5. Iowa State Highway Commission.

C. Discussion of the Various Methods.

D. Conclusion.

Study of Aggregate

Volume of Combined Fine and Coarse Aggregate.

This test gives the relation of the sum of fine and coarse aggregate to the combined volume. The material consisted of bank-run gravel which was separated into fine and coarse aggregate by a U.S. St'd $\frac{1}{4}$ " sieve. The two aggregates were then mixed in different proportions and their combined volume measured. The gravel was kept in a dry condition through-out the work. Measurements were made in a box of 216 Cubic inches capacity. The maximum size of stone was $1\frac{1}{2}$ inches.

Table I

Proportion	Fine Aggregate	Coarse Aggregate	Combined Aggregate	Unit Vol.	Mix.
1:2:4	54	108	135	5.0	1:5.2
	54	108	140	5.2	
	54	108	144	5.3	
	54	108	144	5.3	
1:2:3	54	81	117	4.3	1:4.5
	54	81	121	4.5	
	54	81	121	4.5	
	54	81	121	4.5	
1:1 $\frac{1}{2}$:3	40	81	112	4.2	1:4.0
	40	81	104	3.8	
	40	81	104	3.8	
	40	81	108	4.0	
1:1:3	27	81	99	3.7	1:3.75
	27	81	99	3.7	
	27	81	103	3.8	
	27	81	103	3.8	
1:1:2	27	54	68	2.5	1:2.7
	27	54	72	2.7	
	27	54	72	2.7	
	27	54	72	2.7	
1:1:1	54	54	90	1.7	1:1.8
	54	54	99	1.8	
	54	54	99	1.8	

Data (continued)

Proportion	Fine Agg.	Coarse Agg.	Combined Agg.	Unit Vol.	Mix
1:2:5	54	135	162	6.0	1:6.2
	54	135	167	6.18	
	54	135	171	6.34	
	54	135	171	6.34	
1:2:7	36	126	144	8.0	1:8.0
	36	126	144	8.0	
	36	126	144	8.0	
1:3:6	54	108	149	8.2	1:8.2
	54	108	149	8.2	
1:4:8	72	144	189	10.5	1:10.5
	72	144	189	10.5	

The results that are given above can probably best be seen by means of the following diagram. The mean value of each proportion was plotted by using the sum of the unit volumes of aggregate as abscissa and the measured volume as ordinate. It can readily be seen that these points lie close to a straight line passing through the origin. A mean value for any proportion can thus be obtained from the equation for the line which is $Y = 0.89 X$.

This result can be very conveniently used in determining the amount of fine and coarse aggregate to combine to produce any desired mix; or, the opposite, the equivalent mix can be determined for any given proportion. Thus, if the mix should be 1:6, the sum of the volumes of fine and coarse aggregates must total $\frac{6}{0.89}$ or 6.75 volumes. If, on the contrary, a proportion of 1:2:4 is stated, then the equivalent mix is 6×0.89 or 1:5.3. This equivalent mix must often be used in the present methods for proportioning concrete.

The constant 0.89 will vary slightly as the grad-
 uation of the particles is changed, but with a specified
 gravel and with two sizes of aggregates any difference
 from this cause or from changing the proportion is re-
 latively small. A different gravel is not likely to pro-
 duce any large change but if necessary the factor can
 be determined for one proportion and then used for others
 although preferably with those in which the amount of
 coarse aggregate is from $1\frac{1}{2}$ to 3 times the amount of fine
 aggregate. The relation can be clearly seen from the graph.

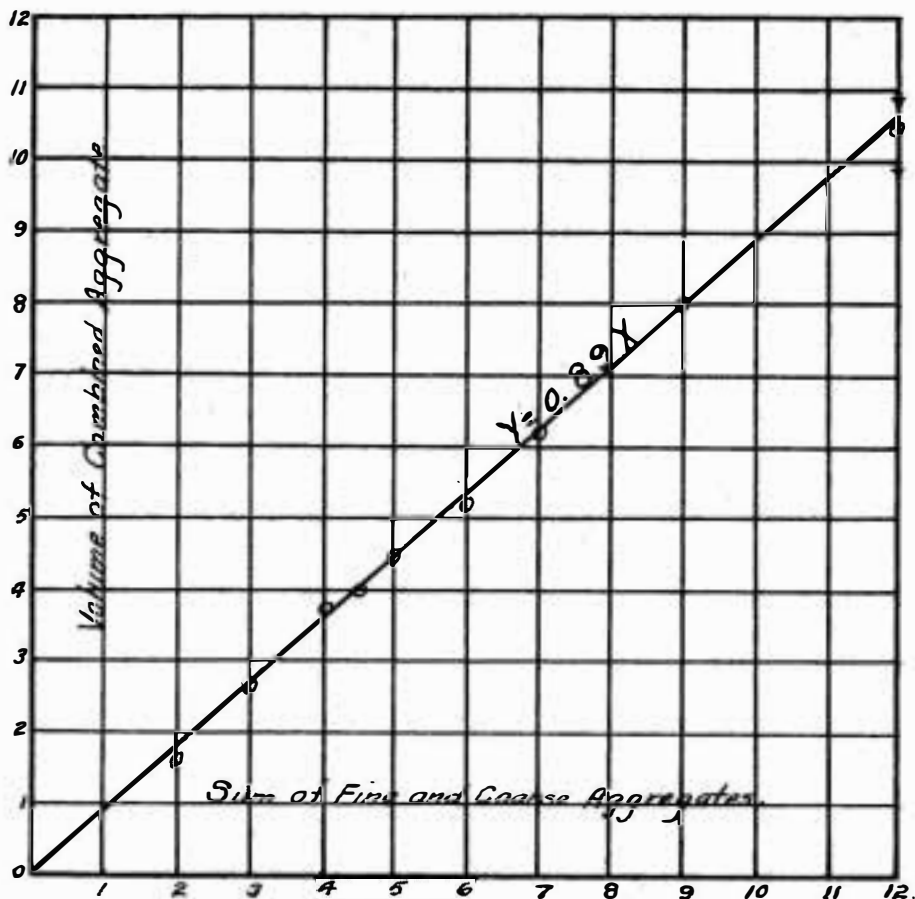


FIG.1. Relation of the Sum of the Volumes of Fine
 and Coarse Aggregate to the Combined Volume.

Use of Colorimetric Test.

Several samples of the sand were mixed with a three per cent solution of sodium hydroxide to test for the presence of any organic impurities. The color that was obtained was equivalent to Plate 2 of the color scale that was adopted by Prof. D. A. Abrams. This color is considered satisfactory from the standpoint of organic impurities.

It has been shown, however, that too much confidence is often placed in this test. Many sands have given normal strength or above, although condemned by the colorimetric test, while others that were considered satisfactory have often contained deleterious mineral material.

Actual tests of 160 normally graded sands were made by C.E. Proudley for the U. S. Bureau of Standards, to determine the reliability of the color test as a means of preventing the use of dangerous sand as a fine aggregate for concrete. The results of this test were recorded in the Engineering News-Record for Oct. 12, 1922, some of which will be briefly stated here.

It was found that differences in the character of the organic substances is very difficult to determine by the color test and that all organic substances do not have the same effect on sand mortars. Out of 77 sands that were considered unsafe from the color test (Plate 3 or below), 53 or 69% gave a strength ratio above normal at 7 days, while from 83 sands that gave a satisfactory color, 8 or about 10% gave a strength ratio

below normal. This result shows that good sands are often rejected by this test.

The presence of objectional mineral material, no doubt accounts for some of the low strength, regardless of the organic substance. About 56% of those sands below normal contained objectional material different from organic. As these sands were of the ordinary type, this result would indicate that a false sense of security may be formed from the color test. In general, over confidence should be avoided, while mechanical analysis and tests should also be used. The color test can frequently be used to determine an extreme change in the material either at the job or at the source of supply.

Sieve Analysis and Calculations of Surface Area.

The gravel, which was obtained from a local supply, was screened through a set of standard sieves that varied in size from $1\frac{1}{2}$ " to #100. All of the screening was done by hand and the amount that was retained on each sieve was weighted on a balance scale to the nearest gram. The percent of the material by weight passing each sieve was then obtained from these values.

The surface area was obtained by counting the number of grains per gram of material between the various sizes of sieves and then by substituting this quantity in the formula $S.A = 236.1 (n/s^2)^{1/3}$. In this formula (n) is the number of grains per gram of material, (s) is the specific gravity, and S.A is the surface area in square feet per 100 lbs. of the

particles between the sieves that were used. This value can be readily changed to surface area per 100 lbs. of aggregate by multiplying it by the per cent of material contained in the aggregate.

An average value of 2.65 was taken for the specific gravity of the gravel used in this analysis.

The above formula is given by R. B. Young in Engineering and Contracting, for July 27, 1921, and is readily derived by considering each particle as a perfect sphere.

$$\text{Volume of sphere} = \frac{4}{3}\pi r^3$$

$$\text{Surface of sphere} = 4\pi r^2$$

n = number of grains per gram.

45,454 n = number of grains per 100 lbs.

s = specific gravity of material

$$\text{or } 45,454 \frac{n \left(\frac{4}{3}\pi r^3 \right)}{1728} = \frac{100}{62.5s}$$

$$r = 0.05951 \left(\frac{1}{n^{\frac{2}{3}} s^{\frac{2}{3}}} \right)^{\frac{1}{3}}$$

$$\begin{aligned} \text{S.A.} &= 45,454 \frac{n \left(\frac{4\pi r^2}{144} \right)}{144} = \frac{(45,454)}{144} (4\pi) \cdot n \left(\frac{1}{n^{\frac{2}{3}} s^{\frac{2}{3}}} \right)^{\frac{2}{3}} (0.05951) \\ &= 236.1 \left(\frac{n}{s^{\frac{2}{3}}} \right)^{\frac{2}{3}} \text{ Q.E.D.} \end{aligned}$$

The following data is the average of several trials, the surface area being taken twice.

Table 2.

Mesh.	Per Cent	n	Passing	Retained	Surface Area	Sq. Ft. per 100#	Material Aggregate.
1½"	100						
1"	87.2	0.044	P.1½"	R 1"	12.8%	43.6	5.6
¾"	79.8	0.072	P 1"	R ¾"	7.4%	51.4	3.8
½"	76.5	0.204	P ¾"	R ½"	3.3%	72.7	2.4
⅜"	68.7	0.706	P ½"	R ⅜"	7.8%	110	8.6
¼"	62.1	2.000	P ⅜"	R ¼"	6.6%	156	10.3
#10	46.7	27.00	P ¼"	R#10	15.4%	370	57
#20	28.2	350.0	P#10	R#20	18.5%	870	161
#30	11.8	2650.	P# 20	R#30	16.4%	1700	280
#40	5.9	6500	P#30	R#40	5.9%	2300	136
#60	2.2	omitted	P#40	R#60	3.7%		180
#80	1.5	"	P#60	R#60	0.7%		40
#100	1.0	"	<u>P#80</u>	<u>R#100</u>	<u>0.5%</u>		

Total S.A. per 100 lbs aggregate 885 sq. ft.

The last two values for the surface area were interpolated from the diagrams given in Vol. 2 of "Concrete Work" by Hatt and Voss, after it was found that the other values checked very closely.

The results of the sieve analysis are shown by the curve for bank-run gravel in Fig. 2, which is formed by plotting the per cent passing as ordinate and the diameter of the particle as abscissa. This curve can be compared to the one for best grading which was obtained from the experiments of W.B. Fuller for maximum density of concrete. It can easily be seen that there is an excess of sand as is commonly found in bank-run gravel.

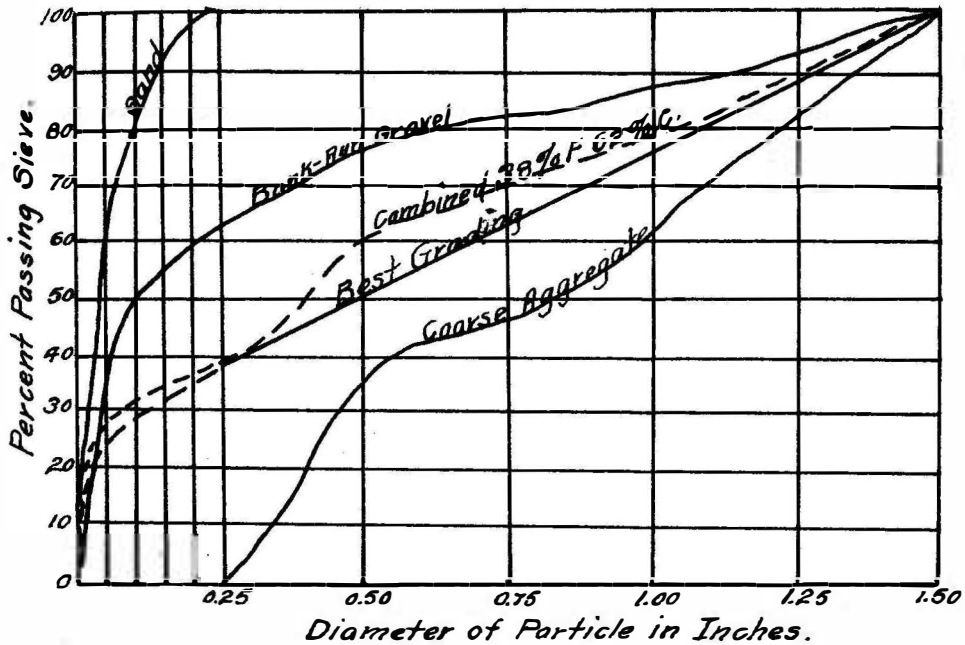


Fig. 2. Mechanical Analysis Curve
and
Ideal Curve

The calculation of surface area was made for 100 lbs. of aggregate as has been explained. Since this amount is a function of only one variable for any particular gravel, that is, the per cent of material between each size of sieves, the variation of the surface area with the grading can be shown graphically by means of the diagrams in Fig. 3, which give the relation for each size of sieve that is desired.

For any change of grading, the surface area can be determined from the diagrams without further computations. If a different gravel is used, the surface area will change with the number of ⁱⁿgrams per gram, but the difference will not ordinarily be very large. It might be desired to make at least two calculations, for example, between $\frac{3}{4}$ and $\frac{1}{2}$, and $\frac{1}{2}$ and $\frac{3}{8}$, from which any difference could be noted.

Unless there was a large difference from the results given, the remainder of the value could be taken from the diagrams given by applying a correction.

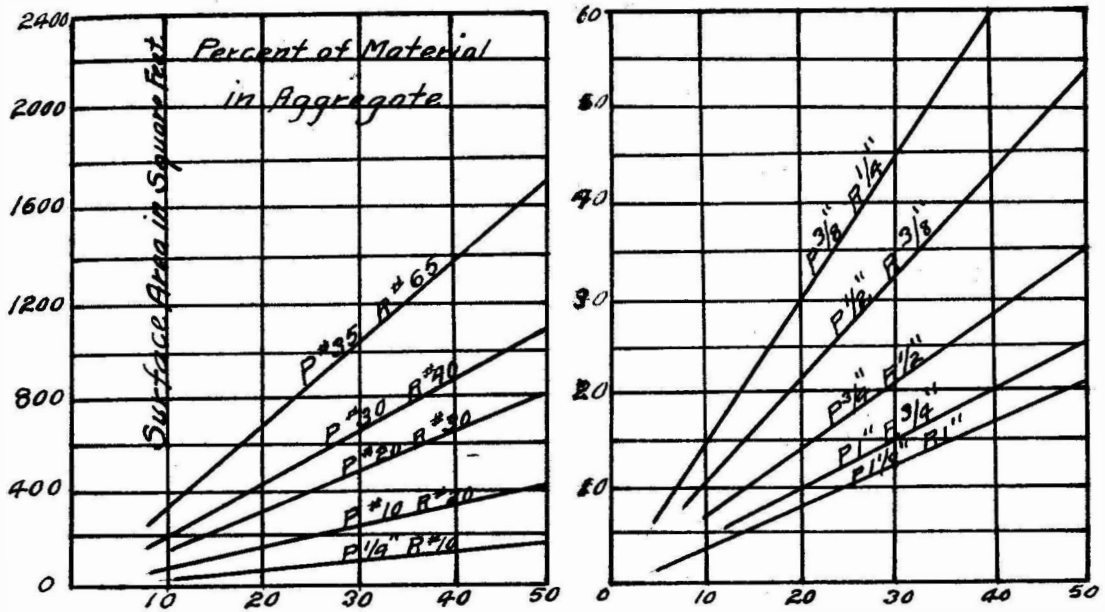


FIG.3. Relation Between the Per Cent of each Grading and the Surface Area.

Determination of the amount of voids and variation in the amount of sand in Bank-run gravel.

Four samples of the gravel were selected from different parts of the pit in order to secure average results. The volume and weight of both fine and coarse aggregate was obtained for all samples. The gravel was kept in a dry condition through-out the work. The per cent of voids was determined from the data by considering the weight of a cubic foot of the solid material to be 165 pounds.

$$\text{Per cent of Voids} = \frac{165 - \text{Wt. of Aggregate}}{165}$$

Table 3.

Sample	Volume in Cu.In.			Weight in Pounds			%Voids		%Sand	
	Total	Fine	Coarse	Total	Fine	Coarse	Fine	Coarse	Vol.	Wt.
1	216	162	72	14.0	9.25	4.75	40	31	69	66
2	216	151	86	13.8	8.8	5.00	39	39	64	64
3	216	166	76	13.8	9.5	4.3	40	40	69	69
4	216	162	86	13.9	9.0	4.9	41	40	65	65
<hr/>										
Aver.	216	160	80	13.9	9.1	4.7	40	38	67	66
Max. Var.		9	8	0.1	0.4	0.4	1	7	3	3
Weight per cubic foot Gravel 110 lbs. Fine 99 lbs. Coarse 133										

These values, although somewhat inaccurate because of the small quantities that were measured, are fairly representative of the results that may be expected from any bank-run gravel. The amount of sand and voids varies throughout the pit as well as in different localities.

This variation is not so important for work in which the gravel is separated into fine and coarse aggregate, but in some work where the gravel is used without separation, such changes must often be considered if a uniform concrete is to be maintained. Any increase in the sand content will necessitate a corresponding increase in the cement content, otherwise a weaker concrete will result. The relation of these constituents to each other will be noted in the method of the Iowa State Highway Commission for proportioning concrete from bank-run gravel. Unless the cement is increased with the sand, a larger quantity of water must be used to give

the same consistency, which, combined with the weaker mortar that is formed, is undoubtedly the most important factors in reducing the strength of the concrete.

Fineness Modulus

The term Fineness Modulus has been used by D.A. Abrams to measure the granulometric composition of the aggregate and to represent the method of proportioning concrete by the use of it. It is defined as the sum of the percentages coarser than a given sieve, as found by the sieve analysis, divided by 100. The sieves that are used in the analysis are the Tyler Standard sieves which have the clear opening of each just double that of the preceding one.

A number of samples of the gravel were tested to secure an average value, from which the two results that are recorded in Table 4 were selected as most representative of the entire material. The Fineness Modulus of both fine and coarse aggregate is given, as well as for the gravel. An amount of 2000 grams was used in each sample, while the amount that was retained on each sieve was determined to the nearest gram on a balance scale. From these values, the per cent coarser than each sieve was computed.

Table 4

Sieve	Size of Square Opening	Am't Retained 1	Am't Retained 2	Percent Fine	Percent of Sample Coarse	Coarser Gravel
1½"	1.50	0	0	0	0	0
¾"	0.75	380	402	0	45	20
3/8"	0.37	232	270	0	74	32
4-Mesh	0.135	195	262	0	100	44
8- "	0.093	238	234	21	100	56
14- "	0.046	275	270	46	100	70
28- "	0.0232	350	306	75	100	86
46- "	0.0116	240	187	98	100	97
100- "	0.0058	50	36	98		98
Residue		20	17			

Fineness Modulus

3.35

7.19

5.03

The different values of the Fineness Modulus show that both fine and coarse aggregate are sufficiently well-graded to form a good concrete aggregate when combined in a better proportion than exists in the natural state. The Fineness Modulus indicates again the presence of too much sand, since its value should be as large as possible and still give workable concrete.

Proportioning Materials for Concrete.

After the aggregate has given satisfactory results in the preceding tests, the next problem is to combine the stone, sand, cement and water in such proportions that the desired physical properties will be obtained with the greatest economy possible. The physical properties that are required will vary somewhat with different types of work; for example, strength, resistance to wear, impermeability, and resistance to acids or alkalis may be desired in various structures. Since the factors affecting the strength, abrasion, and water tightness of concrete are practically the same,

the methods of proportioning that will be considered will take the necessary strength as the objective. The requirements that should govern the proportioning of concrete can thus be stated in a general way as:

- (1) A Strength equal to that used in the design.
- (2) A consistency that will give workable concrete for the specified work.
- (3) A proportion of all ingredients such that the above properties are secured at a minimum cost.

The criterion for good proportions may thus be summarized in the three terms: Strength; Workability; Cost.

Strength is a factor that must be considered as a constant quantity regardless of the methods that are employed to secure it. As a result of many experiments that have been made it would seem as yet that the required strength can only be assured when actual tests are made upon samples of the concrete that is intended to be used. A knowledge of the principles that govern the strength of the concrete will, however, greatly facilitate in making such a concrete without excessive delay or expense.

The workability, or the ease with which the concrete can be placed in the forms, is a somewhat variable factor that can ordinarily be decided by a careful study and investigation of the cost. If more water is added, the cement must also be increased so as to keep the ratio of the two ingredients constant since this has been proved to be a necessary condition for maintaining a constant strength. This will usually mean an increase

in the cost as the cement is an important item. If the quantity of water be diminished, the cost of placing the concrete will be increased. The amount of water must, therefore, be adjusted to give the necessary results at a minimum cost.

The factors involved in any consideration of the cost are so complex and interwoven that no discussion will now be given. The cement is very frequently the most expensive ingredient in concrete, so that any reduction of the quantity may greatly lower the cost. Some suggestion of the problem that is involved is given in the preceding paragraph although this is but one phase of the subject. The scope of this important subject would require an investigation of the mix, cement, workability,^{and} reliability as well as questions concerning the selection of materials.

The various methods that have been used to proportion concrete often conflict with these requisites or else ignore them. The more recent methods, however, include other factors than strength alone. The most important of the methods may be classified as follows:

- (1) Void Measurement.
- (2) Maximum Density.
- (3) Surface Area.
- (4) Fineness Modulus.
- (5) Iowa State Highway Commission.

The results that have already been given of the laboratory study of the aggregate will be used as the

basis of proportioning the gravel by the different methods.

Proportioning by Void Measurement.

The theory upon which this method is based, is that the best concrete can be made from two aggregates when the sand will just fill the voids in the stone, and the cement will fill the voids in the sand. If this condition could be realized, a strong concrete would likely be formed, but in practice, much of the fine material is too large to fill the voids of the coarse, so that maximum density is not obtained. The necessary additions of cement and water bring about conditions that materially change the results that would be expected. The cement is usually proportioned arbitrarily to give a certain mix, as 1:6, rather than to fill the voids in the sand.

The voids in the gravel that was tested was found to be 40% for the sand and 38% for the coarse aggregate. The ratio of fine to coarse would then be 38:100, in order to fill all the voids in the coarse material.

If a mix of 1:6 is required, the sum of the fine and coarse aggregate must equal 6 divided by 0.89 or 6.75 unit volumes. In order to combine them in the ratio given above, the amount of each must be:

Fine-1.85 Coarse-4.9

The resulting proportion would then be 1:1.85:4.9 by volume, or 1:1.95:5.36 by weight.

The correctness of this proportion from the consideration of strength and workability must be verified

by tests upon concrete with this proportion, before it can be finally accepted. From the experiments and tests that have been performed upon this method, it has been found that the amount of sand is almost invariably too small to give maximum density. The principal reasons for this are based on the fact that the particles of stone are thrust apart by the grains of sand, and that much of the sand is too coarse to enter the voids in the stone.

The amount of sand must, therefore, be increased by an assumed quantity that can only be estimated by experience. Thus, it can easily be seen, that it would be nearly as accurate to assume the proportions at the beginning as is done by arbitrary selection.

Proportioning by Maximum Density.

Although the principle of maximum density has been generally accepted for several years, it has recently been criticized and contradicted by a few authorities. The original tests, however, were so complete and elaborate, that much weight must be given them in spite of the more recent results. The proof of this theory is based chiefly upon the results of extensive tests that were made by Mr. W. B. Fuller, and which was stated by him in the following terms, "With the same percentage of cement, the densest mixture, irrespective of the relative proportions of the sand and stone, was in general the strongest." It was, also, claimed that this mixture worked most smoothly in placing.

To make this principle a basis for proportioning materials for concrete, some means must be found that will give a proportion such that, when the cement and water is added, a mixture of maximum density is formed. There has been two methods used to secure this result: Volumetric synthesis, or method of trial mixtures; and, by use of the Ideal Curve.

The first of these methods is very simple in application, and can be performed on the job. It consists in mixing the ingredients in different proportions, in tamping them into a pipe or cylinder, and then, in noting the relative height of each batch in the cylinder. Each trial can be used as a guide to the next, so that a proportion can soon be found that will give a minimum height in the cylinder. This mixture will have maximum density. Care must be taken to use the same consistency for each trial mixture as is intended to be used in the work.

In the experiments performed by Mr. Fuller, it was found that, for proportions giving maximum density, the percentages of the mixed aggregate passing different sizes of sieves follow a curve that is a combination of an ellipse and a straight line. This curve is known as the ideal curve, or, the curve of the best grading, and can be drawn for any combination of materials, as; sand and gravel, broken stone and screenings, or sand and broken stone. If the mechanical analysis curves of the aggregates are given, the problem is to recombine the two materials so that the com-

bined curve of the mixture will follow the ideal curve as closely as possible.

The mechanical analysis curves and the curve of best grading for this particular gravel are shown on page 10. When only two sizes of aggregates are used, that are difficult to combine so as to approximate the curve, the experiments showed that the best results can be secured when the combined curve coincides with the ideal curve at the 40% point. In order to do this, 38% of the sand must be combined with 62% of the coarse aggregate, which at this particular point (40) on the ideal curve would give a combined proportion of 38 and 62% times 4 or 40.5%, which is close enough for practical purposes. The best proportion by weight is then, 38% Fine, and 62% coarse. The cement is considered as part of the fine aggregate, and the quantity must be assumed before the exact proportions can be stated.

Thus, if a 1:6 mix is desired, the cement would be $14 \frac{1}{2}\%$ of the total, which must be subtracted from the per cent of fine material in order to get the amount of sand. The proportion would then be;

$$14 \frac{1}{2} : 23 \frac{1}{2} : 62$$

$$1 : 1 \frac{2}{3} : 4 \frac{1}{4} \text{ by weight}$$

Using the weights given on page 12, the proportions by volume would be;

$$\underline{1} : \underline{1 \frac{1}{2}} : \underline{4.0} \text{ by volume}$$

If a 1:7 mix is taken, the amount of cement is $12 \frac{1}{2}\%$ of the total, and the proportions would be;

$$12 \frac{1}{2} : 25 \frac{1}{2} : 62$$

$$\text{or, } 1 : 2 : 5 \text{ by weight}$$

$$\text{and, } 1 : 2 : 4 \frac{1}{2} \text{ by volume}$$

Proportioning by Surface Area.

The relation that exists between the amount of cement, surface area and the compressive strength of the concrete may be expressed in a general rule, as first stated by Mr. Edwards, that the compressive strength of concrete varies directly with the ratio of cement to surface area. This statement has been corroborated by the tests of the Hydro-Electric Power Commission of Ontario, who have formulated a table of values for the ratio of cement to surface area for certain values of the compressive strength. This ratio can be very conveniently expressed in terms of pounds of cement to 100 square feet of surface area. Thus, for any aggregate, the strongest concrete will be secured with this material by using the largest ratio possible under the given conditions. The value of the ratio can be increased either by increasing the amount of cement or by decreasing the surface area. The latter method, however, will ordinarily be found the most economical.

The method of calculating the surface area has already been given on the preceding pages, so that the values that were obtained there will be used to find a proportion from the above principle with out further explanation.

The surface area for 100 lbs. of the fine aggregate is:

$$(854) \quad (100/62.1) = 1375 \text{ sq. ft.}$$

For 100 lbs. of coarse aggregate, the value is:

$$(31) \quad (100/37.9) = 82 \text{ sq. ft.}$$

From these values, it is obvious that the largest possible amount of the coarse aggregate should be used if the surface area is to be a minimum. If an excess of stone is used, however, the concrete will work harshly and visible voids are likely to form. On the other hand, an excess of fine aggregate will greatly increase the amount and cost of the cement to produce a concrete of required strength. The best proportion of fine and coarse aggregate should be determined from tests of various mixtures in which the density, consistency and quantity of cement is recorded for each. This proportion may be changed in the field, if necessary, as conditions there are somewhat different from those that exist in most laboratories.

Since it was not found possible to conduct these tests in this work, a method involving the maximum density of the concrete was substituted. A mixture coarser than that giving maximum density is usually found most economical and will also give the greatest strength.

It can be considered conservative to use the mixture that will give maximum density, as determined from the ideal curve, and to proportion the cement according to the desired strength. This method will be used to determine the proportion of cement, fine and coarse aggregate necessary to make a 2500 lbs. per sq. in. concrete from the gravel that was tested. The proportions of aggregate were 38% Fine and 62% Coarse, but it should be remembered that the per cent of cement is contained in the fine material. The amount of cement required for 2500 lbs. concrete will be taken at 3.18 lbs. per 100

square feet of surface area.

Assume 12% of cement, which leaves 25% of sand, or the ratio is 12:25:62.

$$(0.25) (1375) = 359 \text{ sq. ft.}$$

$$(0.62) (82) = \underline{51} \text{ " "}$$

$$\text{Total} = 410 \text{ " "}$$

Cement required equals,

(4.10) (3.18) = 13 lbs. of cement, which shows that the assumed amount was not correct.

Using the above computations as a guide, assume the amount of cement at 12.7% which leaves 25.3% sand.

$$(0.253) (1375) = 348 \text{ sq. ft.}$$

$$(0.62) (82) = \underline{51} \text{ " "}$$

$$\text{Total} = 399 \text{ " "}$$

Cement required is,

(3.99) (3.18) = 12.7 lbs. which is the amount assumed.

The correct proportions for the concrete with strength of 2500 lbs. per square inch is then:

$$12.7 : 25.3 : 62$$

$$\text{or } 1 : 2 : 5 \text{ by weight}$$

$$\text{and } 1 : 2 : 4\frac{1}{2} \text{ by Volume.}$$

This proportion will not give the strength of 2500 lbs. per sq. in. as assumed unless the same ratio of water to cement is taken as was used in making the preliminary tests. The amount is given in the same table in Hatt and Voss, "Concrete Work" Vol. 2, from which the quantity of cement was obtained. This table shows the water-cement ratio to be about 0.74 or 5½ gallons of water to a bag of cement. If this quantity of

water does not give a consistency that is adapted to the work, both water and cement must be changed so as to keep the ratio constant. This change allows for variation in the work without increasing the difficulty of placing the concrete.

Proportioning by Fineness Modulus.

Only in the preceding method has the amount of water been regarded as a factor affecting the strength of the concrete. The importance of this ingredient was firmly established by the extensive tests of Professor Abrams in which it was proved that the compressive strength is a function of the water-cement ratio which has already been defined as the ratio of the volume of the water to the volume of cement. The results of these tests were expressed graphically by a curve from which the value of the water-cement ratio can be obtained for the desired value of compressive strength. We have already seen that there is another requirement that also depends upon the amount of water-viz; workability. Since the water-cement ratio must be constant, the last factor, cost, requires that the amount of cement, and, therefore the amount of water, be a minimum.

This problem of securing a workable concrete of definite strength by the use of a minimum quantity of water requires a study of the factors that affect the consistency of concrete when a definite amount of water is used.

These factors may be stated as:

1. The mix, or cement content.
2. The size or grading of the aggregate.

3. The absorption of the aggregate.

4. The contained water in the aggregate.

A rich mix, or a mixture that has a large cement content can be mixed with a lower water-ratio than a lean mix. An increase in the amount of cement would, therefore, give a higher consistency, if the other factors remained the same, without a decrease in the strength. This method is usually most expensive as the cost of the cement is large.

The size and grading of the aggregate can best be expressed in terms of the fineness modulus. Tests have shown that to produce a concrete of the same consistency and strength, less water is required with an aggregate of large fineness modulus than with one that has a low value. Thus, a coarse gradation of material is one means of securing a low water-cement ratio with a minimum amount of water. Many different combinations of sizes of particles can be used to give a particular value for the fineness modulus.

If the aggregate absorbs much water, or if it contains a considerable amount in the natural state, allowance should be made for these conditions when the water is added.

The application of these principles to the proportioning of concrete will now be made in a specific example, by means of the data that is given in Table 4, and by means of the tables and diagrams that are given in Bulletin I, of the Lewis Institute.

The fineness modulus of the fine aggregate was

found to be 3.35 and of the coarse aggregate 7.19. For a 2500 lbs. per square inch concrete, the value of the water-cement ratio is given in Bulletin I, Fig. 1, as about 0.80. We have already seen that this ratio requires a minimum amount of water if the quantity of cement is to be kept a minimum. This condition requires the use of a large fineness modulus for the final mix and of the lowest possible consistency.

The maximum size of aggregate will be taken at $1\frac{1}{2}$ " since 20% is coarser than the $\frac{3}{4}$ " sieve. From Table 3, Bulletin I, the maximum permissible value for the fineness modulus of an aggregate with a maximum size of $1\frac{1}{2}$ " and a mix of 1-5 is 5.80. Since a gravel aggregate is to be used in ordinary reinforced concrete construction, this value will be used without a correction.

The per cent of fine aggregate is:

$$P = 100 \frac{7.19-5.80}{7.19-3.35} = 36\%$$

The proportion necessary to produce a fineness modulus of 5.80 is:

Fine 36%, Coarse 64%

The total amount of fine and coarse aggregate necessary for a 1-5 mix will be $\frac{5}{0.89} = 5.6$ Unit Volumes

The proportion would then be:

1:2.02:3.58 or practically

1:2 : 3 $\frac{1}{2}$

A consistency of 1.2 will be assumed which is equivalent to a slump of 5 or 6 inches with the cone test. The strength of the concrete can now be determined from Fig. 6, Bulletin 1, by placing a straight edge on the two points that indicates a 1-5 mix and a

fineness modulus of 5.80. A horizontal line is then drawn from the point at which the straight edge intersects the reference axis to the vertical line that represents a consistency of 1.2. The strength is found to be 2400 lbs. per square inch. Since this diagram is based upon laboratory tests, however, some allowance should be made for the inaccuracy of field work. It would probably be conservative to assume a strength of 2000 lbs./sq. in. instead of the above value.

After some work has been done on the job, it is often found possible to use a lower consistency than has been assumed in the design. In this particular case, a value of 1.10 with a strength of 2800 lbs/sq.in. might be used in certain parts of the work. The importance of using a low consistency is obvious, as in addition of 10% more water reduces the strength of the concrete 400 lbs./sq.in. or about 14%.

With a fineness modulus of 5.80 and a mix of 1-5, about $7\frac{1}{2}$ gallons of water per sack of cement are required to give a consistency of 1.2, and about 6.8 gallons for a consistency of 1.10. These values were taken from Table 5, Bul. 1.

It is interesting to note here, the method of proportioning that has been developed by the Hydro-Electric Power Commission of Ontario. In their study for a practical method for proportioning concrete, they found neither the fineness modulus nor the surface area methods satisfactory, but they now use a combination of the two methods as the best means of fulfilling the fundamental

requirements for good concrete.

The relation of the Cement-Surface Area ratio to the compressive strength is taken as a means for obtaining the required strength. Tests are made to determine this relation for each class of concrete and for normal consistency. If this consistency does not give workable concrete, more water is added while the cement must also be increased so as to keep the ratio constant. Experiments are, also, made to determine the relation between water and cement content which gives a means of calculating the amount of cement and water necessary for a desired workability.

After this data has been obtained, it is used in stating the amount of cement and water that is necessary for some assumed proportion of aggregate. This proportion is usually made as coarse as possible but should be based upon mechanical analysis, experience, and field conditions. Strict supervision must be maintained over all measurements of the ingredients and the varying conditions of the work. The large amount of experimental work that is necessary with this method will undoubtedly restrict its use to large jobs.

Method of the Iowa State Highway Commission.

Bank-run gravel will usually contain an excess of sand. This superfluous material produces a weak concrete although the mix is sufficient to give good results with a well-graded aggregate. The amount of sand may vary from 40% to 65% in pit-run material instead of 30% to 40% as is commonly used when the aggregate is separated.

Nevertheless, circumstances frequently necessitate the use of pit-run material on relatively small jobs, although in work involving large quantities of concrete, it should only be used after a careful study of all conditions. The effect of a large percentage of sand upon the properties of concrete is therefore an important factor in the proper use of gravel.

As the percentage of sand increases, the strength of the concrete decreases for any one mix. In other words, when the amount of sand increases, the cement must also be increased if the desired strength is to be maintained. The decrease is undoubtedly due to two causes: First, the weakness of the mortar, and, secondly, the additional amount of water that must be used to produce a workable concrete when the amount of fine material has been increased. The relation that exists between the increase in the sand and the cement for a definite strength has been fully investigated by Mr. Crum for the Iowa State Highway Commission.

The method that was finally adopted is to increase the ratio of cement to the total aggregate as the percent of sand increases. Three different classes of concrete were used in these experiments.

Class 1	General Reinforced Concrete	2400-3000 lbs. per sq.in.
Class 2	First-class Foundations	1800-2400
Class 3	For Mass Work	1200-1800

A diagram was made for each class in which the percent of sand in the aggregate was plotted as abscissa and the weight of the aggregate in pounds per cubic foot as ordinate. The mix that corresponds to these

two values for any particular aggregate can then be obtained from these diagrams for any of the three classes. These diagrams can be found in "Concrete Work" Vol.1, Fig.21, by Hatt and Voss.

The process of determining the mix for any aggregate and for any specified work can be summarized as follows: Screen a representative sample of the aggregate through a $\frac{1}{4}$ inch sieve and calculate the per cent of sand by weight; Weigh the bank-run gravel and determine the weight per cubic foot, loose; Then, select the diagram that is suitable for the required work and read the mix that is given by the above values.

An example will be used to illustrate the method that has just been described. The gravel weighed 110 pounds per cubic foot and contained 66% of sand. The mix as given by the graphs is:

Class 1	1:3 $\frac{1}{4}$
Class 2	1:4 $\frac{3}{4}$
Class 3	1:6 $\frac{1}{4}$

To assure developing the strength that was intended, care should be taken to use as small an amount of water as possible. Variation in the amount of sand must be carefully watched and the mix corrected as differences are noted. A table may be formed from which the necessary change in the mix can be readily ascertained.

Class 1 Concrete

Weight 110 pounds per Cubic Foot

Per cent of sand	Mix.
40	1:4 $\frac{3}{4}$
47	1:4 $\frac{1}{2}$
53	1:4 $\frac{1}{4}$
58	1:4
66	1:3 $\frac{3}{4}$

In some kinds of work, a certain amount of screened gravel can often be added to secure greater economy in the use of cement. This extra quantity of coarse material will diminish the total amount of cement that must be used but will also decrease the strength of the concrete if the same consistency is used, although not so much as the same amount of pit-run gravel. The amount to be added will depend upon the standard that is to be maintained, and the per cent of sand that is present in the pit-run material.

The standard that is selected may be either a constant mix or a constant percentage of fine and coarse material which would give a constant fineness modulus. To maintain a constant mix is probably the best and most practical method as can be readily seen from a comparison of the two. In either case, however, the strength of the concrete will vary over a limited range, the amount of variation depending upon the variation in the per cent of sand.

The method that was used in calculating the amount of screened gravel to be added so as to maintain a constant

mix can be most easily explained by a specific example. When the bank-run gravel contained 40% sand, Table 5 gives the necessary mix as 1:4.75. The difference between this and the desired mix 1:5.0 is .25 which is divided by 0.80. This value, 0.32, is then taken as the amount of screened gravel that will give a mix of 1:5.0 when added to $4\frac{3}{4}$ parts of bank-run gravel. The other values were found in a similar manner. The values for the strength were taken from Professor Abrams results as given in Bulletin 1.

Table 6

Mix 1:5.0 (constant)		Factor 0.80			
F. M. (Fine) 3.35		(Coarse) 7.19			
Per cent Passing #4 sieve	Cement	Pit-run Gravel Sacks Cu. Ft.	Screened Gravel Cu. Ft.	F.M.	Strength lbs./sq. in.
35%	1	5.00	0.00	5.85	2900
40%	1	4.75	0.32	5.74	2800
47%	1	4.50	0.63	5.58	2700
53%	1	4.25	0.94	5.47	2600
58%	1	4.00	1.25	5.43	2550
66%	1	3.75	1.56	5.30	2500

Discussion of the Various Methods.

The values that have been determined in the preceding pages will now be used as the basis of several tests which, with other experiments that have been conducted else where, will furnish some data for comparison.

Several cylinders, 5" x 12", were made of the various proportions and tested. The material for each

cylinder was carefully weighted and then mixed in a metal pan before it was tamped into the mold. The specimens were then placed in damp sand for 28 days at the end of which they were broken in the compression machine. The data and results are tabulated below.

Table 7

Test No. 1

Proportion by Weight	1:1 $\frac{2}{3}$: 4 $\frac{1}{4}$
Slump 4 $\frac{1}{4}$ inches	w.-C. Ratio 0.981
Amounts by Weight	Ultimate Strength
Cement 18 lbs.	1450 lbs/sq.in.
Fine Agg. 30 lbs.	1360 lbs/sq.in.
Coarse Agg. 76.5 lbs.	1360 lbs/sq.in.
Water 11.75 lbs.	
	Average 1390 lbs/sq.in.

Test No. 2

Proportion by Weight	1:2:3 $\frac{1}{2}$
Slump 1"	w.-C. Ratio 0.860
Amounts by weight	Ultimate Strength.
Cement 7 lbs.	3020 lbs/sq.in.
Fine 14 lbs.	2550 lbs/sq.in.
Coarse 24 $\frac{1}{2}$ lbs.	
Water 4.56 lbs.	Average 2785 lbs/sq.in.

Test No. 3

Proportion	1:4 $\frac{3}{4}$ by Volume
Amounts by Weight	Ultimate Strength
Cement 3 $\frac{1}{2}$ lbs.	2010 lbs/sq.in.
Gravel 19 lbs.	2210 lbs/sq.in.
Water 2.2 lbs.	1880 lbs/sq.in.
	Average 2030 lbs/sq.in.

Test No. 4.

Proportion 1:4.0 by Volume

Slump about 8"

Ultimate Strength

2240 lbs/sq.in.

1900 lbs/sq.in.

2400 lbs/sq.in.

3) 6540

Average 2180 lbs/sq.in.

Void Measurement.

As there has been a number of experiments that have clearly indicated the impracticability of proportioning by the amounts of voids in the aggregate, it hardly seemed necessary to produce more experimental results for a discussion of this method. Not only is there much difficulty in making accurate measurements out there is also an error in the hypothesis that was discovered through the extensive tests of the U. S. Bureau of Standards that are recorded in Bulletin #58. These tests show that there is no relation between strength and density in two mixtures in which different aggregates are used or in which a different proportion of cement to total aggregate is taken. It was found, however, that in different mixtures in which all conditions were the same except the proportion of fine and coarse aggregate, the proportion that gave the greatest density produced a concrete of high compressive strength. Thus, the proportioning of the cement to fill the voids of the sand is not correct since the ratio of cement to total aggregate largely determines the strength. If the

mix is assumed, then the proportion of fine and coarse aggregate could be made upon the basis of maximum density with the expectation of securing a high compressive strength for that particular mix if other conditions are kept favorable.

Other limitations are: that the mix is frequently too coarse to work easily and that no provision is made for the amount of water to be used. As only approximations can be made at the beginning, and change that is necessary to make the concrete more workable must be assumed from experience.

The consistency has been definitely shown to be an important factor in determining the strength of any concrete. Any proportion of aggregate should therefore be investigated as to strength that can be obtained with the desired consistency. It thus, seems that this method is too inconsistent to produce a desired strength of concrete.

Ideal Curve and Method of Trial Mixtures.

The relation of density to strength must also be applied to the other methods of proportioning that are based on that property of concrete; that is, by means of the ideal curve and volumetric synthesis.

This assumption that the gradation for maximum density of all aggregates in any particular type, such as gravel, follows a common curve is erroneous, as it has been found that "the gradation curve for maximum density, differs for each aggregate." Thus the curves that have been formed will only apply practically to the

aggregates that were used in the experiments, although frequently comparable results can be secured from similar aggregates. In general, however, higher compressive strength will be given by curves different from those obtained by Fuller in his experiments.

This does not mean that these curves are of no use for any kind of material, but that the results obtained from different aggregates with identical proportions are so dissimilar that it does not appear logical to apply one curve indiscriminately. The variation in result is probably due to differences in the shape and amount of each size of particle, the amount of water used, and the method of mixing.

The test cylinders that were made with the proportion $1:1\frac{2}{3}:4\frac{1}{4}$ as determined by the ideal curve gave very poor results for compressive strength. The average for three cylinders was about 1400 lbs/sq.in. which was the lowest of any of the specimens. Other tests, however, have indicated that ordinarily much better results can be obtained if the other factors are carefully controlled.

Surface Area

The use of the cement-surface area-strength ratio must still be regarded in the experimental stage of development. Under any conditions it seems reasonable to believe that the relation of these factors must be determined anew for each different aggregate because of the effect that the character of the material may have upon the properties of the concrete. This means that a series of tests must be made to determine the strength

for various ratios of cement to surface area and water. Often the amount of concrete to be used will not justify the expense that is liable to be incurred by these tests.

It was impossible to conduct sufficient tests to determine the necessary values for the aggregate that was used. The values that were used in proportioning by this method were secured in tests made by the Hydro-Electric Power Commission, so it would be useless to expect similar results with different aggregate.

Practical application of the surface area theory indicates in a general way that it can be used to apply the results of laboratory tests to field conditions by varying the cement when the aggregate changes according to the established ratio. It is somewhat restricted in use by the difficulty of keeping careful supervision over the exact proportions and quantities used. The calculation of the surface area is also a difficult and laborious task although the field work can be diminished by the use of tables similar to those on page (//), which are plotted from the laboratory analysis. The number of grains per unit weight of the smaller sizes is very difficult to obtain while any error in these sizes effect the results more than in the larger particles.

Some of the obstacles mentioned above may account for the results obtained by Prof. Abrams, which did not show any definite relation between surface area and strength. From tests made upon concrete of 27 different gradings of the same aggregate, with all other conditions constant, the surface area was found to vary from 390 to

to 1,992 sq. in. per lb. of aggregate while the strength only varied from 2,440 to 2,890 lbs/sq.in. Because of the limited data on this theory, it is difficult to make any definite conclusions. Nevertheless, it does not seem applicable to ordinary proportioning of concrete although it may be used to correlate the laboratory tests and the field work on large jobs.

Fineness Modulus.

The results of many tests upon concrete of different degrees of plasticity has indicated that the amount of water greatly controls the compressive strength. The statement can almost be made that it does control the compressive strength when the method of preparation is considered so that it must be regarded as the paramount factor in the mix.

The variation in the amount of water contained in the aggregate has much to do with the difficulty of obtaining the desired consistency. Anyone familiar with making concrete knows that after enough water has been added for the hydration of the cement, a slight increase produces a marked change in the consistency. The moisture contained in the aggregate may thus change the consistency from dry to wet with the same amount of water, as well as change the volume of the sand. The amount of moisture can be determined approximately, the greatest difficulty being in the variation. Another reason for the trouble that is often found in supplying the correct amount of water is caused by the variation in the quantities of the aggregates placed in the mixture. A solution for this

problem may gradually be developed by the inundation method for measuring the sand, that has been tried by the U. S. Bureau of Standards.

Some idea of the results that can be secured with this method may be obtained from the tests that are recorded. Three test cylinders of the proportions 1:2:3½ were made with a consistency of about 1.0, the water-cement ratio being 0.860. After curing for 28 days in water, these cylinders gave an average compressive strength of 2785 lbs/sq.in. which is close to the theoretical value used in the design. Although this test is not sufficient to prove or disprove any of the basic principles, it serves to show that by making proper allowance for field conditions and the necessary consistency, the proportions obtained by this method will be conservative and will greatly assist in making a final decision. The proportions selected from the tables may not be the most economical one but it will usually work easily. This is partly due to the fact that both workability and strength have been considered as necessary and related factors.

Method of the Iowa State Highway Commission.

The practice of applying a certain standard mix to all bank-run gravel, regardless of its characteristics, to obtain any degree of strength, resistance to wear, or permeability, is one of the most pernicious habits in the proportioning of concrete at the present time. The fact that the concrete is still in existence is no conclusive proof that the assumed factor of safety was

realized or that the mix was economical. The method of the Iowa State Highway Commission furnishes a means of taking into consideration certain characteristics of the aggregate that may affect the properties of the concrete.

The practical use of this method can best be illustrated by a specific example. The specifications for the new power house of South Dakota State College required a 1:2:4 proportion for the concrete in the floor slab. The compressive strength of this concrete was estimated at 2000 lbs/sq.in. at 28 days. The contractor decided that it would be more economical to use a richer mix without separating the gravel. An analysis of the gravel gave 68% passing the $\frac{1}{4}$ " sieve, and the weight about 110 lbs/cu.ft. Under these conditions this method gave a 1:4.0 mix as necessary for a strength of 2000 lbs/sq. in. with an allowance for field conditions. The floor slab contained a quantity of small reinforced steel which made a rather wet consistency necessary. A test of the consistency with the cone gave an average slump of about 9 inches. An average of three out of four test cylinders gave a compressive strength of 2200 lbs/sq.in. A higher strength would undoubtedly have been obtained if less water had been used.

Laboratory tests upon the gravel that was used in the example verified the assumptions that were made when a dry consistency was used and the concrete was stored in water. Some allowance should be made for field conditions. Three test cylinders gave an average

compressive strength slightly over 2000 lbs/sq.in. which was the estimated value. It would therefore seem that approximate results can be expected. At least, these diagrams furnish a tentative solution for the problem of using gravel that contains various amounts of sand, which is a decided improvement over the use of a standard proportion regardless of the character of the material that is used.

Conclusion

The outstanding features of the study that has been made of the different methods of proportioning concrete are; the effect of water upon the properties of concrete and the impracticability of determining the properties of concrete of some definite proportion without making actual test.

A study of tests that have been made indicates that certain methods, particularly the fineness modulus, gives ~~✓~~ good results although a more economical mix might perhaps be used. A series of accurate tests upon concrete of the estimated proportions will be found useful in making a final decision. Tests that are carelessly conducted, however, will be misleading and may be worse than none. The selection of proportions from tables that are based upon the results of laboratory tests should be made with due regard to the effect of such factors as; aggregate, consistency, density, and curing conditions.

While the fineness modulus method considers only

the effect of the water as a basis of proportioning, the neglect of the other factors does not seem to seriously interfere with the results. At the present time, this method seems to take care of one of the most important factors in a satisfactory manner. In any event, it is a decided improvement over the inaccurate method of void measurement and is based upon a more definitely established theory than the ideal curve method. The difficulty of maintaining the necessary conditions in the field is one of the largest obstacles. This trouble can be largely overcome by using a water regulator on the mixer, by mixing the concrete for sufficient time and by accurate measuring of the fine aggregate. The latter factor may perhaps be solved by the inundation method.

With respect to the results that have been obtained in this investigation, the following procedure appears to give the best results when extensive tests are not desired.

1. Examine the aggregate carefully, and make tests for silt and organic impurities. The colorimetric test will be found convenient for the latter.
2. Make a sieve analysis of the aggregate with the Tyler Standard sieves and, also, determine the weight per cubic foot.
3. Determine the per cent of moisture that is contained in the fine aggregate; the absorption can usually be assumed as 2% except with soft stone.
4. Notice the appearance of the sand with various amounts of moisture, and also the change in weight; the wet sand should weigh the least.

5. Mix some concrete with different proportions and with different percentages of water to determine the consistency that will be necessary for the work.

6. With the desired strength, consistency and mix known, find the required fineness modulus from the results of tests that are expressed graphically in Fig. 6, Bulletin 1, of the Lewis Institute. Allowance must be made for field conditions; about 10 or 15% of the laboratory results should be sufficient.

7. Calculate the relative amounts of fine and coarse aggregate that will give the desired fineness modulus. The sum of the fine and coarse aggregate should equal the mix divided by 0.82.

8. Use the least amount of water that will give the desired consistency, and after the concrete has set, keep it as moist as possible.

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