volumes A practice that deserves serious consideration by highway engineers is that of the separate measurement of sizes of coarse aggregates

DESIGN OF CONCRETE MIXTURES

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THEORY

In so far as strength is concerned it is now possible, by means of preliminary studies, to arrange mixtures of water, cement, fine and coarse aggregates, which will produce concrete of predetermined quality

Present knowledge of the various factors affecting strength, and methods of design have been summarized by the sub-committee on Design of Concrete of Committee C-9 on Concrete and Concrete Aggregates, of the American Society for Testing Materials, 1927 Report, as follows:

"The strength of concrete made from sound durable material depends upon

"(a) The extent to which the solid particles are glued or bonded together

"(b) The actual amount of solid material in the concrete

"Assuming a given set of aggregates and the same conditions of fabrication, two of the most important factors which affect the bond between particles are

"1 The proportion of cement in a given quantity of concrete

"2 The amount of mixing water

"Under ordinary conditions of mixing and placing, the actual amounts of solid material in the concrete depend primarily upon the quantity of mixing water present and to a lesser extent upon the entrained air which in turn depends upon the type of mixing equipment used It will be affected also by the amount of work done upon the concrete, but with plastic mixes and the usual methods and equipment, the influence of the work done is small

"*Water* The mixing water not only influences the quality of the bond between the particles and the density of the concrete, but, if in excess, it has deleterious effects other than these on the cement One such deleterious effect is in the formation of laitance

"*Cement* From the above, it follows that the gluing action of the cement will be in direct proportion to the amount of cement in the concrete Again, existing data supports this theory of mixtures and the expressions thus far formulated for the variation in the strength of concrete are in conformity with it

"These theories have been variously expressed by different investigators There are those that deal with the inter-relations of the absolute volumes of cement, aggregates and voids, for example the relation of the strength to the void-cement ratio and the relation of strength to the space-cement ratio and there is the relation between strength and the water-cement ratio

"*Space-Cement-Strength Relationship* In the first group of expressions the measure of the bonding effect of the cement is taken as directly proportional to the quantity of cement present, expressed as *c*, and the effect of the proportion of solids is measured either by means of the voids, *v*, or by means of the space, $v + c$

"The available data show that the relation between strength and space-cement ratio or void-cement ratio is affected by the amount of water used Talbot and Richart show that this effect can be measured by means of the relative water content, which is defined by them as being the ratio of the amount of water used, to that amount which would yield the smallest volume of mortar when mixed with cement and fine aggregate in the proportions under consideration (they call this the "basic" water content)

"*Water-Cement Ratio Relationship* In the water-cement ratio relationship again the proportion of cement, *c*, is used as a measure of the bonding effect, but in this case, the quantity of water, *w*, is used not only as a measure of the effect of the solids present but in addition as a measure of the effect of water upon the bonding or gluing action of the cement

"The truth of the relation of the strength to the water-cement ratio is well established by the data of Abrams, Talbot and Richart, Young, Graf, and the cooperative tests, Series 201, sponsored by this sub-committee, an analysis of which has been prepared by R A Nelson to accompany this report and appearing in Appendix I

"*Utilization* Mixtures can be correctly designed by either the use of the relationship between strength and the space-cement ratio, strength and the void-cement ratio, or strength and the water-cement ratio as is exemplified in the paper by R W Crum, being presented at this annual meeting of the Society (1927) Methods based on space or voids-cement ratio, as developed by Talbot and Richart seem to be the most precise statement of the fundamental concepts, but to date those who have utilized these theories in designing mixtures for strength have very generally adopted the water-cement ratio as it has been found simple in application and to give results of sufficient accuracy"

The references upon which this report is based are given in the report of Committee C-9, A S T M Proceedings 1927

PRACTICAL APPLICATION

Use of the basic theories of concrete design is progressing steadily, although somewhat slowly Reference is made to the 1926 report of the Committee on Character and Use of Road Materials, for the more prominent instances of concrete scientifically designed A recent Bulletin by Mr. A T. Goldbeck on "The Water-Ratio Specification for Concrete and its Limitations"[1] discusses the various points covered by the Specification for Concrete and Concrete Material, as used in the construction of the Portland Cement Association Building, and concludes by proposing a specification based upon the use of the water-cement ratio. This proposed specification differs from the usual water-

[1] Bulletin No 3, National Crushed Stone Association

cement ratio specification, in that preliminary strength tests are required to establish the particular water-ratio curve applicable to the materials to be used on the job, and second, the proper adjustments are made for different temperatures to be expected during the progress of the work Numerical example of design by this specification is presented in the bulletin

Examples of design by both the water-ratio method (Abrams) and the mortar-void method (Talbot) are presented in the section on Proportioning, in the Symposium on Field Control of the Quality of Concrete, A S T M Proceedings, 1927.

No matter upon what method or theory the design of mixture is based, the authorities agree that upon construction it is necessary that a constant ratio of water to cement be maintained. This entails the accurate measurement of all materials The basis for uniform concrete is uniform measurement of all materials so that all batches will have identical composition This involves in addition to accurate measuring devices, means for rapid and frequent determination of free water content or absorption of aggregate and adjustment of batches therefor References to suitable methods are noted in the section on fine aggregates

In the letting of contracts for public work involving large quantities of concrete as in concrete pavements, it is desirable to specify permitted mixtures for the various materials, with enough definiteness for the contractor to have reasonable certainty of the amounts of material needed for the work If definite proportions of water, cement, and aggregates are specified, the quantities of cement and aggregates can be very accurately estimated. This is important because any specification provisions that lessen contractural uncertainties will lower cost

Either the water-cement ratio method or the mortar-void method of design are adaptable to this case If the water-cement ratio method is used, the specimens upon which the design is based must include a range of proportions mixed in the consistency required on the job as well as a range of water-cement ratios The mortar-void method will yield the necessary information since the derivation of proportions for all materials is a part of the process

In the appendix to this report are given some examples from practice in the use of the Talbot "Mortar-void" theory

MEASUREMENT

The report of Committee C-9 quoted herein states that the strength of concrete is partially dependent upon the actual amount of solid material in the concrete Therefore in order to produce uniform concrete it is necessary that each batch contain the same actual volume of solid particles This can be accomplished by weighing The weight per unit of absolute volume of cement and aggregates is a constant so long as the specific gravity is constant Inundation will serve in the case of sand because the relations involved are constant. There is no such constant relation in the case of loose volume measurement, and such measurements cannot be expected to produce the desired result of uniformity in batch composition.

The proportions of materials for a given case determined by scientific analysis are on the basis of absolute volumes They can best be expressed for use by weight, since weight is a direct function of absolute volume.

If it be assumed that all of the space concreted is occupied by water, cement, and aggregates, it is possible to make a close estimate of quantities required, from a proportion specified by weight

For instance take the following example The mix is to be 1 to 3 5 by weight using 4 83 gallons of water per bag of cement The specific gravity of the cement is 3 14 and of the aggregate is 2 65 The volumes of materials in a one bag batch would be as follows:

Cement	$94 \text{ lbs} = \dfrac{94}{3\,14 \times 62\,4}$	$= 48$ cu ft
Aggregate	$329 \text{ lbs} = \dfrac{329}{2\,65 \times 62\,4}$	$= 1\,99$ cu ft
Water	$4\,83 \text{ gal} = \dfrac{4\,83}{7\,5}$	$= 64$ cu ft
		3 11 cu ft

It follows therefore that 3 11 cu ft of concrete will require 1 bag of cement Hence one cubic yard of concrete will require 8 68 bags or 2 17 bbl.

It should be evident from this discussion that arrangement of proportions by weight is in accord with the basic facts upon which the strength of concrete depends, and therefore these factors can be much more accurately controlled in the field if weight proportions and measurement by weight are used.

MEASUREMENT OF WATER

The maintenance of the correct volume of water per batch is dependent upon three factors accuracy of measurement, correction for the free water carried by the aggregates, and correction for the water to be absorbed by the aggregates.

Since water is volume constant it can be accurately measured However, in connection with concrete mixers, the design of the apparatus is complicated by the necessity for rapid measurement and discharge of large quantities At stationary plants, satisfactory accuracy with easy means of adjustment for variable quantity as needed can be secured either by weight or by volume At moving plants such as are used on highway pavement construction, the problem is more complicated. The chief difficulties are leakage into the mixer after the discharge valve is closed, crude measurement by means of water gage, and variable effect of pipe line pressure At the present time many paving mixers are equipped with water tanks which will furnish a constant quantity of water for a given setting of the adjusting device, under uniform water pressure Some are designed to be independent of gradient and super-elevation and some require adjustment for these factors Valves are procurable that are free from leakage for a considerable time The most common principle used in measuring water at paving mixers is to draw the water from a full tank down to some level which can be controlled from the outside The common source of error is the filling of the tank If the pipe line pressure is low, the tank may not fill during the allotted time With higher pressures, unless the air vents are very carefully designed air may be trapped and spoil the measurement Some improvements insuring against these sources of inaccuracy are needed The cycle of operations upon a modern paving mixer requires that about 42 gal. be measured in 60 sec and discharged in 10 sec or less

The inundation method of measuring sand offers good possibilities for accurate measurement of water, especially at stationary plants The bulk of the water can be accurately measured with the sand The remainder to be measured by the usual methods is small enough that the problem is much simplified

It seems evident from the improvements already made that water-measuring devices, accurate under all usual conditions, will soon be developed. Accurate water measurement will not be of much value unless account is taken of the water that comes with the aggregates and that which is lost by absorption into the stone. In order to fully control water content it is necessary to have the inspector in charge of the proportioning plant equipped with the necessary laboratory outfit for making determinations of these factors and making corrections therefor

MEASUREMENT OF AGGREGATES

The measurement of sand by loose volume is difficult because of the wide variation in bulk due to moisture and to the manner in which the measure is filled The volume of sand is approximately constant when dry Therefore, proportions to mean anything must be based upon a dry condition, and, in actual measuring, corrections must be made for the expected bulking Since the bulking also depends upon the manner of filling the measure, this correction will never be better than an approximation Undoubtedly in the interests of uniformity the actual volume of material in all batches should be the same, and it would seem that in order to accomplish this, more accurate methods of measurement should be used

Two methods are available for accurate measurement of sand—inundation and direct weighing It is known that sand measured under water will yield the same absolute volume of sand grains per unit of volume as dry sand. The inundation method of measurement can, therefore, be used to give definite quantities of sand and water per batch The method was first described by R L Bertin in the American Society for Testing Materials, Proceedings for 1922, page 404, and has been used on many operations

Sand can be easily weighed to a high degree of accuracy, and moisture corrections can be easily and accurately made The equipment cost is practically negligible, and there are no practical difficulties in handling the material.

Neither inundation nor weighing cause delay in production Coarse aggregates are not subject to the bulking effect of moisture, and can, therefore, be more accurately measured volumetrically However, greater accuracy is attainable with weights, more definite records of quantities used are secured, and more accurate advance estimates of quantities are possible

Difficulty is sometimes met in the use of coarse aggregate from large stockpiles, due to segregation of sizes If the aggregate is weighed, the same absolute volume of particles will be put in each batch irrespective of grading If the mix is so designed that the mortar will more than fill the voids in the worst combination of sizes to be expected in the course aggregate, the strength will not be affected by the stockpile variation There may be some effect upon workability If considerations of economy require the use of a minimum proportion of mortar, the stockpile variation of the coarse aggregate may cause trouble In such a case volumetric measurement of the coarse aggregate would roughly compensate for the effect of segregation, for with an increase in voids less stone would go into the batch The advantage of definite batch composition and yield would be lost in this case

A much more definite method would be to supervise the building of the stockpile so that segregation could be kept within allowable limits Upon important work it is possible that it may be found worth while to separate the coarse aggregate into several sizes

Apparatus Several arrangements of weighing apparatus have been successfully used Simple field-built bins and hoppers used with ordinary platform or mill scales have been found satisfactory, as well as permanent equipment designed and built by manufacturers of paving equipment

Four general types are in use as follows:

1. Bottom-dumping hopper on lever-weighing system, with direct reading dial scale
2 Batcher device adapted to weighing system, usually with pipe lever scales
3 Bottom-dumping hopper on platform scales
4. Side-dumping hopper on platform scales.
   Stationary scales
   Movable scales for loading industrial railway boxes.

In the design of plants for weighing aggregates, special attention should be given to the following points

The weighing system should be sturdy and not easily thrown out of adjustment

The number of points requiring adjustment should be a minimum Scales which have sixteen bolts to adjust in setting up are not so satisfactory in practice as those which have four or less.

All bearings should be well protected against penetration of sand and dust

The inside of the weighing hopper should be accessible, so that the operator can very easily remove excess material in getting the correct weight

The committee also wishes to call attention to the desirability of providing an interlocking arrangement between the discharge gate from the bins and the hopper discharge, so that additional material cannot leave the bins while the hopper is being emptied.

APPENDIX

1 Example of the use of mortar-void method in designing a mixture to meet an unusual condition From practice of the Iowa Highway Commission

Owing to the scarcity of coarse aggregate in a certain locality, it was desired to provide a specification for the use of a prepared mixture of sand and fine gravel, known locally as sand-gravel, which would yield concrete equal in strength to the other mixtures provided in the specifications The composition of the typical material is as follows

Sieve No	Percentage passing
100	0 6
50	5 7
30	15 3
14	31 3
8	57 3
4	82 3
1	100 0

The specific gravity of the cement used was 3 13 and of the aggregate was 2 65 The weight of a cubic foot of water was assumed to be 62 4 lbs The weights per cubic foot of absolute volume of the materials was, therefore,

$$\text{Cement} = 3\ 13 \times 62\ 4 \text{ lb} = 195\ 4 \text{ lb}$$
$$\text{Aggregate} = 2\ 65 \times 62\ 4 \text{ lb} = 165\ 4 \text{ lb}$$

Analysis of this material by the methods described by Talbot and Richart, Bulletin No 137, Engineering Experiment Station, University of Illinois, yielded the data characteristic of the material from which the curves shown in Figures 1 and 2 were plotted

Having this information, it was desired to design a mixture of suitable consistency for paving work that would have a crushing strength of at least 3500 pounds per square inch at 28 days of age The procedure was as follows·

From the data it was noted that mixtures having a water content 1 2 times the water content needed to produce mortar of minimum volume (basic water) would be of suitable consistency or workability The mixture was, therefore, designed for 1 2 relative water content

The strength required is 3500 pounds per square inch at 28 days Since the strength curve (Figure 1) applies to concrete or mortar of basic water content, it will be necessary to know the probable strength of mortar of similar composition at basic water content According to Talbot and Richart, such mortar or concrete is 1.19 times stronger than at 1 2 relative water content Therefore, the strength at basic

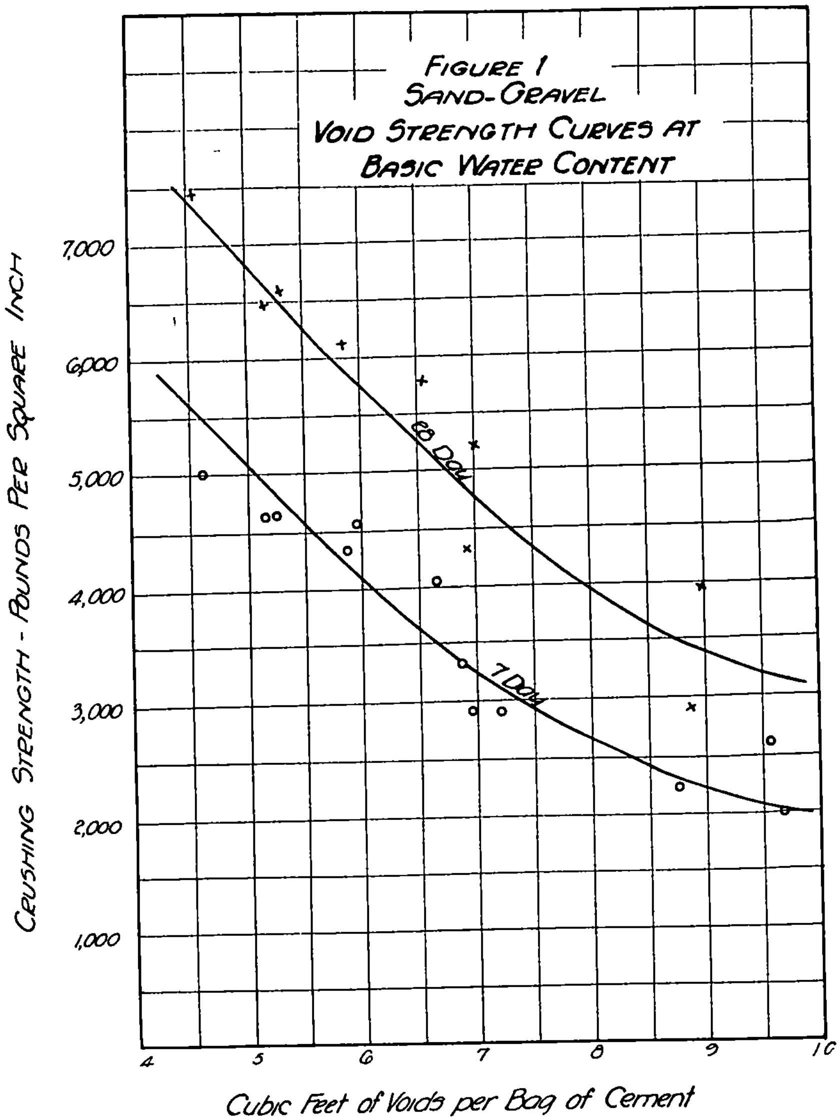

Figure 1

water content would need to be 1 19 x 3500 pounds, or 4165 pounds per square inch

Referring to Figure 1, we find that for a strength of 4165 pounds per square inch at 28 days, or 2800 pounds per square inch at 7 days, the concrete must have 775 cubic feet of voids per bag of cement This means that concrete having 775 cubic feet of void space per bag of cement should develop strength of 4165 pounds per square inch at 28 days, or 2800 pounds per square inch at 7 days, if the water content is such as will yield minimum volume (basic) or 3500 pounds per square inch and 2350 pounds per square inch, respectively, if the concrete is 1 2 times wetter than the basic condition

Referring to the characteristic curves for 1 2 relative water content in Figure 2, we find that for 775 cubic feet of voids per bag the ratio

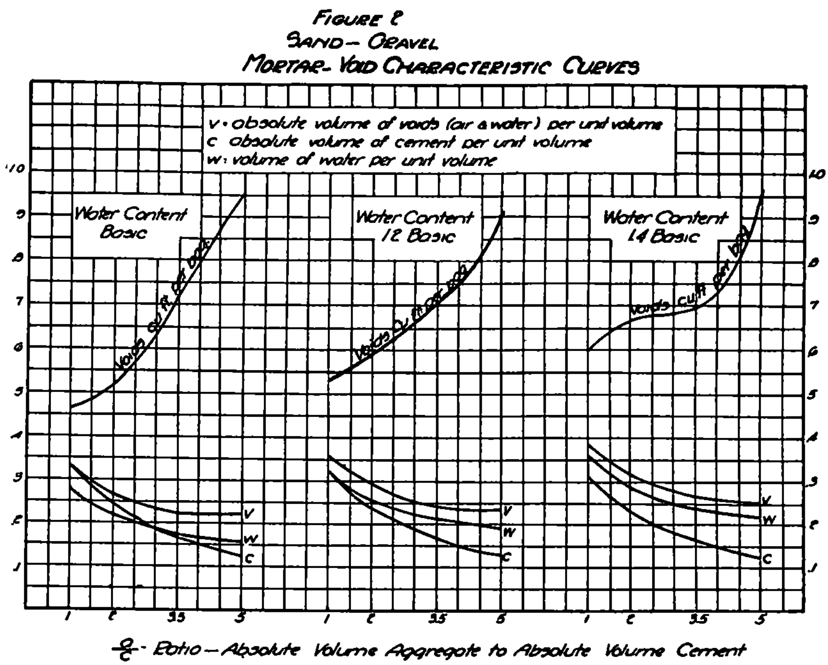

Figure 2

of aggregate to cement by absolute volume would need to be 4 125, and that the unit composition of the concrete would be as follows:

Cement	148 cu ft abs vol per cu ft of concrete
Aggregate	611 cu ft abs vol per cu ft of concrete
Water	198 cu ft per cu ft concrete
Air Voids	042 cu ft per cu ft concrete
	999

Reducing these volumes to pounds, we find the composition of the concrete to be as follows.

Cement	$= 148 \times 195\,4$ lb $= 28\,9$ lb per cu ft of concrete
Aggregate	$= 611 \times 165\,4$ lb $= 101\,0$ lb per cu ft of concrete
Water	$= 198 \times 62\,4$ lb $= 12\,35$ lb per cu ft of concrete

The mix is, therefore, 28 9 lb cement to 101 0 lb aggregate = 1 to 3 5

The water cement ratio is 12 35 lb per 28.9 lb cement $= \frac{12\ 35}{28\ 9} \times 94 = 40\ 25$ lb $= 4\ 83$ gal per bag of cement

The concrete will require 28 9 lb cement per cu ft $= 27 \times 28\ 9$ lb $= 780$ lb $= 2\ 08$ bbl per cu yd of concrete

Having the mixture designed, a trial batch was made up, with the following comparative results.

	Design	Trial
Cement	28 9 lb cu ft	28 72 lb cu ft
Aggregate	101 0 lb cu ft	100 30 lb cu ft
Water	12 35 lb cu ft	12 35 lb cu ft
7-day crushing strength	—2300 lb per sq in	—2740 lb per sq in

2. Example of design including coarse aggregate with the material of the preceding example

A more common case would be the one where it is desired to add coarse aggregate to such a material, thereby reducing the cement required for the concrete

Assume that a crushed stone having a specific gravity of 2 55 and about 45 0 voids is to be added in such an amount that the voids in the coarse aggregate will be somewhat more than filled by the mortar. Let us, therefore, add to each cubic foot of the sand-gravel concrete 0.75 cubic feet of stone, absolute volume, this procedure being based upon the assumption that adding coarse aggregate will not change the unit strength, within the limits of workability, and that the total voids will remain the same The elements of the concrete would then become:

Cement	148 cu ft abs vol per 1 75 cu ft concrete
Sand-Gravel	611 cu ft abs vol per 1 75 cu ft concrete
Crushed stone	750 cu ft abs vol per 1 75 cu ft concrete
Water	198 cu ft abs vol per 1 75 cu ft concrete
Air voids	042 cu ft abs vol per 1 75 cu ft concrete
	1 749

Reducing these volumes to pounds as before, we find the probable composition of the concrete to be as follows·

Cement $= 148 \times 195\ 4$ lb $= 28\ 9$ lb per 1 75 cu ft of concrete

Sand-Gravel $= 611 \times 165\ 4$ lb $= 101\ 0$ lb per 1 75 cu ft of concrete

Crushed stone $= 750 \times 2\ 55 \times 62\ 4$ lb $= 119\ 3$ lb per 1 75 cu ft of concrete

Water $= 198 \times 62\ 4$ lb $= 12\ 35$ lb per 1 75 cu ft of concrete

The mix is, therefore, 28 9 lb cement to 101 0 lb sand-gravel to 119 3 lbs crushed stone = 1 to 3.5 to 4 13

The water cement ratio as in the other example = 12 35 lbs water per 28 9 lbs of cement = 4 83 gal per bag of cement

The concrete will require 28 9 lbs cement per 1.75 cu. ft of concrete $= \frac{27}{1\ 75} \times 28.9 = 446$ lb per cu. yd = 1.19 bbl. per cu yd

It is possible that this mix would be found too dry for good workability, in which case, a redesign for higher relative water content would be necessary

TESTS ON FINISHED CONCRETE

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Portland cement concrete is a manufactured product. The materials used are Portland cement, water, and mineral aggregates In general, these materials are combined to form concrete on the job For this reason the manufacture of concrete presents problems in quality control not encountered in the majority of manufacturing processes This local manufacture results in the use of a large number of relatively small portable manufacturing plants, and, for the most part, unskilled local labor is employed The production varies at any one location from a few cubic yards for monolithic culverts to thousands of cubic yards for pavements The manufacturing process should be such that concrete of the desired properties is obtained with the most economical use of the available materials. Tests of the concrete are necessary to determine its properties

When large quantities of concrete are required, it may be economical to apply the latest developed principles, using laboratories and employing very rigid control for every operation This would assure obtaining uniform quality of concrete at lowest cost for materials used. For such concrete a small factor of safety could be used in design On the other hand, for small yardages it may be more economical to spend less for field control and more for materials This would result in less uniform concrete and necessitate the use of a larger factor of safety

Accordingly, we may divide the concrete to be tested into two classes:

1 Concrete produced in large quantities, scientifically designed as to mix and rigidly controlled in the field Concrete produced under these conditions will be uniform in its properties