

THE PROPORTIONING OF WORKABLE CONCRETE FOR ANY DESIRED STRENGTH*

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It is the purpose of the present paper to describe a method for proportioning concrete which has been used successfully in important structures and which permits of predetermining the necessary proportions for any required strength and consistency so closely that very little, if any, change will be required in the field mix. The method was developed by the writer and J. E. Gray of the National Crushed Stone Association. Its originality lies, not in the basic principles pertaining to concrete, but rather in the use of those principles in a practical and simple manner. It recognizes the validity of the water-cement ratio, compressive strength relationship as announced by Abrams; it utilizes the solid volume calculations as employed by Ferét, Talbot, Richart, and others; it recognizes the desirability of a variable fine to coarse aggregate relationship, depending not only on the gradation of these aggregates, but also on the shape of the coarse aggregate. It likewise takes into account the specific gravities of the respective concrete ingredients.

Concretes are not all employed for the same kind of service and, hence, the concrete proportions and the size and even the character of the coarse aggregate must be made to best suit the conditions. For illustration, a reinforced concrete beam in a structure requires much more workable concrete than a pavement slab. Further, in structures, compressive strength is important, while in pavement slabs high beam strength is necessary. The outstanding physical property of structural concrete which can be determined readily is compressive strength and related to this property are durability, permeability and absorption. Consequently, for structural concrete, compressive strength is quite universally used as a measure of quality and almost all methods of proportioning are devised for producing concrete of the correct degree of workability and having the required compressive strength.

It is quite necessary that certain fundamental conceptions used in the present method be very clearly understood and the first of these is specific gravity and the method of using it for determining solid volume.

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BULK SPECIFIC GRAVITY AND SOLID VOLUME

In general, specific gravity is the weight of a material compared with the weight of an equal volume of water. If a material has a specific gravity of 3.0, it weighs three times as much as water. By bulk specific gravity is meant the weight in air of an oven-dried sample of material divided by the weight of water displaced by this material including its permeable and impermeable voids. In Fig. 1 are shown two methods for determining bulk

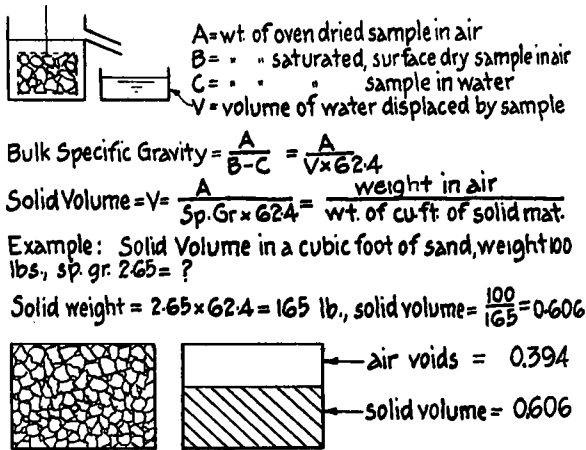


FIG. 1

specific gravity which need not be described here. By definition, bulk specific gravity equals weight in air divided by the weight of an equal volume of water. If V equals the volume of the sample or volume of water displaced by the sample, the weight of displaced water equals V x 62.4 lbs. and if A is the oven-dry weight of the sample—

$$\text{Bulk Specific Gravity} = \frac{A}{V \times 62.4} \quad \text{from which}$$

$$V = \frac{A}{\text{Specific Gravity} \times 62.4} = \frac{\text{Weight in Air}}{\text{Weight of Cu. Ft. of Solid Material}}$$

Accordingly, if the weight per cubic foot in air of any aggregate is known, its solid volume is merely that weight divided by the weight of a cubic foot of that same aggregate if it were in a solid condition. A conception of the solid volume of a cubic foot of aggregate may be obtained if it is imagined that the aggregate is melted down without changing its physical structure.

The aggregate would now occupy a solid space in the bottom of the cubic foot measure and the top portion would be air, having exactly the same volume as the air voids in the original aggregate. (Fig. 1, bottom.)

As an example of the calculations of solid volume, let it be required to determine the solid volume in a cubic foot of sand whose weight is 100 lbs., and whose specific gravity is 2.65.

Solution: The solid weight per cu. ft. is $2.65 \times 62.4 = 165$ lbs.

Solid volume of 100 lbs. of sand then $= \frac{100}{165} = 0.606$.

The voids in that sand would be :

One cu. ft. minus 0.606 = 0.394 cu. ft. (39.4% voids)

It is important that this use of specific gravity in determining solid volume and the meaning of solid volume be thoroughly understood.

IMPORTANCE OF THE AMOUNT OF COARSE AGGREGATE IN CONTROLLING CONCRETE WORKABILITY

When aggregate is in a stockpile or is compacted in a cubic foot measure by rodding, it may be stirred or moved only with great difficulty. Correspondingly, if concrete were to contain coarse aggregate to such an amount that the pieces were interlocked and in contact with one another, there would be no opportunity for relative motion of the particles with respect to one another and, consequently, the concrete would be extremely non-workable. The mortar portion of concrete not only fills the voids but it separates the particles of coarse aggregate, and the wider that separation, the more workable will the concrete be. It is immediately apparent, therefore, that the quantity of coarse aggregate in a cubic foot or a cubic yard of a concrete mixture is one of the most important factors controlling workability. The more widely separated the pieces of coarse aggregate, the more mortar must the concrete contain and, although this condition may create great workability, it also produces undesirable properties in the concrete, such as excessive shrinkage and lack of economy. It is important, therefore, that the amount of coarse aggregate in a given volume of concrete be so selected that when it is mixed with the mortar, the pieces of coarse aggregate will have sufficient separation to create adequate workability, but have no more separation than is necessary to accomplish that purpose.

QUANTITY OF COARSE AGGREGATE TO USE

The question of what constitutes proper workability is, after all, a matter of judgment. We have used our own judgment in determining how much coarse aggregate to use on the basis of laboratory tests, and also by observing field concrete having known proportions. The quantities of coarse aggregate which are considered desirable are shown in Table I.

TABLE I
DRY, RODDED VOLUME OF COARSE AGGREGATE, ANY TYPE, PER UNIT VOLUME OF CONCRETE

Size of Coarse Aggregate Square Opening	Fine Sand		Medium Sand			Coarse Sand		
			Fineness Modulus of Sand					
Laboratory Sieves	2.40	2.50	2.60	2.70	2.80	2.90	3.00	3.10
	Value for b/b_0							
No. 4— $\frac{3}{4}$ in.	.71	.70	.69	.68	.67	.66	.65	.64
No. 4—1 in.	.72	.71	.70	.69	.68	.67	.66	.65
No. 4— $1\frac{1}{2}$ in.	.74	.73	.72	.71	.70	.69	.68	.67
No. 4—2 in.	.76	.75	.74	.73	.72	.71	.70	.69
No. 4— $2\frac{1}{2}$ in.	.78	.77	.76	.75	.74	.73	.72	.71

They are expressed as dry, rodded volumes of coarse aggregate per unit volume, that is, per cubic foot or cubic yard of concrete. These dry-rodded quantities are variable, depending upon the size of the coarse aggregate and also upon the fineness of the sand as expressed by Fineness Modulus. The same values are used for all kinds of coarse aggregate, whether round or angular.

Note in Table I that as the size of the coarse aggregate increases the larger should be its volume in the concrete and the less will be the quantity of mortar. Furthermore, the finer the sand, as shown by a low fineness modulus value, the greater can be the volume of coarse aggregate used, the reason probably being that a fine sand tends to separate the coarse aggregate less than a coarse sand. This table is in line with general experience and with other methods, notably the Fineness Modulus method for determining the relative amounts of fine and coarse aggregates in concrete mixtures.

Note that the quantities of coarse aggregate are expressed in terms of the dry, rodded volume and that these quantities are designated by the fraction b/b_0 ,—

Where

b is the solid volume of coarse aggregate per unit volume of concrete, and
 b_0 is the solid volume of coarse aggregate per unit volume of coarse aggregate.

It is important that these quantities be understood. There may be some question why the dry, rodded volume of coarse aggregate, b/b_0 , can be expressed in terms of the solid volume of the coarse aggregate and reference to Fig. 2 will help to clarify this matter.

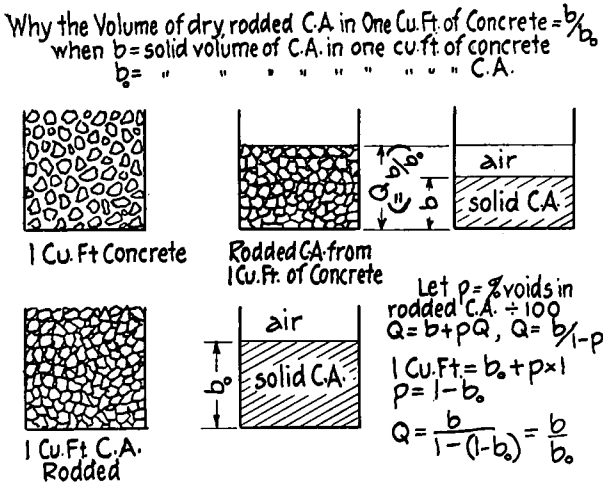


FIG. 2

Imagine that one cubic foot of concrete is subjected to a washing process leaving only the coarse aggregate and this coarse aggregate is then rodded into the cubic foot measure and has a compacted volume of "Q" cu. ft. Imagine further that this dry, rodded coarse aggregate is melted down, giving a solid volume which by definition is solid volume b : remember b = solid volume of coarse aggregate in one cubic foot of concrete. Now imagine that there is a cubic foot measure containing dry, rodded coarse aggregate. The solid volume of coarse aggregate in this measure, if it were melted down, would be as shown—and its value would be b_0 by definition. Of course the air voids in dry, rodded coarse aggregate and the solid volumes would be in direct proportion to the respective dry, rodded volumes and, consequently, we can write immediately that $\frac{Q \text{ cu. ft.}}{1 \text{ cu. ft.}} = b/b_0$.

A proof of this relationship is also given in Fig. 2.

VOLUME OF CONCRETE EQUALS SUMMATION OF SOLID VOLUMES OF INGREDIENTS

Another important concept in connection with the present method is that the volume of freshly mixed concrete is equal to the sum of the solid volumes of the constituents in that concrete. This statement is almost exactly true except for a small percentage of air which adds to the concrete volume, but the method of treating included-air will be explained later.

PROPORTIONING FOR COMPRESSIVE STRENGTH AND DESIRED CONSISTENCY

Quite obviously, since the strength of concrete depends to a very considerable degree upon the adhesion of the aggregates, the strength of the cement paste has an important influence on the strength of the concrete. Consequently any method for proportioning must be based on strength tests of concrete which may be generalized to show the number of sacks of cement per cubic yard and the quantity of water per cubic yard necessary to give the required strength and also the required consistency. Such tests have been made in our own laboratory on different types of coarse aggregates and likewise similar tests have been made by others. As a result, Table II has been prepared.

TABLE II

CEMENT FACTORS (SACKS OF CEMENT PER CU. YD. OF CONCRETE) REQUIRED FOR 28-DAY COMPRESSIVE STRENGTHS LISTED

Size of Coarse Aggregate		No. 4— ¾ in.		No. 4— 1 in.		No. 4— 1½ in.		No. 4— 2 in.		No. 4— 2½ in.	
Slump (inches)		3	6	3	6	3	6	3	6	3	6
Water Gal. per Cu. Yd. of Concrete	Angular Coarse Aggregate	40	42	38	40	36	38	35	37	34	36
	Rounded Coarse Aggregate	36	38	34.5	36.5	33	35	32	34	31	33
28-Day Compressive Strength	2000 Sacks of Cement Per Cu. Yd. of Concrete	4.6	4.9	4.4	4.6	4.2	4.4	4.1	4.3	4.0	4.2
	2500	5.0	5.3	4.8	5.0	4.5	4.8	4.4	4.6	4.3	4.5
	3000	5.5	5.8	5.2	5.5	4.9	5.2	4.8	5.1	4.7	4.9
	3500	6.0	6.3	5.7	6.0	5.4	5.7	5.2	5.5	5.1	5.4
	4000	6.5	6.8	6.1	6.5	5.8	6.1	5.7	6.0	5.5	5.8
4500	7.1	7.4	6.7	7.1	6.3	6.7	6.2	6.5	6.0	6.3	
5000	7.7	8.1	7.3	7.7	6.9	7.3	6.8	7.1	6.5	6.9	

In this table are shown the number of sacks of cement required per cubic yard of concrete for different sizes of coarse aggregate and different slumps,

and, likewise, it gives the quantities of water required to produce these slumps, depending on the type of coarse aggregate. This water is the available mixing water and is not necessarily the water which is added to the concrete, because a certain amount of free water may be present on the surfaces of the aggregates.

Referring to Table II, note that as the size of the coarse aggregate increases, the quantity of water and the quantity of cement decrease. Note, also, that the same amount of water per cubic yard of concrete is used irrespective of the cement content or strength of the concrete. It will also be found that, for any given strength, the quantity of water divided by the quantity of cement is approximately a constant as it should be in accordance with the water-cement ratio relationship.

Likewise, it should be noted that a different quantity of water is used for angular, coarse aggregate as compared with rounded coarse aggregate for producing the same strength. It will be found, in general, that the strengths of laboratory cured specimens will exceed by some 15 or 20 per cent those shown in the table when the indicated quantities are used. The table has been purposely arranged with this excess strength to allow for the fact that the curing conditions in the field frequently are not as favorable as those in the laboratory, nor can the field concrete be expected to be as uniform as the laboratory mixed and cured concrete.

HOW TO PROPORTION CONCRETE

With the above preliminary considerations in mind, it now becomes a simple matter to make use of Tables I and II and to calculate the weights of the respective ingredients required per cubic yard of concrete. It will be assumed that the concrete is to have a certain designated strength at 28 days; it will be made of a given size and type of coarse aggregate and should have a given consistency as determined by the slump test.

Reference to Table I will show the dry, rodded volume of coarse aggregate to be used. From Table II may be obtained the number of sacks of cement and the number of gallons of water per cubic yard of concrete. The solid volumes of the cement, the coarse aggregate and the water are then calculated and their sum subtracted from 27 gives the solid volume of the sand to be used in the mixture. These respective solid volumes multiplied by the solid weights per cu. ft. of the respective materials give the weights per cu. yd. of the various ingredients. The weights of the fine and coarse aggregates are in terms of their oven-dried condition and, hence, when their field moisture condition is known, these weights must be corrected for their

moisture content and also the amount of mixing water must be corrected to allow for the free moisture on the aggregate.

The following example of proportioning structural concrete will show in detail the various steps in the procedure.

EXAMPLE OF PROPORTIONING STRUCTURAL CONCRETE

Strength—2500 psi at 28 days — slump 6 inches.

- Cement —Specific Gravity = 3.17
- Sand —Fineness Modulus = 2.70, Specific Gravity = 2.65
- Stone —Specific Gravity = 2.97, Size No. 4— $\frac{3}{4}$ in., square opening.

Preliminary Calculations

- Cement —Solid Weight = $3.17 \times 62.4 = 198$ lbs.
- Solid Volume per bag = $94/198 = 0.475$ cu. ft.
- From Table II, 5.3 bags per cu. yd. are required.
- Sand —Solid Weight = $2.65 \times 62.4 = 165.5$
- Stone —Solid Weight = $2.97 \times 62.4 = 185.3$
- Dry, rodded weight = 103.9, $b_0 = 103.9/185.3 = 0.56$

b/b_0 from Table I = 0.68; $b = b/b_0 \times b_0 = 0.68 \times 0.56 = 0.381$

Quantities per Cu. Yd. of Concrete

Cement from Table II = 5.3 bags; water from Table II = 42 gal.; $b = 0.381$

	<i>Cu. Ft. Solid Vols.</i>		<i>Solid Wts.</i>		<i>Lb. per. Cu. Yd.</i>
Cement — 5.3 x 0.475	= 2.52	x	198	=	498
Stone — 0.381 x .27	= 10.29	x	185.3	=	1910
Water — 42 gal. ÷ 7.5	= 5.60	x	62.4	=	349
	<hr/>				
	18.41				
Sand — 27 — 18.41	= 8.59	x	165.5	=	1420
					<hr/>
					4177 lb.
					per cubic yard.

Field Quantities—Corrections for Moisture

By test, sand has 4.0% of surface water and 0.7% absorption
 By test, stone has 0.5% of surface water and 0.2% absorption

Weight of wet sand required	= 1420 + 4.7% of 1420	=	1487
Weight of wet stone required	= 1910 + 0.7% of 1910	=	1923
Weight of mixing water	= 349 — 4.0% of 1420 — 0.5% of 1910	=	283
Weight of cement		=	498
			<hr/>
			4191 lb.
			per cu. yd.

In the above example it is necessary that the specific gravities of the cement, sand and coarse aggregate be known or be determined. It is likewise necessary that the dry, rodded weight of the coarse aggregate be determined; the Fineness Modulus is obtained knowing the gradation of the sand and a gradation determination must be made on the coarse aggregate

to determine its size. These are the only preliminary determinations to be made.

The preliminary calculations consist in determining the solid weights of the cement, sand and stone, the solid volume of the cement and of the coarse aggregate per cubic foot of coarse aggregate which, by definition, is b_0 . The quantity, b/b_0 , is obtained from Table I, and b , the solid volume of coarse aggregate per cubic foot of concrete, is merely $b/b_0 \times b_0$. The solid volumes of the respective ingredients per cu. yd. are then calculated. For the cement this equals the number of bags of cement multiplied by the solid volume per bag. The solid volume of the stone in a cubic yard is the solid volume per cubic foot multiplied by 27 cubic feet. The volume of water in cubic feet is the number of gallons per cubic yard divided by 7.5 gal. per cu. ft. The solid volume of the sand is the sum of the solid volumes of the cement, stone and water subtracted from 27 cu. ft. The weights of the respective ingredients are obtained by multiplying the solid volumes by the respective solid weights.

This method of proportioning automatically takes account of the fact that aggregates have different specific gravities and that the coarse aggregate may have a wide range in gradation which may result in differences in voids. It likewise takes account of the effect of shape of coarse aggregate on voids. When the calculations are made correctly, the separation of the particles of coarse aggregates of the same gradation will be the same and approximately equal workabilities will be obtained, irrespective of differences in particle shape. Likewise the workability of the concrete will be adequate. The method also automatically takes account of the effect of the sand gradation. The calculations are extremely simple and may be made within a comparatively few minutes of time when the method is thoroughly understood.

It will be of some interest to see how very different the proportions as determined in the preceding example are from the old 1:2:4 proportions to which some engineers and architects still cling so tenaciously.

The above proportions may be expressed approximately as follows, making due allowance for the effect of moisture on the "bulking"¹ of sand and for the effect of method of measurement, whether "loose" or "compacted" on the weight of aggregates:

By weight	1	3	3.85
By moist, rodded volume	1	3.1	3.45
By moist, loose volume	1	3.2	3.66
By dry, loose volume	1	2.8	3.69

¹ See A.S.T.M. Proceedings, 1920, Vol. XX, page 340.

See N.C.S.A. Bulletin No. 1, "The Bulking of Sand and Its Effect on Concrete".

These proportions are far from the 1:2:4 proportions which obviously do not provide enough sand to make workable concrete when 3/4 inch maximum size coarse aggregate is used. There is no place in specifications nowadays for so archaic a specification as that containing the arbitrary proportions of 1:2:4. In lieu thereof I would require each ingredient to be specified by weight per cubic yard, making the minimum cement factor and maximum allowable water content mandatory but allowing for a small adjustment in the fine and coarse aggregate as may be necessary to create workability.

PAVEMENT CONCRETE

The design of pavement concrete is based on the same principles as the design of structural concrete with one very importance difference, namely, that pavement concrete should be designed for beam strength. Pavement concrete should not be as workable as structural concrete and no more mortar should be used than is necessary to produce a rather thin film of mortar on the pavement surface after the finishing operation. In view of the sensitivity of beam strength or modulus of rupture to the influence of certain factors such as the strength of the cement and the characteristics of coarse aggregates, and perhaps others, it is necessary to determine the required cement factor by the use of beam tests. It is not sufficient merely to assume that the beam strength is a fractional part of the compressive strength, for that is not a safe assumption.

To design pavement concrete, Table III is provided.

TABLE III

DRY, RODDED VOLUME OF COARSE AGGREGATE PER UNIT VOLUME OF HIGHWAY CONCRETE (b/b₀)

Coarse Aggregate Square Opening Laboratory Sieves	Fine Sand		Medium Sand			Coarse Sand			Approximate Gallons of Water per Cu. Yd. of Concrete for 2 inch Slump	
	Fineness Modulus of Sand									
	2.40	2.50	2.60	2.70	2.80	2.90	3.00	3.10	Coarse Aggregate	
									Angular	Rounded
No. 4 to 1 in.	.79	.78	.77	.76	.75	.74	.73	.72	35	32
No. 4 to 1 1/2 in.	.81	.80	.79	.78	.77	.76	.75	.74	33	30
No. 4 to 2 in.	.83	.82	.81	.80	.79	.78	.77	.76	32	29
No. 4 to 2 1/2 in.	.85	.84	.83	.82	.81	.80	.79	.78	31	28

b₀ = solid volume of coarse aggregate per cu. ft. of dry, rodded coarse aggregate.
 b = solid volume of coarse aggregate per cu. ft. of concrete.
 b/b₀ = dry, rodded volume of coarse aggregate per unit volume of concrete.

Note that the values for b/b_0 in this table are higher than those in Table I. Note also that because a drier consistency is desired in pavement concrete and also because less mortar is used, the quantities of water are less in Table III than in Table II. With these exceptions the method of proportioning pavement concrete is the same as that for proportioning structural concrete. There is another difference, however, that might be pointed out, namely, that in pavement concrete it is becoming the practice very rapidly to use air-entraining cements and in the following example it is assumed that an air-entraining cement is used.

EXAMPLE OF PROPORTIONING PAVEMENT CONCRETE

Cement factor — 6.4 sacks per cu. yd., slump 2" — 3", limestone No. 4 — 2"
 Cement—Sp. Gr. 3.15 — air-entraining, preliminary assumption 4% air
 Sand—Fineness Modulus 2.90, Sp. Gr. 2.63, 1% absorption, 5% free water
 Stone—Sp. Gr. 2.70, Size No. 4 — 2", 0.3% absorption, 0% free water

Preliminary Calculations

Cement—Solid weight = $3.15 \times 62.4 = 196.8$, solid volume = $94/196.8 = 0.478$
 Sand—Solid weight = $2.63 \times 62.4 = 164.2$
 Stone—Solid weight = $2.70 \times 62.4 = 168.7$ dry rodded wt. = 101 lb. per cu. ft.
 Solid volume per cu. ft. of dry, rodded stone = $101/168.7 = 0.598$
 $b_0 = 0.598$; from Table $b/b_0 = 0.78$, $b = b/b_0 \times b_0 = .78 \times .598 = .467$

Calculation of Concrete Proportions

				<i>First Trial Mix</i>	
Cement—6.4 x .478	= 3.06	x 196.8	= 602		602 lb.
Stone—.467 x 27	= 12.62	x 168.7	= 2130 + 0.3%	2130	= 2136 lb.
Water—.32/7.5	= 4.27	x 62.4	= 266 — 5%	980	= 217 lb.
Air—4% of 27	= 1.08				
	21.03				
Sand—27 — 2103	= 5.97	x 164.2	= 980 + 6%	980	= 1039 lb.

Weight per cu. yd. of the first trial batch is theoretically 3994 lb. or 147.7 lb. per cu. ft. An actual weight determination shows 149 lb. per cu. ft. Concrete containing no air would weigh $100/96 \times 147.7 = 154.0$.

The actual percent of air = $\frac{154 - 149}{154} = 3.2\%$ instead of 4.0%.

Recalculation of the Mix

				<i>Corrected Mix</i>	
Cement	3.06		602		602
Stone	12.62		2130		2136
Water 31/7.5	4.13	x 62.4	258 — 5%	1008	= 209
Air .032 x 27	0.875				
	20.685				
Sand	6.315	x 164.2	= 1008 + 6%	1008	= 1068
					4015
					$4015 \div 27 = 149$ lb. per cu. ft.

In the above example it is assumed that 6.4 bags of cement per cu. yd. are specified; that the slump is to be between 2 and 3 inches, and that limestone of No. 4 to 2 in. size will be used. Also, it will be assumed that an air-entraining cement is to be used and that 4 percent of air will be entrained. The specific gravities, gradations of aggregates, and dry, rodded weight per cubic foot of the stone are determined by test. The solid unit weights of the cement, sand and stone, the solid volumes of the cement and stone and the solid volume of stone in a cubic yard of concrete are calculated as shown under "Preliminary Calculations", after which the concrete proportions are calculated by obtaining the solid volumes of the cement, stone, water and air per cu. yd. of concrete. Their sum subtracted from 27 equals the solid volume of sand required in the concrete. The solid volumes in cubic feet of the respective ingredients multiplied by their solid weights per cubic foot equal the weights of the ingredients required in the concrete per cubic yard.

The above quantities are in terms of dry aggregates and, hence, to apply them to the moisture conditions of the aggregates in the actual work, corrected quantities must be calculated in the manner shown under "Example of Proportioning Structural Concrete."

Suppose that although 4 percent of air was assumed, only 3.2 percent of air is found in the mix obtained by a weight per cubic foot test on the concrete and by the calculation shown in the "Example of Proportioning Pavement Concrete" It will now be desirable to re-calculate the mix using 3.2 percent of air in the manner indicated under "Recalculation of the Mix".

ADJUSTMENT OF THE MIX IN THE FIELD

No method of proportioning concrete, especially paving concrete in which the mortar has been purposely reduced to prevent an excess on the finished slab, is always entirely satisfactory and adjustment may be needed in the finished mix. Some types of equipment and contracting organizations can handle harsher concrete than others. If the concrete seems too harsh, reduce b/b_0 by 0.01 and again calculate the mix. If still too harsh, try another reduction of 0.01. Generally, however, the original proportion will produce concrete very closely approaching the kind desired. The b/b_0 values shown in Table III are probably on the harsh rather than on the over-sanded side of the scale and are intended for use with suitable field equipment and expert personnel. Some organizations prefer a more workable mix.

DESIGN OF CONCRETE FOR A REQUIRED BEAM STRENGTH

If it is required that the concrete have a given beam strength as measured by Modulus of Rupture, laboratory beam tests are necessary. Concrete should be designed following the preceding method for four different cement factors. At the required age, the beams should be tested and the modulus of rupture values plotted, together with cement factors as shown in Fig. 3.

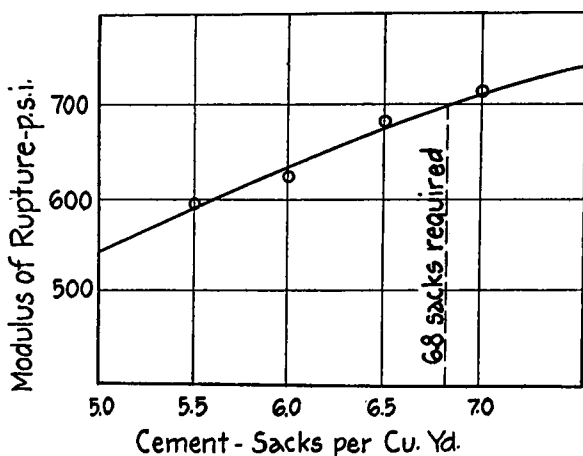


FIG. 3

From such a curve the required cement factor can be estimated. The mix is then calculated using the cement factor thus obtained and this mix may be used as the first field mix made. The adjustments to this mix will be apparent after some 5 or 10 batches have been made. The first batch should not be used as the criterion of suitability. If the workability is suitable, but the concrete is too dry, or too wet, adjust the water slightly, keeping the weight of coarse aggregate constant, merely changing the solid volume of the sand to compensate for the change in the volume of mixing water.

Because of the detail used in the present description, the method may seem complicated, but actually it is extremely simple and easy to apply in the field. It has been used successfully in a number of ready-mixed concrete plants and in large concrete jobs including structures and pavements.

DISCUSSION

PRESIDENT BUCK: I noted that in Table I and Table III you used the fineness modulus of the sand. Does the uniformity co-efficient of sand have any bearing on the stability?

MR. GOLDBECK: I think perhaps it does, but we are not taking the uniformity coefficient into account. Fineness Modulus is a term or method for determining the fineness of the

sand which is in rather universal use for fine aggregate in concrete. The uniformity co-efficient is practically never used in connection with fine aggregate for concrete. It is used in other ways, I realize, but not that.

I also realize that Fineness Modulus is not a perfect way for expressing fineness of sand but, none the less, is the best way we have.

CHAIRMAN CHAMBERLAIN: Is there anyone else who might have a question?

MR. HOGG: I notice nothing was said there, Mr. Goldbeck, about absorption in concrete, and the relation of the rodding to the mixing time. What is the relation to the mixing time, that is, putting your concrete in the mixture, and the rodding time to obtain a certain strength? Some mixer manufacturers claim that you should mix a certain amount of time dry, and a certain amount of time wet to get certain results or certain approximate results. What is the relation there to your rodding twenty-five times to the length of time that that concrete should be mixed to attain a certain strength?

MR. GOLDBECK: Well, the rodding has to do primarily with the determination of weight per cubic foot of the coarse aggregate. In compacting the concrete in the cylinders, the test cylinders or beams, we also rod a given number of times, but there is no relationship between that and the strength of the concrete whatever. That rodding is simply a means for uniformly placing the concrete into the specimens. Now, I think there is some relationship between time of mixing of the concrete and the compressive strength. I am assuming that you are going to have adequate mixing of this concrete. Some mixers, of course, are more efficient than others, too. A lot of things enter into this matter. Those things will disturb the results to some extent, that is very true, but, as I say, there is not a single theory for proportioning concrete which will enable you to predict all these matters with extreme accuracy. You are bound to make use of all the test results that have been obtained in a general sort of way. That is the way theories are built up as a rule. It is a question of generalizing on the test results that have been obtained and then making use of those results in the best possible manner and in a general way.

I run into this same problem in a number of different ways. We had the problem put up to us some four years ago of attempting to devise a theory for determining the thickness of a flexible pavement under traffic loads. We made a lot of tests in which we measured the pressures under these flexible pavements on the sub-grade when the pavements were subjected to traffic loads, and we ended up with a lot of different curves—curves showing the pressure distributions under the pavements.

If the pavement was thin, we got a curve that showed a very high intensive pressure. If the pavement was thick, of course the pressure intensity was lower and was more widely distributed. We had, I think, fifty such curves, and when we got through with them, I wondered what to do with them. Well, we finally hit on a way of generalizing those results.

That is what I mean. You have to devise theories on the basis of the best general application of those results you possibly can. And, that is what we have done here and, fortunately, it turns out pretty well. It seems to work. We are able to actually get the compressive strengths we say we are going to get within very close limits.

This table of compressive strengths, by the way, is purposely designed with a factor of safety. Actually, as a rule, you will get anywhere from fifteen to twenty per cent higher compressive strengths in laboratory test specimens than this table says you will get, and we do that purposely because we realize that in the field you run into different curing conditions and different temperatures and a lot of other things. Therefore, you must have a factor of safety when you devise a table of this kind.