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Guide for Selecting Proportions for No-Slump Concrete

Reported by ACI Committee 211

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This guide is intended as a supplement to ACI 211.1. A procedure is presented for proportioning concrete that has slumps in the range of zero to 25 mm (1 in.) and consistencies below this range, for aggregates up to 75 mm (3 in.) maximum size. Suitable equipment for measuring such consistencies is described. Tables and charts similar to those in ACI 211.1 are provided which, along with laboratory tests on physical properties of fine and coarse aggregate, yield information for obtaining concrete proportions for a trial mixture.

This document also includes appendixes on proportioning mixtures for roller-compacted concrete, concrete roof tile, concrete masonry units, and pervious concrete for drainage purposes. Examples are provided as an aid in calculating proportions for these specialty applications.

Keywords: durability; mixture proportioning; no-slump concrete; roller-compacted concrete; slump test; water-cementitious materials ratio.

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ACI 211.3R-02 supersedes ACI 211.3R-97 and became effective January 11, 2002.

CHAPTER 1—SCOPE AND LIMITS

ACI 211.1 provides methods for proportioning concrete with slumps greater than 25 mm (1 in.) as measured by ASTM C 143/C 143M. This guide is an extension of ACI 211.1 and addresses the proportioning of concrete having slump in the range of zero to 25 mm (1 in.).

The paired values stated in inch-pound and SI units are the results of conversions that reflect the intended degree of accuracy. Each system is used independently of the other in the examples. Combining values from the two systems may result in nonconformance with this guide.

In addition to the general discussion on proportioning no-slump concrete, this guide includes proportioning procedures for these classes of no-slump concrete: roller-compacted concrete (Appendix 3); roof tiles (Appendix 4); concrete masonry units (CMU) (Appendix 5); and pervious concrete (Appendix 6).

CHAPTER 2—PRELIMINARY CONSIDERATIONS

2.1—General

The general comments contained in ACI 211.1 are pertinent to the procedures discussed in this guide. The description of the constituent materials of concrete, the differences in proportioning the ingredients, and the need for knowledge of the physical properties of the aggregate and cementitious materials apply equally to this guide. The level of overdesign indicated in ACI 301 and ACI 318/318R should be applied to the compressive strength used for proportioning.

2.2—Methods for measuring consistency

Workability is the property of concrete that determines the ease with which it can be mixed, placed, consolidated, and finished. No single test is available that will measure this property in quantitative terms. It is usually expedient to use some type of consistency measurement as an index to workability. Consistency may be defined as the relative ability of freshly mixed concrete to flow. The slump test is the most familiar test method for consistency and is the basis for the measurement of consistency under ACI 211.1.

Table 2.1—Comparison of consistency measurements for slump and Vebe apparatus

Consistency description	Slump, mm	Slump, in.	Vebe, s
Extremely dry	—	—	32 to 18
Very stiff	—	—	18 to 10
Stiff	0 to 25	0 to 1	10 to 5
Stiff plastic	25 to 75	1 to 3	5 to 3
Plastic	75 to 125	3 to 5	3 to 0
Very plastic	125 to 190	5 to 7-1/2	—

Table 2.2—Approximate relative water content for different consistencies

Consistency description	Approximate relative water content, %	
	Thaulow[5]	Table 6.3.3, ACI 211.1
Extremely dry	78	—
Very stiff	83	—
Stiff	88	—
Stiff plastic	93	92
Plastic	100	100
Very plastic	106	106

No-slump concrete will have poor workability if consolidated by hand-rodding. If vibration is used, however, such concrete might be considered to have adequate workability. The range of workable mixtures can therefore be widened by consolidation techniques that impart greater energy into the mass to be consolidated. The Vebe apparatus,[1,2] the compacting factor apparatus,[3] the modified compaction test, and the Thaulow drop table[4] are laboratory devices that can provide a useful measure of consistency for concrete mixtures with less than 25 mm (1 in.) slump. Of the three consistency measurements, the Vebe apparatus is frequently used today in roller-compacted concrete and will be referred to in this guide. The Vebe test is described in Appendix 2. If none of these methods are available, consolidation of the trial mixture under actual placing conditions in the field or laboratory will, of necessity, serve as a means for determining whether the consistency and workability are adequate. Suitable workability is often based on visual judgement for machine-made precast concrete products.

A comparison of Vebe test results with the conventional slump test is shown in Table 2.1. Note that the Vebe test can provide a measure of consistency in mixtures termed “extremely dry.” Vebe time at compaction is influenced by other factors such as moisture condition of aggregates, time interval after mixing, and climatic conditions.

2.3—Mixing water requirement

In ACI 211.1, approximate relative mixing water requirements are given for concrete conforming to the consistency descriptions of stiff plastic, plastic, and very plastic, as shown in Table 2.2 of this guide. Considering the water requirement for the 75 to 100 mm (3 to 4 in.) slump as 100%, the relative water contents for those three consistencies are 92, 100, and 106%, respectively. Thaulow[5] extended this concept of relative water contents to include stiffer mixtures, as shown in Table 2.2.

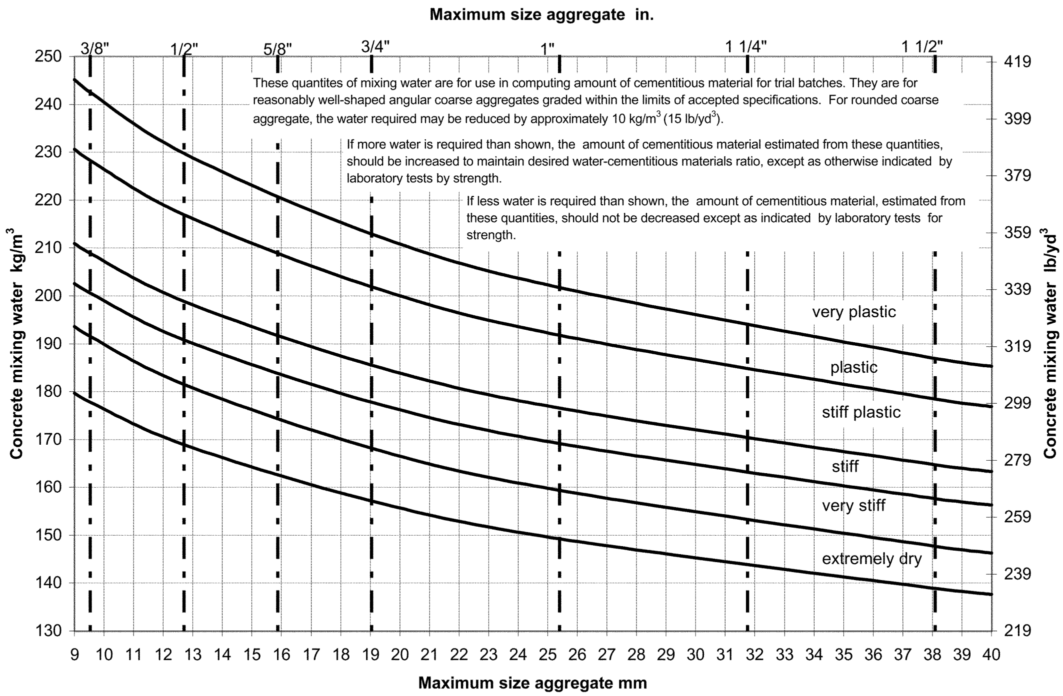


Fig. 2.1—Approximate mixing water requirements for different consistencies and maximum-size aggregate for nonair-entrained concrete.

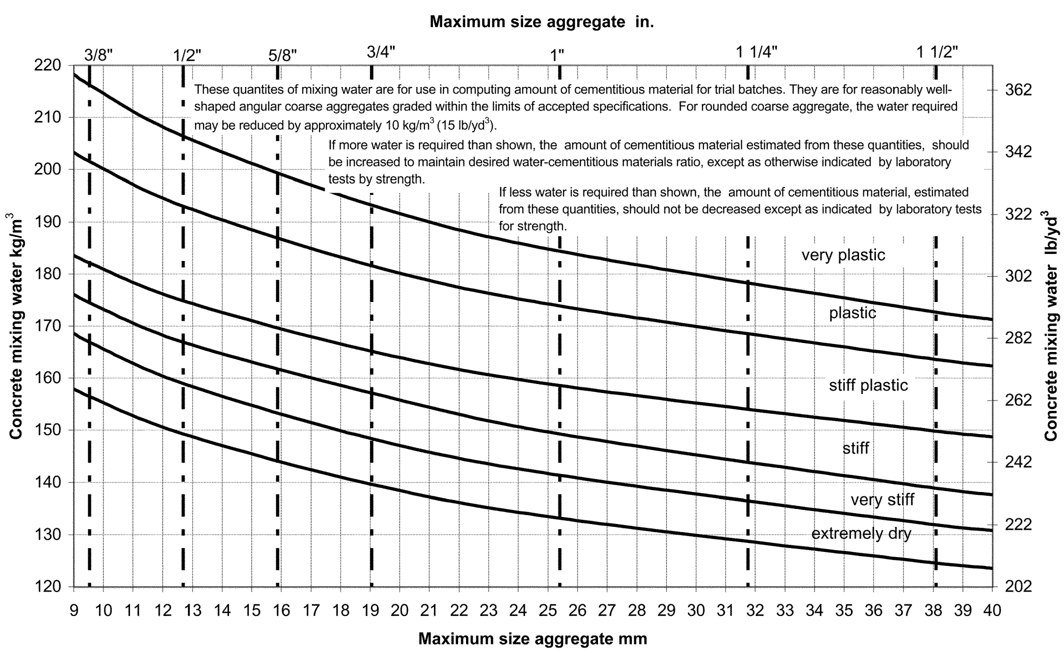


Fig. 2.2—Approximate mixing water requirements for different consistencies and maximum-size aggregate for air-entrained concrete.

Figures 2.1 and 2.2 have been prepared based on the results from a series of laboratory tests in which the average air contents were as indicated in Fig. 2.3. These tests show that the factors in Table 2.2 need to be applied to the quantities given in ACI 211.1 to obtain the approximate water content for the six consistency designations. Approximate relative mixing water requirements are given in kg/m^3 (lb/yd^3) using the relative water contents shown by Thaulow[5] for the stiff, very stiff, and extremely dry consistencies. For a given combination of materials, a number of factors will affect the actual mixing water requirement and can result in a considerable difference from the values shown in Fig. 2.1 and 2.2. These factors include particle shape and grading of the aggregate, air content and temperature of the concrete, the effectiveness of mixing, chemical admixtures, and the method of consolidation. With respect to mixing, for example, spiral-blade and pan-type mixers are more effective for no-slump concretes than are rotating-drum mixers.

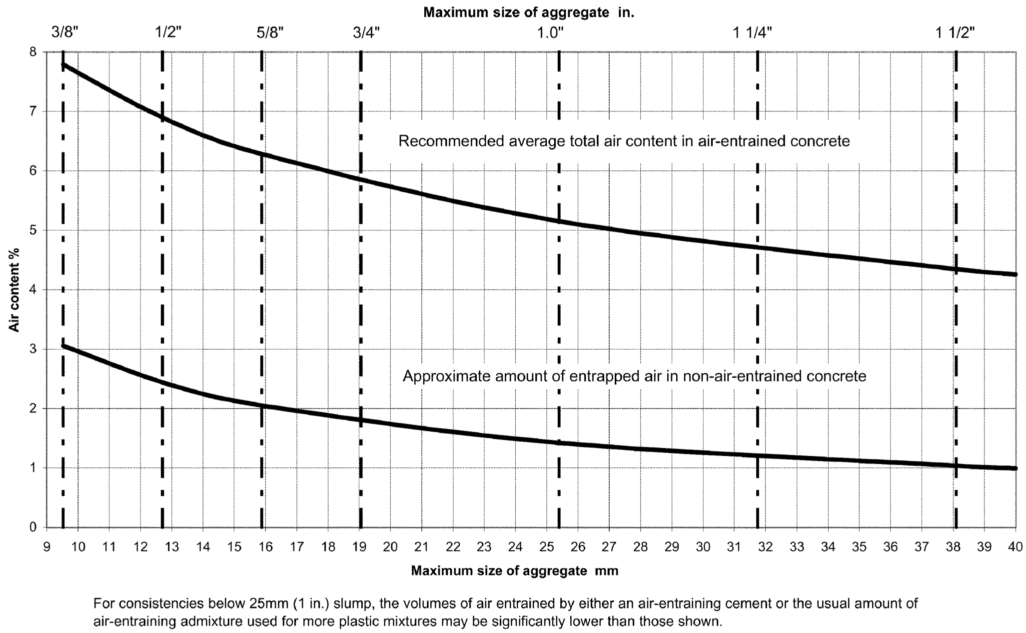


Fig. 2.3—Air content of concrete mixtures for different maximum size aggregate.

CHAPTER 3—SELECTING PROPORTIONS

3.1—General

Cementitious materials include the combined mass of cement, natural pozzolans, fly ash, ground granulated-blast-furnace slag (GGBFS), and silica fume that are used in the mixture.

As recommended in ACI 211.1, concrete should be placed using the minimum quantity of mixing water consistent with mixing, placing, consolidating, and finishing requirements because this will have a favorable influence on strength, durability, and other physical properties. The major considerations in selecting proportions apply equally well to no-slump concretes as to the more plastic mixtures. These considerations are:

- Adequate durability in accordance with ACI 201.2R to satisfactorily withstand the weather and other destructive agents to which it may be exposed;
- Strength required to withstand the design loads with the required margin of safety;
- The largest maximum-size aggregate consistent with economic availability, satisfactory placement, and concrete strength;
- The stiffest consistency that can be efficiently consolidated; and
- Member geometry.

3.2—Slump and maximum-size aggregate

ACI 211.1 contains recommendations for consistencies in the range of stiff plastic to very plastic. These, as well as stiffer consistencies, are included in Fig. 2.1 and 2.2. Consistencies in the very-stiff range and drier are often used in the fabrication of various precast elements such as, pipe, prestressed members, CMU, and roof tiles. Also, roller-compacted and pervious concretes fall into the no-slump categories as discussed in Appendix 3 through 6. There is no apparent justification for setting limits for maximum and minimum consistency in the manufacture of these materials because the optimum consistency is highly dependent on the equipment, production methods, and materials used. It is further recommended that, wherever possible, the consistencies used should be in the range of very stiff or drier, because the use of these drier consistencies that are adequately consolidated will result in improved quality and a more economical product.

The nominal maximum size of the aggregate to be selected for a particular type of construction is dictated primarily by consideration of both the minimum dimension of a section and the minimum clear spacing between reinforcing bars, prestressing tendons, ducts for post-tensioning tendons, or other embedded items. The largest permissible maximum-size aggregate should be used; however, this does not preclude the use of smaller sizes if they are available and their use would result in equal or greater strength with no detriment to other concrete properties.

For reinforced, precast concrete products such as pipe, the maximum coarse aggregate size is generally 19 mm (3/4 in.) or less.

3.3—Estimating water and aggregate-grading requirements

The quantity of water per unit volume of concrete required to produce a mixture of the desired consistency is influenced by the maximum size, particle shape, grading of the aggregate, and the amount of entrained air. It is relatively unaffected by the quantity of cementitious material below about 360 to 390 kg/m^3 (610 to 660 lb/yd^3). In mixtures richer than these, mixing water requirements can increase significantly as cementitious materials contents are increased. Acceptable aggregate gradings are presented in ASTM C 33 and AASHTO M 6 and M 80.

Aggregate grading is an important parameter in selecting proportions for concrete in machine-made precast products such as pipes, CMU, roof tile, manholes, and prestressed products. Forms for these products are removed immediately after the concrete is placed and consolidated, or the concrete is placed by an extrusion process. In either case, the concrete has no external support immediately after placement and consolidation; therefore, the fresh concrete mixture should be cohesive enough to retain its shape after consolidation. Cohesiveness is achieved by providing sufficient fines in the mixtures. Some of these fines can be obtained by careful selection of the fine aggregate gradings. Pozzolans, such as fly ash, have also been used to increase cohesiveness. In some cases, the desired cohesiveness can be improved by increasing the cementitious materials content. This approach is not recommended, however, because of negative effects of excessive cementitious materials such as greater heat of hydration and drying shrinkage.

The quantities of water shown in Fig. 2.1 and 2.2 of this guide are sufficiently accurate for preliminary estimates of proportions. Actual water requirements need to be established in laboratory trials and verified by field tests. This should result in water-cementitious materials ratios (*w/cm*) in the range of 0.25 to 0.40 or higher. Examples of such adjustments are given further in this guide.

For machine-made, precast concrete products such as pipes and CMU, the general rule is to use as much water as the product will tolerate without slumping or cracking when the forms are stripped.

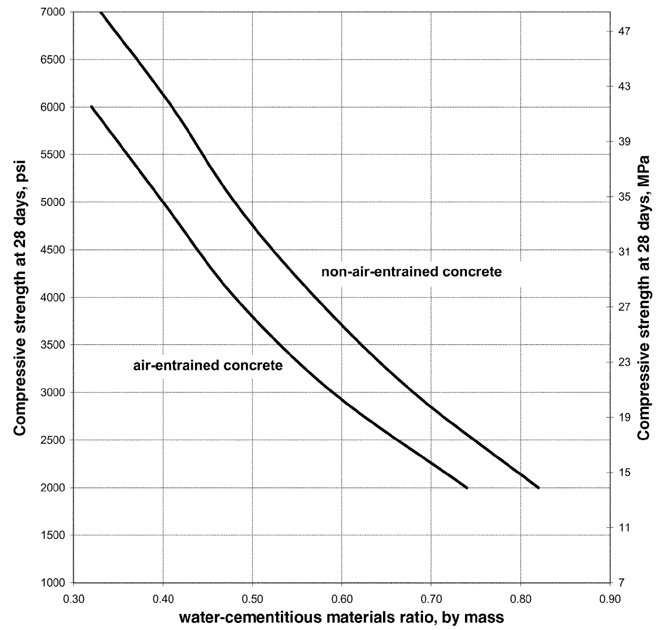
3.4—Selecting water-cementitious materials ratio

The selection of *w/cm* depends on the required strength. Figure 3.1 provides initial information for *w/cm*. The compressive strengths are for 150 x 300 mm (6 x 12 in.) cylinders, prepared in accordance with ASTM C 192, subjected to standard moist curing, and tested at 28 days in accordance with ASTM C 39 for the various ratios. The required *w/cm* to achieve a desired strength depends on whether the concrete is air-entrained.

Using the maximum permissible *w/cm* from Fig. 3.1 and the approximate mixing water requirement from Fig. 2.1 and 2.2, the cementitious material content can be calculated by dividing the mass of water needed for mixing by the *w/cm*. If the specifications for the job contain a minimum cementitious material content requirement, the corresponding *w/cm* for estimating strength can be computed by dividing the mass of water by the mass of the cementitious material. The lowest of the three *w/cm*—those for durability, strength, or cementitious material content—should be selected for calculating concrete proportions.

Air-entraining admixtures or air-entraining cements can be beneficial in ensuring durable concrete in addition to providing other advantages, such as reduction in the mixture harshness with no increase in water. Air-entrained concrete should be used when the concrete products are expected to be exposed to frequent cycles of freezing and thawing in a moist, critically saturated condition. ASTM C 666 testing before construction is recommended to assess resistance to freezing-and-thawing characteristics of the no-slump concrete. If these no-slump concrete mixtures may be exposed to deicer salts, they should also be tested in accordance with ASTM C 666.

Figure 3.1 is based on the air contents shown in Fig. 2.3. In Fig. 3.1 at equal *w/cm*, the strengths for the air-entrained



Values are estimated average strengths for concrete containing not more than the percentage of air shown in Fig. 2.3. For a constant water-cementitious materials ratio, the strength of concrete is reduced as the air content is increased.
Strength is based on 150 x 300 mm (6 x 12 in.) cylinders prepared in accordance with ASTM C 31/31M and moist-cured 28 days at 23 ± 1.7 °C (73.4 ± 3 °F).
Relationship assumes maximum size aggregate about 19 to 25 mm (3/4 to 1 in.) for a given source; strength produced for a given water-cementitious materials ratio will increase as maximum size of aggregate decreases.

Fig. 3.1—Relationships between water-cementitious materials ratio and compressive strength of concrete.

concrete are approximately 20% lower than for the nonair-entrained concrete. These differences may not be as great in the no-slump mixtures because the volume of entrained air in these mixtures using an air-entraining cement, or the usual amount of air-entraining admixture per unit of cementitious material, will be reduced significantly with practically no loss in resistance to freezing and thawing and density. In addition, when cementitious material content and consistency are constant, the differences in strength are partially or entirely offset by reduction of mixing water requirements that result from air entrainment.

The required average strength necessary to ensure the strength specified for a particular job depends on the degree of control over all operations involved in the production and testing of the concrete. See ACI 214 for a complete guide. If flexural strength is a requirement rather than compressive strength, the relationship between *w/cm* and flexural strength should be determined by laboratory tests using the job materials.

3.5—Estimate of coarse aggregate quantity

The largest quantity of coarse aggregate per unit volume of concrete should be used and be consistent with adequate placeability. For the purpose of this document, placeability is defined as the ability to adequately consolidate the mixture with the minimum of physical and mechanical time and effort. For a given aggregate, the amount of mixing water required will then be at a minimum and strength at a maximum. This quantity of coarse aggregate can best be determined from laboratory investigations using the materials for the intended work with later adjustment in the field or plant.

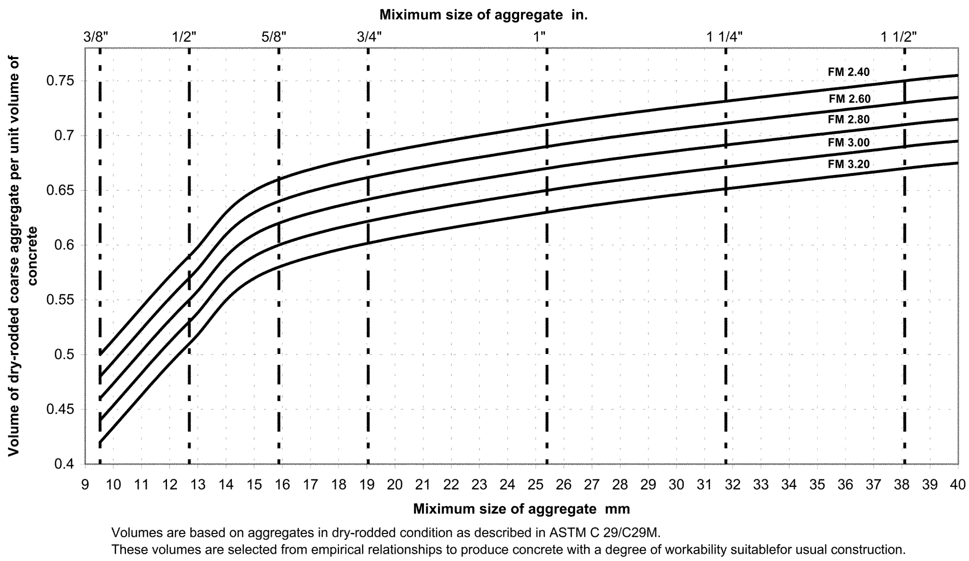


Fig. 3.2—Volume of coarse aggregate per unit volume of concrete of plastic consistency (75 to 125 mm [3 to 5 in.] slump).

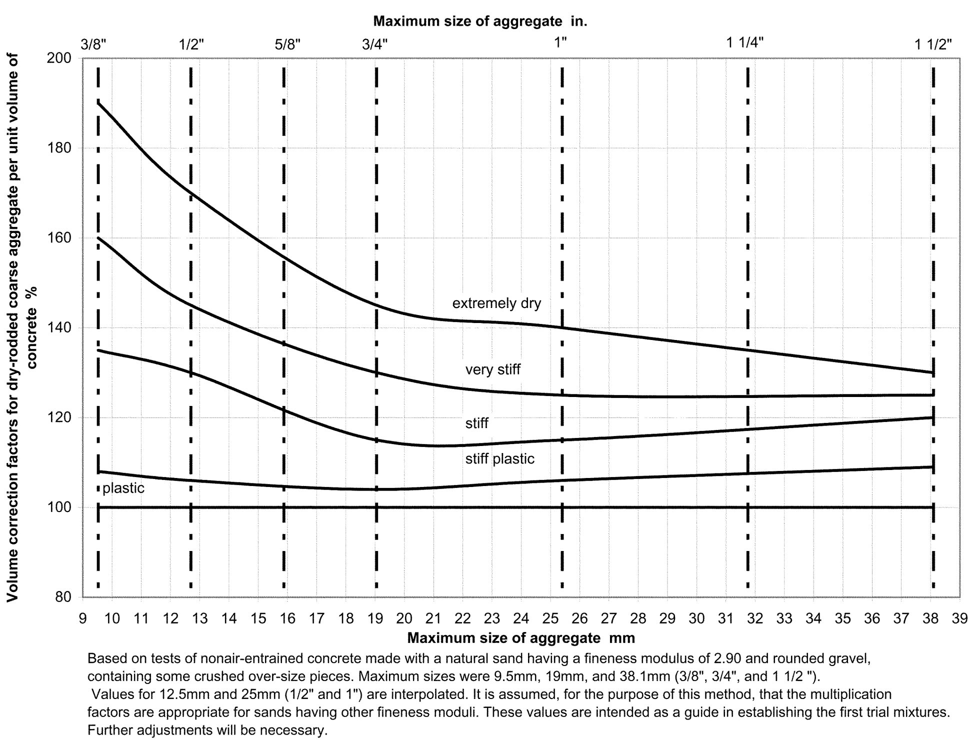


Fig. 3.3—Volume correction factors for dry-rodded coarse aggregate for concrete of different consistencies.

If such data are not available or cannot be obtained, Fig. 3.2 provides a good estimate of the amount of coarse aggregate for various concrete having a degree of workability suitable for usual reinforced concrete construction (approximately 75 to 100 mm [3 to 4 in.] slump). These values of dry-rodded volume of coarse aggregate per unit volume of concrete are based on established empirical relationships for aggregates graded within conventional limits. Changes in the consistency of the concrete can be affected by changing the amount of coarse aggregate per unit volume of concrete. As greater amounts of coarse aggregate per unit volume are used, the consistency will decrease. For the very plastic and plastic consistencies, the volume of coarse aggregate per unit volume of concrete is essentially unchanged from that shown in Fig. 3.2. For the stiffer consistencies—those requiring vibration—the amount of coarse aggregate that can be accommodated increases rather sharply in relation to the amount of fine aggregate required. Figure 3.3 shows some typical values of the volume of coarse aggregate per unit volume of concrete for different consistencies, expressed as a percentage of the values shown in Fig. 3.2. The information contained in these two figures provides a basis for selecting an appropriate amount of coarse aggregate for the first trial mixture. Adjustments in this amount will probably be necessary in the field or plant operation.

In precast concrete products where cohesiveness is required to retain the concrete shape after the forms are stripped, the volume of coarse aggregate can be reduced somewhat from the values indicated in Fig. 3.2. The degree of cohesiveness required depends on the particular process used to make the concrete product. Uniformly graded aggregate is important in precast concrete pipe; therefore, blends of two or more coarse aggregates are frequently used.

Concrete of comparable workability can be expected with aggregates of comparable size, shape, and grading when a given dry-rodded volume of coarse aggregate per unit volume of concrete is used. In the case of different types of aggregates, particularly those with different particle shapes, the use of a fixed dry-rodded volume of coarse aggregate automatically makes allowance for differences in mortar requirements as reflected by void content of the coarse aggregate. For example, angular aggregates have a higher void content, and therefore, require more mortar than rounded aggregates.

This aggregate-estimating procedure does not reflect variations in grading of coarse aggregates within different maximum-size limits, except as they are reflected in percentages of voids. For coarse aggregates falling within the limits of conventional grading specifications, this omission probably has little importance. The optimum dry-rodded volume of coarse aggregate per unit volume of concrete depends on its maximum size and the fineness modulus of the fine aggregate as indicated in Fig. 3.2.

CHAPTER 4—PROPORTIONING COMPUTATIONS (SI UNITS)

4.1—General proportioning criteria

Computation of proportions will be explained by one example. The following criteria are assumed:

- The cement specific gravity is 3.15;
- Coarse and fine aggregates in each case are of satisfactory quality and are graded within limits of generally accepted specifications such as ASTM C 33 and C 331;
- The coarse aggregate has a specific gravity, bulk oven dry, of 2.68, and an absorption of 0.5%; and
- The fine aggregate has a specific gravity, bulk oven dry, of 2.64, an absorption of 0.7%, and fineness modulus of 2.80.

4.2—Example of proportioning computations

Concrete is required for an extruded product in northern France that will be exposed to severe weather with frequent cycles of freezing and thawing. Structural considerations require it to have a design compressive strength of 30 MPa at 28 days. From previous experience in the plant producing similar products, the expected coefficient of variation of strengths is 10%. It is further required that no more than one test in 10 will fall below the design strength of 30 MPa at 28 days. From Fig. 4.1(a) of ACI 214, the required average strength at 28 days should be 30 MPa × 1.15, or 35 MPa. The size of the section and spacing of reinforcement are such that a nominal maximum-size coarse aggregate of 40 mm, graded to 4.75 mm, can be used and is locally available. Heavy internal and external vibration are available to achieve consolidation, enabling the use of very stiff concrete. The dry-rodded density of the coarse aggregate is 1600 kg/m^3. Because the exposure is severe, air-entrained concrete will be used. The proportions may be computed as follows:

From Fig. 3.1, the *w/cm* required to produce an average 28-day strength of 35 MPa in air-entrained concrete is shown to be approximately 0.40 by mass.

The approximate quantity of mixing water needed to produce a consistency in the very stiff range in air-entrained concrete made with 40 mm nominal maximum-size aggregate is 130 kg/m^3 (Fig. 2.2). In Fig. 2.3, the required air content for the more plastic mixture is indicated to be 4.5%, which will be produced by using an air-entraining admixture. An air-entraining admixture, when added at the mixer as liquid, should be included as part of the mixing water. The note to the figure calls attention to the lower air contents entrained in stiffer mixtures. For this concrete, assume the air content to be 3.0% when the suggestions in the note are followed.

From the preceding two paragraphs, it can be seen that the required cementitious material is 130/0.40 = 325 kg/m^3. Only portland cement will be used.

Figure 3.2, with a nominal maximum-size aggregate of 40 mm and a fineness modulus of sand of 2.80, 0.71 m^3 of coarse aggregate on a dry-rodded basis, would be required in each cubic meter of concrete having a slump of about 75 to 100 mm.

In Fig. 3.3, for the very stiff consistency desired, the amount of coarse aggregate should be 125% of that for the plastic consistency, or 0.71 × 1.25 = 0.89 m^3. The quantity in a cubic meter will be 0.89 m^3, which in this case is 0.89 m^3 × 1600 kg/m^3 = 1424 kg.

With the quantities of cement, water, coarse aggregate, and air established, the sand content is calculated as follows:

Solid volume of cement	=	$\frac{325}{3.15 \times 1000}$	= 0.103 m^3
Volume of water	=	$\frac{130}{1000}$	= 0.130 m^3
Solid volume of coarse aggregate	=	$\frac{1424}{2.68 \times 1000}$	= 0.531 m^3
Volume of air	=	1×0.030	= 0.030 m^3
Total volume of ingredients except sand			= 0.794 m^3
Solid volume of sand required	=	$1 - 0.794$	= 0.206 m^3
Required mass of oven-dry sand	=	$0.206 \times 2.64 \times 1000$	= 544 kg
Water absorbed by oven-dry aggregates	=	$(544 \times 0.007) + (1424 \times 0.005)$	= 11 kg

Table 4.1—Comparison between computed batch quantities and those used in production

Ingredients	Batch quantities of concrete per cubic meter	
	Computed, kg	Used in production, kg
Cement	325	325
Net mixing water	130	130
Sand	544 (oven dry)	571 (moist)
Coarse aggregate	1424 (oven dry)	1438 (moist)
Water absorbed	11	—
Excess water	—	–30
Total	2434	2434
Water added at mixer	141	100

The estimated batch quantities per cubic meter of concrete are:

Cement	= 325 kg
Water	= 141 kg (130 + 11)
Sand, oven-dry	= 544 kg
Coarse aggregate, oven-dry	= 1424 kg
Air-entraining admixture	= (as required) for 3% air

4.3—Batching quantities for production-size batching

For the sake of convenience in making trial mixture computations, the aggregates have been assumed to be in an oven-dry state. Under production conditions, they generally will be moist and the quantities to be batched into the mixer should be adjusted accordingly.

With the batch quantities determined in the example, assume that tests show the sand to contain 5.0% and the coarse aggregate 1.0% total moisture. Because the quantity of oven-dry sand required was 544 kg, the amount of moist sand to be weighed out should be 544 kg × 1.05 = 571 kg. Similarly, the amount of moist, coarse aggregate should be 1424 × 1.01 = 1438 kg.

The free water in the aggregates, in excess of their absorption, should be considered as part of the mixing water. Because the absorption of sand is 0.7%, the amount of free water which it contains is 5.0 – 0.7 = 4.3%. The free water in the coarse aggregate is 1.0 – 0.5 = 0.5%. Therefore, the mixing water contributed by the sand is 0.043 × 544 = 23 kg and that contributed by the coarse aggregate is 0.005 × 1424 = 7 kg. The quantity of mixing water to be added is 130 – (23 + 7) = 100 kg. Table 4.1 shows a comparison between the computed batch quantities and those to be used in the field for each cubic meter of concrete. The actual quantities used during production will vary because it depends on the moisture contents of the stockpiled aggregates which will vary.

The preceding trial mixture computations provide batch quantities for each ingredient of the mixture per cubic meter of concrete. It is seldom desirable or possible to mix concrete in exactly 1 m^3 batches. It is therefore necessary to convert these quantities in proportion to the batch size to be used. Let it be assumed that a 0.55 m^3 capacity mixer is available. Then to produce a batch of the desired size and maintain the same proportions, the cubic meter batch quantities of all ingredients should be reduced quantities to the following quantities:

Cement	= 0.55 × 325	= 179 kg
Sand (moist)	= 0.55 × 571	= 314 kg
Coarse aggregate (moist)	= 0.55 × 1438	= 791 kg
Water to be added	= 0.55 × 100	= 55 kg

4.4—Adjustment of trial mixture

The estimate of total water requirement given in Fig. 2.1 and 2.2 may understate the water required. In such cases, the amount of cementitious materials should be increased to maintain the *w/cm*, unless otherwise indicated by laboratory tests. This adjustment will be illustrated by assuming that the concrete for the example was found in the trial batch to require 135 kg of mixing water instead of 130 kg. Consequently, the cementitious materials content should be increased from 325 to (135/130) × 325 = 338 kg/m^3 and the batch quantities recomputed accordingly.

Sometimes less water than indicated in Fig. 2.1 and 2.2 may be required, but it is recommended that no adjustment be made in the amount of cementitious materials for the batch in progress. Strength results may warrant additional batches with less cementitious materials. Adjustment in batch quantities is necessary to compensate for the loss of volume due to the reduced water. This is done by increasing the solid volume of sand in an amount equal to the volume of the reduction in water. For example, assume that 125 kg of water is required instead of 130 kg for the concrete of the example. Then 125/1000 is substituted for 130/1000 in computing the volume of water in the batch. This results in 0.005 m^3 less water; therefore, the solid volume of sand becomes 0.206 + 0.005 = 0.211 m^3.

The percentage of air in some no-slump concrete that can be consolidated in the container by vibration can be measured directly with an air meter (ASTM C 231) or it can be computed gravimetrically from measurement of the fresh concrete density in accordance with ASTM C 138. For any given set of conditions and materials, the amount of air entrained is approximately proportional to the quantity of air-entraining admixture used. Increasing the cementitious materials content or the fine fraction of the sand, decreasing slump, or raising the temperature of the concrete usually decreases the amount of air entrained for a given amount of admixture. The grading and particle shape of aggregate also have an effect on the amount of entrained air. The job mixture should not be adjusted for minor fluctuations in *w/cm* or air content. A variation in *w/cm* of ± 0.02, 0.38 to 0.42 in the above example, resulting from maintaining a constant consistency, is considered normal for no-slump concrete where compactability and densification respond better to target values for *w/cm*. A variation of ±1% in air content is also considered normal. This variation in air content will be smaller in the drier mixtures.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards of the various standards producing organizations applicable to this document are listed below with their serial designations. Since some of these standards are revised frequently, generally in minor details only, the user of this document should contact the sponsoring group, if it is desired to refer to the latest document.

American Association of State Highway and Transportation Officials (AASHTO)

M 6	Fine Aggregate for Portland Cement Concrete
M 80	Coarse Aggregate for Portland Cement Concrete

American Concrete Institute (ACI)

116R	Cement and Concrete Terminology
201.2R	Guide to Durable Concrete
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete
207.1R	Guide to Mass Concrete
207.5R	Roller-Compacted Mass Concrete
214	Recommended Practice for Evaluation of Strength Test Results of Concrete
301	Specifications for Structural Concrete
318/318R	Building Code Requirements for Structural Concrete and Commentary
325.10R	Report on Roller-Compacted Concrete Pavements

ASTM International

C 29/ C 29M	Standard Test Method for Unit Weight and Voids in Aggregate
C 31/ C 31M	Standard Practice for Making and Curing Concrete Test Specimens in the Field
C 33	Standard Specification for Concrete Aggregates
C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 78	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 90	Standard Specification for Load Bearing Concrete Masonry Units
C 136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate
C 138	Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
C 143/ C 143 M	Standard Test Method for Slump of Hydraulic Cement Concrete
C 150	Standard Specification for Portland Cement
C 192/ C 192M	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 331	Standard Specification for Lightweight Aggregate for Concrete Masonry Units
C 566	Standard Test Method for Total Moisture Content of Aggregate by Drying
C 618	Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 1170	Standard Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
C 1176	Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table
D 1557	Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort
SI 10	Use of the International System of Units (SI): The Modern Metric System

The above publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
444 N. Capitol St. NW Suite 225
Washington, DC 20001

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428-2959

5.2—Cited references

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APPENDIX 1—PROPORTIONING COMPUTATIONS (INCH-POUND UNITS)

A1.1—General proportioning criteria

Computation of proportions will be explained by one example. The following criteria are assumed:

- The cement specific gravity is 3.15;
- Coarse and fine aggregates in each case are of satisfactory quality and are graded within limits of generally accepted specifications;
- The coarse aggregate has a specific gravity, bulk oven-dry, of 2.68 and an absorption of 0.5%; and
- The fine aggregate has a specific gravity, bulk oven-dry, of 2.64, an absorption of 0.7%, and fineness modulus of 2.80.

A1.2—Example of proportioning computations

Concrete is required for an extruded product that will be exposed to severe weather with frequent cycles of freezing and thawing. Structural considerations require it to have a design compressive strength of 4000 psi at 28 days. From previous experience in the plant producing similar products, the expected coefficient of variation of strengths is 10%. It is further required that no more than one test in 10 will fall below the design strength of 4000 psi at 28 days. From Fig. 4.1(a) of ACI 214, the required average strength at 28 days should be 4000 × 1.15, or 4600 psi. The size of the section and spacing of reinforcement are such that a nominal maximum-size coarse aggregate of 1-1/2 in. graded to No. 4 can be used and is locally available. Heavy internal and external vibrations are available to achieve consolidation, enabling the use of very stiff concrete. The dry-rodded density of the coarse aggregate is found to be 100 lb/ft^3. Because the exposure is severe, air-entrained concrete will be used. The proportions may be computed as follows:

From Fig. 3.1, the *w/cm* required to produce an average 28 day strength of 4600 psi in air-entrained concrete is shown to be approximately 0.43 by mass.

The approximate quantity of mixing water needed to produce a consistency in the very stiff range in air-entrained concrete made with 1-1/2 in. nominal maximum-size aggregate is to be 225 lb/yd^3 (Fig. 2.2). In Fig. 2.3, the desired air content, which in this case will be produced by use of an air-entraining admixture, is indicated as 4.5% for the more plastic mixtures. An air-entraining admixture, when added at the mixer as liquid, should be included as part of the mixing water. The note to the figure calls attention to the lower air contents entrained in these stiffer mixtures. For this concrete, assume the air content to be 3.0% when the suggestions in the note are followed.

From the preceding two paragraphs, it can be seen that the required cementitious material is 225/0.43 = 523 lb/yd^3. Portland cement only will be used.

From Fig. 3.2, with a nominal maximum-size aggregate of 1-1/2 in. and a fineness modulus of sand of 2.80, 0.71 ft^3 of coarse aggregate, on a dry-rodded basis, would be required in each cubic foot of concrete having a slump of about 3 to 4 in.

In Fig. 3.3, for the very stiff consistency desired, the amount of coarse aggregate should be 125% of that for the plastic consistency, or 0.71 × 1.25 = 0.89. The quantity in a cubic yard will be 27 × 0.89 = 24.03 ft^3, which in this case is 100 × 24.03, or 2403 lb.

With the quantities of cement, water, coarse aggregate, and air established, the sand content is calculated as follows:

Solid volume of cement	=	[523 / (315 × 62.4)]	= 2.66 ft^3
Volume of water	=	[225 / 62.4]	= 3.61 ft^3
Solid volume of coarse aggregate	=	[2403 / (2.68 × 62.4)]	= 14.37 ft^3
Volume of air	=	27.00 × 0.030	= 0.81 ft^3
Total volume of ingredients except sand			= 21.45 ft^3
Solid volume of sand required	=	[27.00 – 21.45]	= 5.55 ft^3
Required weight of oven-dry sand	=	[5.55 × 2.64 × 62.4]	= 914 lb
Water absorbed	=	[(914 × 0.007) + (2403 × 0.005)]	= 18 lb

The estimated batch quantities per cubic yard of concrete are:

Cement	= 523 lb
Water	= 243 lb (225 + 18)
Sand, oven-dry	= 914 lb
Coarse aggregate, oven-dry	= 2403 lb
Air-entraining admixture	= (as required) for 3% air

A1.3—Batching quantities for production use

For the sake of convenience in making trial mixture computations, the aggregates have been assumed to be in an oven-dry state. Under production conditions they generally will be moist and the quantities to be batched into the mixer must be adjusted accordingly.

With the batch quantities determined in the example, let it be assumed that tests show the total moisture of sand to be 5.0 and 1.0% for the coarse aggregate. Because the quantity of oven-dry sand required was 914 lb, the amount of moist sand to be weighed out must be 914 × 1.05 = 960 lb. Similarly, the weight of moist coarse aggregate must be 2403 × 1.01 = 2427 lb.

The free water in the aggregates, in excess of their absorption, must be considered as part of the mixing water. Because the absorption of sand is 0.7%, the amount of free water which it contains is 5.0 – 0.7 = 4.3%. The free water in the coarse aggregate is 1.0 – 0.5 = 0.5%. Therefore, the mixing water contributed by the sand is 0.043 × 914 = 39 lb and that contributed by the coarse aggregate is 0.005 × 2403 = 12 lb. The quantity of mixing water to be added, then, is 225 – (39 + 12) = 174 lb. Table A1.1 shows a comparison between the computed batch quantities and those actually to be used in the field for each cubic yard of concrete.

The preceding computations provide batch quantities for each ingredient of the mixture per cubic yard of concrete. It is seldom desirable or possible to mix concrete in exactly 1 yd^3 batches. It is therefore necessary to convert these quantities in proportion to the batch size to be used. Let it be assumed that a 16 ft^3 capacity mixer is available. To produce a batch of the desired size and maintain the same proportions, the cubic yard batch quantities of all ingredients for the project must be reduced in the ratio 16/27 = 0.593, thus:

Cement	= 0.593 × 523 = 310 lb
Sand (moist)	= 0.593 × 960 = 569 lb
Coarse aggregate (moist)	= 0.593 × 242 = 144 lb
Water to be added	= 0.593 × 174 = 103 lb

Table A1.1—Comparison between computed batch quantities and those used in production

Ingredients	Batch quantities of concrete per cubic yards	
	Computed, lb	Used in production, lb
Cement	523	523
Net mixing water	225	225
Sand	914 (dry)	960 (moist)
Coarse aggregate	2403 (dry)	2427 (moist)
Water absorbed	18	—
Excess water	—	–51
Total	4083	4084
Water added at mixer	243	174

A1.4—Adjustment of trial mixture

The estimate of total water requirement given in Fig. 2.1 and 2.2 may underestimate the water required. In such cases, the amount of cementitious materials should be increased to maintain the *w/cm*, unless otherwise indicated by laboratory tests. This adjustment will be illustrated by assuming that the concrete for the example was found in the field trial batch to require 240 lb/yd^3 of mixing water instead of 225 lb/yd^3. Consequently, the cementitious materials content should be increased from 523 to (240/225) × 523 = 558 lb/yd^3 and the batch quantities recomputed accordingly.

Sometimes less water than indicated in Fig. 2.1 and 2.2 may be required, but it is recommended that no adjustment be made in the amount of cementitious materials for the batch in progress. Strength results may warrant additional batches with less cementitious materials. Adjustment in batch quantities is necessary to compensate for the loss of volume due to the reduced water. This is done by increasing the solid volume of sand in an amount equal to the volume of the reduction in water. For example, assume that 215 lb of water are required instead of 225 lb for the concrete of the example. Then 215/62.4 is substituted for 225/62.4 in computing the volume of water in the batch, and the solid volume of sand becomes 5.71 instead of 5.55 ft^3.

APPENDIX 2—LABORATORY TESTS

A2.1—General

As stated in the Introduction, selection of concrete mixture proportions can be accomplished most effectively from results of laboratory tests that determine basic physical properties of materials needed for proportioning no-slump concrete mixtures; that establish relationships between *w/cm*, air content, cement content, and strength; and which furnish information on the workability characteristics of various combinations of ingredient materials. The extent of investigation of fresh and hardened concrete properties for any given job will depend on the size of the project, and importance and service conditions involved. Details of the laboratory program will also vary depending on facilities available and on individual preferences.

A2.2—Physical properties of cement

Physical and chemical characteristics of cement influence the properties of hardened concrete. The only property of cement directly concerned in computation of concrete mixture proportions is specific gravity. The specific gravity of cement may be assumed to be 3.15 without introducing appreciable error in mixture computations.

A sample of cement of the type selected for the project should be obtained from the mill that will supply the job. The sample quantity should be adequate for tests contemplated with a liberal margin for additional tests that might later be considered desirable. Cement samples should be shipped in airtight containers or in moisture-proof packages.

A2.3—Properties of aggregate

Sieve analysis, specific gravity, absorption, and moisture content of both fine and coarse aggregate and dry-rodded density of coarse aggregate are essential physical properties required for mixture computations. Other tests that may be desirable for large or special types of work include petrographic examination, tests for chemical reactivity and soundness, durability, resistance to abrasion, and for various deleterious substances. All such tests yield valuable information for judging the ultimate quality of concrete and in selecting appropriate proportions.

Aggregate grading or particle-size distribution is a major factor in controlling unit water requirement, proportion of coarse aggregate to sand, and cement content of concrete mixtures for a given degree of workability. Numerous "ideal" aggregate grading curves have been proposed, but a universally accepted standard has not been developed. Experience and individual judgment must continue to play important roles in determining acceptable aggregate gradings. Additional workability, realized by use of air entrainment, permits the use of less restrictive aggregate gradings to some extent.

Undesirable sand gradings may be corrected to desired particle size distribution by:

- Separation of the sand into two or more size fractions and recombining in suitable proportions;
- Increasing or decreasing the quantity of certain sizes to balance the grading;
- Reducing excess coarse material by grinding; or
- By the addition of manufactured sand.

Undesirable coarse aggregate gradings may be corrected by:

- Crushing excess coarser fractions;
- Wasting excess material in other fractions;
- Supplementing deficient sizes from other sources; or
- A combination of these methods.

The proportions of various sizes of coarse aggregate should be held closely to the grading of available materials to minimize the amount of waste material. Whatever processing is done in the laboratory should be practical from a standpoint of economy and job operation. Samples of aggregates for concrete mixture tests should be representative of aggregate selected for use in the work. For laboratory tests, the coarse aggregates should be cleanly separated into required size fractions to provide for uniform control of mixture proportions.

The particle shape and texture of both fine and coarse aggregate also influence the mixing water requirement of concrete. Void content of compacted dry, fine, or coarse aggregate can be used as an indicator of angularity. Void contents of more than 40% in conventionally graded aggregates

Fig. A2.1—Modified Vebe apparatus. Photograph provided by Soiltest Division, ELE International.

indicate angular material that will probably require more mixing water than given in Fig. 2.1 and 2.2. Conversely, rounded aggregates with voids below 35% will probably need less water.

A2.4—Concrete mixture tests

The values listed in the figures (2.1, 2.2, 2.3, 3.1, 3.2, and 3.3) can be used for establishing a preliminary trial mixture. They are based on averages obtained from a large number of tests and do not necessarily apply exactly to materials being used on a particular job. If facilities are available, it is advisable to make a series of concrete tests to establish the relationships needed for selection of appropriate proportions based on the materials actually to be used.

Air-entrained concrete or concrete with no measurable slump must be machine-mixed. Before mixing the first batch, the laboratory mixer should be "buttered," as described in ASTM C 192/ C 192 M, because a clean mixer retains a percentage of mortar that should be taken into account. Similarly, any processing of materials in the laboratory should simulate, as closely as practicable, corresponding treatment in the field. Adjustments of the preliminary trial mixture will almost always be necessary. It should not be expected that field results will check exactly with laboratory results. An adjustment of the selected trial mixture on the job is usually necessary.

Some of the variables that may require a more extensive program are alternative aggregate sources and different aggregate gradings, different types and brands of cement, different admixtures, different nominal maximum sizes of aggregate, considerations of concrete durability, thermal properties, and volume change, which includes drying shrinkage and temperature due to cement hydration.

A2.5—Specifications and test methods

Appropriate specifications and test methods for the various ingredients in concrete and for freshly mixed and hardened concrete are published by the American Society for Testing and Materials, the American Association of State Highway and Transportation Officials, and various Federal and State agencies. A list of useful test methods is shown in the appendix to ACI 211.1.

A2.6—Equipment and techniques for measuring consistency

The following is a more detailed description of the equipment and techniques involved in a method for measuring consistency described in Section 2.2.

A2.7—Vebe apparatus

The Vebe apparatus consists of a heavy base, resting on three rubber feet, a vibrating table supported on rubber shock absorbers, a motor with rotating eccentric mass, a cylindrical metal container to hold the concrete sample (approximate inside dimensions: 240 mm [9-1/2 in.] in diameter and 195 mm [7-3/4 in.] high), a slump cone (ASTM C 143/ C 143 M), a funnel for filling the slump cone, a swivel arm holding a graduated metal rod, and a clear plastic disk (diameter of disk slightly less than diameter of cylindrical metal container). The vibrating table is typically 380 mm (15 in.) in length, 260 mm (10-1/4 in.) in width, and 300 mm (12 in.) in height. The overall width, with the disk swung away from the container, is 675 mm (26-1/2 in.). The overall height above floor level from the top edge of the funnel used to fill the slump cone is approximately 710 mm (28 in.). The total mass of the equipment is approximately 95 kg (210 lb). Figure A2.1 shows the apparatus mounted on a concrete pedestal approximately 380 mm (15 in.) in height.

To carry out the Vebe test devise shown in Fig. A2.1, the sample of concrete is compacted in the slump cone, the top struck off, the cone removed, and the slump measured, as per ASTM C 143/C 143 M. The swivel arm is then moved into position with the clear plastic disk and graduated rod resting on top of the concrete sample. The vibrator is switched on and the time in seconds to deform the cone into a cylinder, at which stage the whole face of the plastic disk is in contact with the concrete, is determined. This time in seconds is used as a measure of the consistency of the concrete.

APPENDIX 3—ROLLER-COMPACTED CONCRETE MIXTURE PROPORTIONING

A3.1—General

Roller-compacted concrete (RCC) is defined in ACI 116R as "concrete compacted by roller compaction; concrete that in its unhardened state will support a roller while being compacted." Conventional concrete cannot generally be reproportioned for use as RCC by any single action, such as altering the proportions of mortar and coarse aggregate, reducing the water content, changing the *w/cm*, or increasing the fine aggregate content. Differences in conventional portland cement concrete and RCC mixture proportioning procedures are primarily due to the relatively dry consistency of RCC and the possible use of unconventionally graded aggregates.

This guide describes methods for selecting proportions for RCC mixtures for use in mass concrete and horizontal concrete slab or pavement construction applications. The methods provide a first approximation of proportions intended to be checked by trial batches in the laboratory or field, and adjusted, as necessary, to produce the desired characteristics of the RCC. Additional information on RCC can be found in ACI 207.5R and ACI 325.10R.

A3.2—Consistency

For RCC to be effectively consolidated, it must be dry enough to support the weight mass of a vibratory roller yet wet enough to permit adequate compaction of the paste throughout the mass during the mixing and compaction operations. Concrete suitable for compaction with vibratory rollers differs significantly in appearance in the unconsolidated state from that of concrete having a measurable slump. There is little evidence of any paste in the mixture except for coating on the aggregate until it is consolidated. RCC mixtures should have sufficient paste volume to fill the internal voids in the aggregate mass and therefore may differ from related materials such as soil cement or cement-treated base course.

Although the slump test is the most familiar means of measuring concrete consistency in the United States and is the basis for the measures of consistencies shown in ACI 211.1, it is not suitable to measure RCC consistency. RCC will have poor workability if compaction by hand-rodding is attempted. If vibration is used, however, the workability characteristics of the same concrete might be considered as excellent. The range of workable mixtures can be broadened by adopting compaction techniques that impart greater energy into the mass to be consolidated. The standard test method for measuring the consistency of RCC is ASTM C 1170, which uses the modified Vebe apparatus.

The modified Vebe apparatus shown in Fig. A2.1 consists of a vibrating table of fixed frequency and amplitude, with a 0.009 m^3 (0.33 ft^3) container attached to the table. A representative sample of RCC is loosely placed in the container under a surcharge of 23 kg (50 lb). The measure of consistency is the time of vibration, in seconds, required to fully consolidate the concrete, as evidenced by the formation of a ring of mortar between the edge of the surcharge and the wall of the container. The Vebe time is normally determined for a given RCC mixture and compared with the field results of onsite compaction tests conducted with vibratory rollers to determine if adjustments in the mixture proportions are necessary. The optimum Vebe time is influenced by the mixture proportions, particularly the water content, nominal maximum aggregate size, fine aggregate content, and the amount of aggregate finer than the 75 μm (No. 200) sieve.

A3.3—Durability

Although the resistance of RCC to deterioration due to cycles of freezing and thawing has been good in some pavements and other structures, RCC should not be considered resistant to freezing and thawing unless it is air-entrained or some other protection against critical saturation is provided. If the RCC does not contain a sufficiently fluid paste, proper air entrainment will be difficult, if not impossible, to achieve. In addition, a test method for measuring the air content of fresh RCC has not been standardized.

Other ways of protecting RCC from frost damage in mass concrete applications may include sacrificial RCC on exposed surfaces, a conventional air-entrained concrete facing, or some means of membrane protection.

RCC produced with significant amounts of clay will check and crack when exposed to alternating cycles of wetting and drying, while that proportioned with nonplastic aggregate fines generally experiences no deterioration.

A3.4—Strength

The strength of compacted RCC, assuming the use of consistent quality aggregates, is determined by the water-cement ratio (*w/c*). Differences in strength and degree of consolidation for a given *w/cm* can result from changes in maximum size of aggregate; grading, surface texture, shape, strength, and stiffness of aggregate particles; differences in cement types and sources; entrapped air content; and the use of admixtures that affect the cement hydration process or develop cementitious properties themselves. ASTM C 1176 is the standard method practice for fabricating test specimens, which involves molding specimens by filling the molds in layers and consolidating each layer of RCC under a surcharge on a vibrating table.

A3.5—Selection of materials

A3.5.1 *General*—Materials used to produce RCC consist of cementitious materials, water, fine and coarse aggregate, and sometimes chemical admixtures. Materials and mixture proportions used in various projects to date have ranged from pit- or bank-run, minimally processed, aggregates with low cementitious material contents, to fully processed concrete aggregates having normal size separations and high cementitious materials contents. Mixture proportions and materials selection criteria for RCC in massive concrete applications are based on the need to provide bond between layers while still maintaining a cementitious material content low enough to minimize temperature rise due to the heat of hydration that can cause thermal cracking when the RCC cools quickly. The specified strength, durability requirements, and intended application affect the materials selected for use in RCC slabs and pavements.

Cementitious materials—Cementitious materials used in RCC can include portland cement, blended hydraulic cements, or a combination of portland cement and pozzolans. The selection of cement types should be based in part on the design strength and the age at which this strength is required. In addition, applicable limits on chemical composition required for different exposure conditions and alkali reactivity should follow standard concrete practices. For massive RCC structures, the use of cement with heat of hydration limitations is recommended. A detailed discussion of cementitious materials for use in mass concrete is found in ACI 207.1R.

Selection of a pozzolan suitable for use in RCC should be based on conformance with applicable standards or specifications, its performance in the concrete, and its availability to the project location. Pozzolans have been successfully used in RCC to reduce heat generation, increase ultimate strength beyond 180 days age, and increase the paste volume of mixtures to improve compaction characteristics. The use of fly ash is a particularly effective means of providing additional fine material to aid in the compaction of those RCC mixtures that contain standard graded concrete fine aggregate.

A3.5.3 *Aggregates*—The aggregates generally comprise 75 to 85% of the volume of an RCC mixture, depending on the intended application, and significantly affect both the fresh and hardened concrete properties. In freshly mixed RCC, aggregate properties affect the workability of a mixture and its potential to segregate, which in turn affects the ability of the mixture to consolidate under a vibratory roller. Aggregate properties also affect hardened concrete characteristics such as strength, elastic and thermal properties, and durability. The aggregate grading and particle shape affect the paste requirement of an RCC mixture. For high-quality RCC, both the coarse and fine aggregate fractions should be composed of hard, durable particles, and the quality of each should be evaluated by standard physical property tests such as those given in ASTM C 33. If lower-quality RCC is acceptable, then a variety of aggregate sources that may not meet ASTM grading and quality requirements may be satisfactory as long as design criteria are met. For example, in stiff, lean RCC mixtures to be used in massive sections, broader limits for some deleterious substances than those specified in ASTM may be acceptable.

Greater economy may be realized by using the largest practical nominal maximum-size aggregate (NMSA). Increasing the NMSA reduces the void content of the aggregate and thereby lowers the paste requirement of a mixture. Lower cementitious material contents, in turn, reduce the potential for cracking due to thermal stress in massive sections. The disadvantages of increasing the NMSA are primarily associated with RCC mixing and handling problems. In the United States, the NMSA has generally been limited to 25.0 mm (1 in.) in RCC produced for horizontal applications such as pavements and slabs, and to 75 mm (3 in.) in RCC used in massive sections.

The range in gradings of aggregate used in RCC mixtures has varied from standard graded concrete aggregate with normal size separations to pit- or bank-run aggregate with little or no size separation. Changes in consistency and workability are affected by changes in aggregate grading. The relative compactability of RCC is also affected by the aggregate grading and fines content.

The volume of coarse aggregate in an RCC mixture directly affects the effort required to compact the mixture. Assuming an adequate volume of paste is available in the mixture, a wide range of coarse and fine aggregate gradings is not likely to significantly affect the densities achieved in the field. For RCC pavement applications in which longitudinal and transverse pavement smoothness are of importance, the coarse and fine aggregates should be combined so that a dense-graded aggregate blend is produced that approaches a maximum-density grading. Equation (A3.1), the equation for Fuller's maximum density curve, gives an approximate cumulative percentage of material finer than each sieve. This grading results in a mixture that is compactible yet stable under the roller.

$$P = (d/D)^{1/2}(100) \tag{A3.1}$$

where

P = cumulative percent finer than the d-size sieve;
d = sieve opening, mm (in.); and
D = NMSA, mm (in.).

In areas where pozzolans are not readily available, the use of blended sands or mineral fines can be a beneficial means of reducing or filling aggregate voids; in some instances, however, their use can also increase the amount of water required to achieve the consistency needed to ensure thorough consolidation. The effects of these materials on the RCC mixture proportions should be evaluated by determining their effect on minimum paste volume requirements or by evaluation of test specimens for strength, shrinkage, or both.

A3.5.4 *Admixtures*—Chemical admixtures, including water-reducing and retarding admixtures, have experienced wide use in RCC placed in massive sections, but their use has been more limited in pavement applications. The ability of these admixtures to lower the water requirements or to provide extended workability to a mixture appears to be largely dependent on the amount and type of aggregate finer than the 75 μm (No. 200) sieve. Air-entraining admixtures have seen limited use in RCC. Conventional methods of adding air-entraining admixtures at the mixer have only been marginally successful in entraining proper air-void systems in lean RCC mixtures. Limited data have shown, however, that if air can be entrained in RCC, significant improvements in resistance to freezing and thawing can be achieved.

A3.6—Selection of mixture proportions

A3.6.1 *General*—A number of RCC mixture proportioning methods have been successfully used to produce mixtures for mass concrete applications and pavements and other horizontal concrete construction applications. These methods have differed significantly for a number of reasons. One significant reason has been the philosophy of the treatment of the aggregates as either conventional concrete aggregates or as aggregates used in the placement of stabilized materials.

Two methods are described herein for selecting proportions for RCC mixtures. The first is recommended primarily for use in selecting proportions of lean mixtures, which typically contain a 37.5 mm (1-1/2 in.) or larger NMSA and are intended for use in relatively massive sections. The second method is recommended primarily to proportion mixtures for relatively thin sections such as pavements or slabs. The former method is based on proportioning RCC to meet specified limits of consistency, and the latter method is based on proportioning RCC, using soil's compaction concepts. Although RCC designed for use in horizontal concrete construction applications can be proportioned using the first method, the second method is limited for use on those mixtures containing 19 mm (3/4 in.) or smaller NMSA. Proportions determined by the use of either procedure should result in mixtures that contain sufficient paste volume to fill voids between aggregate particles and coat individual aggregate particles.

A3.6.2.1 *Procedure for proportioning RCC to meet specified limits of consistency*—This method uses the modified Vebe test, as previously described in Section A3.2, as the basis for determining optimum workability and aggregate proportions. The vibration time for full consolidation is measured and compared with field-compaction tests conducted with vibratory rollers. The desired time is determined based on the results of density tests and evaluation of cores. The vibration time is influenced by a number of parameters of the mixture, including water content, combined aggregate grading, NMSA, fine aggregate content, and content of material finer than the 75 µm (No. 200) sieve. Mixtures that contain relatively clean concrete sands and fixed aggregate grading in lines 18 and 19 with 38 mm (1-1/2 in.) NMSA generally require 15 to 30 s to fully consolidate. Those mixtures containing clean sands, fixed aggregate grading, and 19 mm (3/4 in.) or smaller NMSA to be used for horizontal construction applications require approximately 35 to 50 s to fully consolidate.

A3.6.2.2 *Water content*—Those mixtures with paste volumes in excess of aggregate void volumes will fully consolidate to approximately 98% of their theoretical densities as defined by ASTM C 138. Variations in mixture water contents will directly affect the compactive effort required to achieve full consolidation. The optimum water content of a given mixture is that whose variability has the least effect on compactive effort for full consolidation. If the water content of a mixture is too low, the aggregate voids will no longer be filled with paste and the strength of the mixture will decrease even though the *w/cm* has decreased. Figure A3.1 shows an example of the variation in strength with water content for a fixed cementitious materials content.

A3.6.2.3 *Cementitious material content*—The cementitious material content used in RCC mixtures depends on the specified strength, bond requirement between layers, and thermal considerations. For a given cementitious materials content, the strength at a given age will be maximized when the paste volume is just enough to fill the aggregate voids. Strength will be reduced if the paste volume is not sufficient to fill the entrapped air voids or if the water content is increased to a point that creates excess paste but a higher *w/cm*. Therefore, as the paste content increases, the water content can be reduced and strength optimized without losing workability. For most ASTM C 150 Type I or II cements, Fig. A3.2 can be used as a guide to proportion equal-strength RCC for varying proportions of portland cement and ASTM C 618 Class F pozzolans. Similar results can be expected with other pozzolans. The use of mortar compressive strength tests have also been

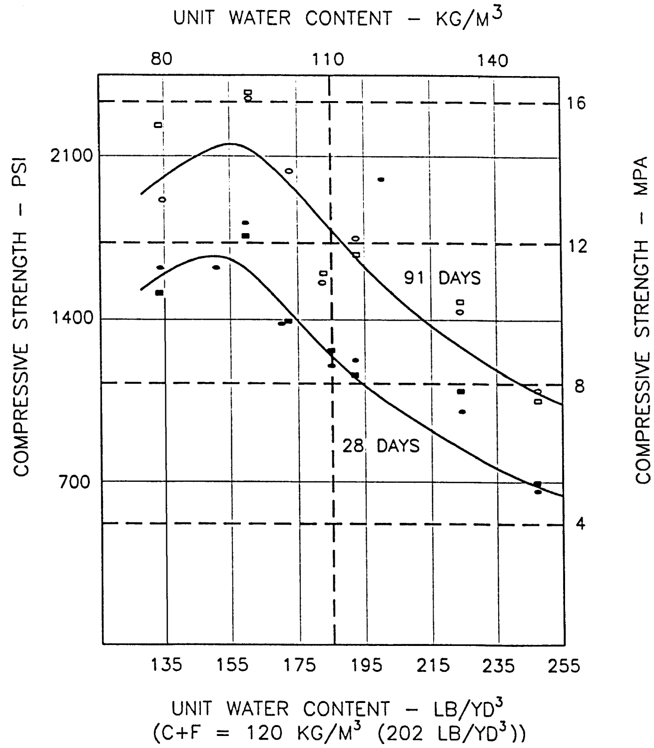


Fig. A3.1—Relation between unit water content and compressive strength of mass concrete.

found to be a suitable means of determining the *w/cm* required for strength considerations. Once mortar is proportioned to meet strength requirements, varying percentages of mortar and coarse aggregate can be proportioned to achieve a given workability as measured by Vebe time. These determinations are based upon the mortar required per unit volume of RCC.

A3.6.2.4 *Fine aggregate content*—The void content of fine aggregate, as determined in dry-rodded density measurements, normally ranges from 34 to 42%. The minimum paste volume can be determined by maximum density curves in much the same way as optimum water content is determined in soils. Fine aggregate is added in equal increments to paste proportioned at the *w/c* determined for the mixture, and specimen density measurements are made using ASTM D 1557 or extended vibration. The density values are plotted versus the calculated paste volumes and the paste volume producing the maximum density of the mortar specimens may be determined. The paste volume, as a ratio of the total mortar volume, should be increased from 5 to 10% for mass concrete mixtures, and 20 to 25% for those mixtures designed for use when a bonding mortar is not used between horizontal lifts of RCC.

A3.6.2.5 *Coarse aggregate content*—For any NMSA, the minimum aggregate volume to produce no-slump consistency can be determined by proportioning the mortar fraction to yield the approximate strength that is required and then adjusting the proportions of coarse aggregate and mortar to achieve a zero slump. Once the coarse aggregate-mortar ratio that yields zero slump is determined, the coarse aggregate can be increased until the ratio is reached that results in the desired modified Vebe time. The absolute

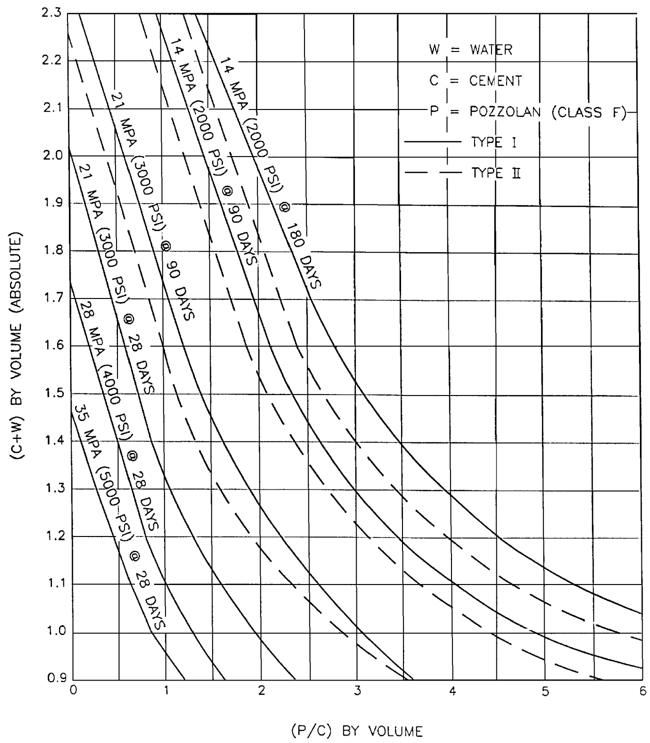


Fig. A3.2—Proportioning curves for equal-strength concrete.

Table A3.1—Recommended absolute volumes of coarse aggregate per unit volume of RCC

NMSA*, mm (in.)	Absolute volume, % of until RCC volume
150 (6)	63 to 64
115 (4-1/2)	61 to 63
75 (3)	57 to 61
37.5 (1-1/2)	52 to 56
19 (3/4)	46 to 52
9.5 (3/8)	42 to 48

*NMSA = nominal maximum size aggregate.

volume for coarse aggregate per unit volume of RCC will generally fall within the limits of Table A3.1.

A3.6.3 *Proportioning steps—*

Step 1—Select the volumetric pozzolan-cement ratio (p/c) and $w/(c+p)$ from Fig. A3.2 for the production of trial mortar and concrete batches.

Step 2—Determine the minimum paste content P_T as a percentage of the total mortar volume using procedures previously discussed. As an alternative, the ratio of the air-free volume of paste to the air-free volume of mortar, P_v, in the range of 0.38 to 0.46 can be selected. Careful attention should be given to selecting this value if it is not based on specific test results.

Step 3—Determine the volume of coarse aggregate, V_{CA}, by trial methods as previously discussed until the desired modified Vebe time is obtained or by selection from Table A3.1.

Step 4—Assume the entrapped air content is 1.0 to 2.0% of the total concrete volume. Calculate the volume of air in the mixture from

$$V_A = (\text{air content}/100) \times C_V$$

Table of notation

p/c =	volumetric ratio of pozzolan to cement
P_T =	minimum paste content
P_v =	ratio of air-free volume of paste to air-free volume of mortar
V_{CA} =	volume of coarse aggregate
V_A =	volume of air in mixture
C_v =	unit volume of concrete upon which proportions are based
V_P =	air-free volume of paste
V_{MT} =	total mortar volume
V_m =	air-free volume of mortar
V_{FA} =	volume of fine aggregate
V_W =	volume of water
V_C =	volume of cement
V_F =	volume of pozzolan
$w/c+p$ =	volumetric ratio of water to cement plus pozzolan

Step 5—Calculate the air-free volume of paste, V_P, from

$$V_P = (P_T/100 \times V_{MT}) - V_A$$

where V_{MT} = Total mortar volume = $C_V - V_{CA}$

Or if a value of P_v is selected in Step 2

$$V_P = V_m \times P_v$$

where V_m = air-free volume of mortar $= C_V - V_{CA} - V_A$

Step 6—Determine the fine aggregate volume, V_{FA}, from

$$V_{FA} = C_V - V_{CA} - V_P - V_A$$

or

$$V_{FA} = V_m \times (1 - P_v)$$

Step 7—Determine the trial water volume, V_W, from

$$V_W = V_P \times w/(c+p)/[1 + w/(c+p)]$$

where:

$w/(c+p)$ = water-cementitious materials ratio, by volume (Fig. A3.2).

Step 8—Determine the cement volume, V_C, from

$$V_C = V_W/\{w/(c+p) \times [1 + (p/c)]\}$$

Step 9—Determine the pozzolan volume, V_F, from

$$V_F = V_C \times (p/c)$$

Step 10—Calculate the mass of each material by multiplying its absolute volume by its respective solid bulk density.

Step 11—Perform consistency tests on trial batches as previously discussed to achieve the desired modified Vebe time or to determine the minimum vibration duration needed to achieve maximum compacted density.

Step 12—After the final aggregate volumes are selected, proportion at least two additional batches—one having a higher and one having a lower w/cp. Plot strength versus w/cp to determine the final mixture proportions.

A3.6.4 *Example problem*—Concrete is required for a large, 1200 mm (48 in.) thick overflow slab located in a moderate exposure environment. The specified compressive strength is 14 MPa (2000 psi) at 90 days. Water velocities will be less than 12 m/s (40 ft/s), and the concrete will be continuously submerged. No reinforcement is required and the area is accessible to large equipment. Placement conditions allow the use of 75 mm (3 in.) NMSA. Three coarse-aggregate size groups, consisting of 4.75 to 19 mm (No. 4 to 3/4 in.), 19 to 37.5 mm (3/4 to 1-1/2 in.), and 37.5 to 75 mm (1-1/2 to 3 in.), will be used in the concrete. These coarse aggregates will be combined in the proportions of 34, 26, and 40% by volume, respectively, to match the idealized combined grading given in ACI 211.1. Type II portland cement and Class F fly ash are available and will be specified. Proportion an RCC mixture having a modified Vebe time of 15 to 20 s, which will achieve the specified compressive strength.

Step 1—An initial mixture will be proportioned with p/c = 3. (Subsequent mixtures would also likely be proportioned with other p/cs). From Fig. A3.2, $w/(c+p)$ = 1.3 by volume.

Step 2—Based upon previous experience, a value of P_v = 0.39 is selected for the ratio of air-free volume of paste to the air-free volume of mortar.

Steps 3-10 are presented in SI units and are repeated in inch-pound units, which are shown in the framed text.

Step 3—From Table A3.1, the percentage of aggregate, by absolute volume, per unit volume of concrete is selected to be 59. Therefore,

$$V_{ca} = 0.59 \times 1 \text{ m}^3 = 0.59 \text{ m}^3$$

and

4.75 to 19 mm = 0.34 × 0.59 m^3 = 0.201 m^3
19 to 37.5 mm = 0.26 × 0.59 m^3 = 0.153 m^3
37.5 to 75 mm = 0.40 × 0.59 m^3 = 0.236 m^3

Step 4—An entrapped air content of 1.0% is assumed. The volume of air, V_A, is:

$$V_A = (1.0/100) \times 1 \text{ m}^3 = 0.01 \text{ m}^3$$

Step 5—The air-free volume of mortar, V_m, is:

$$V_m = 1 \text{ m}^3 - (0.59 \times 1 \text{ m}^3) - 0.01 \text{ m}^3 = 0.40 \text{ m}^3$$

The value of V_P is:

$$V_P = 0.40 \text{ m}^3 \times 0.39 = 0.156 \text{ m}^3$$

Step 6—The fine aggregate volume, V_{FA}, is:

$$V_{FA} = 0.40 \text{ m}^3 \times (1 - 0.39) = 0.244 \text{ m}^3$$

Step 7—The volume of water, V_W, is:

$$V_W = (0.156 \times 1.3)/(1 + 1.3) = 0.088 \text{ m}^3$$

Step 8—The volume of cement, V_C, is:

$$V_C = 0.088/[1.3 \times (1 + 3)] = 0.017 \text{ m}^3$$

Step 9—The volume of fly ash, V_F, is:

$$V_F = 0.017 \times 3 = 0.051 \text{ m}^3$$

Step 10—The bulk density (saturated surface dry basis) of each of the materials is:

cement	=	3150 kg/m^3
fly ash	=	2300 kg/m^3
4.75 to 19 mm	=	2710 kg/m^3
19 to 37.5 mm	=	2730 kg/m^3
37.5 to 75 mm	=	2730 kg/m^3
fine aggregate	=	2690 kg/m^3
water	=	1000 kg/m^3

Then the mass of each material (saturated-surface dry basis) required for 1 m^3 of concrete is (volume in proportions × bulk density):

cement	=	54 kg
fly ash	=	117 kg
4.75 to 19 mm	=	545 kg
19 to 37.5 mm	=	418 kg
37.5 to 75 mm	=	644 kg
fine aggregate	=	656 kg
water	=	88 kg

Step 11—A sample taken from the trial batch indicates the modified Vebe time is only 11 s. Adjust the trial mixture proportions by either increasing P_v or decreasing V_{CA}, or both, and recalculate the material absolute volumes and masses.

Step 12—After the aggregate volumes are finalized, proportion two additional mixtures; one having a higher and one having a lower $w/(c+p)$. Plot compressive strength versus $w/(c+p)$ to determine the final mixture proportions.

Steps 3-10 in inch-pound units

Step 3—From Table A.3.1, the percentage of aggregate, by absolute volume, per unit volume of concrete is selected to be 59. Therefore,

$$V_{ca} = 0.59 \times 27 \text{ ft}^3 = 15.93 \text{ ft}^3$$

and

No. 4 to 3/4 in. = 0.34 × 15.93 ft^3 = 5.42 ft^3
3/4 to 1-1/2 in. = 0.26 × 15.93 ft^3 = 4.14 ft^3
1-1/2 to 3 in. = 0.4 × 15.93 ft^3 = 6.37 ft^3

Step 4—An entrapped air content of 1.0% is assumed. The volume of air, V_A, is:

$$V_A = (1.0/100) \times 27 \text{ ft}^3 = 0.27 \text{ ft}^3$$

Step 5—The air-free volume of mortar, V_m, is:

$$V_m = 27 \text{ ft}^3 - (0.59 \times 27 \text{ ft}^3) - 0.27 \text{ ft}^3$$

The value of V_p is:

$$V_p = 10.80 \text{ ft}^3 \times 0.39 = 4.22 \text{ ft}^3$$

Step 6—The fine aggregate volume, V_{FA}, is:

$$V_{FA} = 10.80 \text{ ft}^3 \times (1 - 0.39) = 6.59 \text{ ft}^3$$

Step 7—The volume of water, V_W, is:

$$V_W = (4.22 \times 1.3)/(1 + 1.3) = 2.39 \text{ ft}^3$$

Step 8—The volume of cement, V_c, is:

$$V_c = 2.39/[1.3 \times (1 + 3)] = 0.46 \text{ ft}^3$$

Step 9—The volume of fly ash, V_F, is:

$$V_F = 0.45 \times 3 = 1.38 \text{ ft}^3$$

Step 10—The bulk density of each material is (specific gravity × 62.4):

cement	=	196.6 lb/ft^3
fly ash	=	143.5 lb/ft^3
No. 4 to 3/4 in.	=	169.1 lb/ft^3
3/4 to 1-1/2 in.	=	170.4 lb/ft^3
1-1/2 to 3 in.	=	170.4 lb/ft^3
fine aggregate	=	167.9 lb/ft^3
water	=	62.4 lb/ft^3

Then the mass of each material (saturated-surface dry basis) required for 1 yd^3 of concrete is (volume in proportions × bulk density):

cement	=	88.5 lb
fly ash	=	198.1 lb
No. 4 to 3/4 in.	=	916.5 lb
3/4 to 1-1/2 in.	=	705.3 lb
1-1/2 to 3 in.	=	1085.1 lb
fine aggregate	=	1106.2 lb
water	=	147.9 lb

Steps 11 and 12 remain the same as before.

A3.7—Proportioning using soil compaction concepts

A3.7.1 *General*—This proportioning method involves establishing a relationship between the dry density and moisture content of the RCC by compacting specimens at a

Table A3.2—Recommended RCC pavement combined aggregate grading limits

Sieve size	Cumulative percent passing
25 mm (1 in.)	100
19 mm (3/4 in.)	82 to 100
12.5 mm (1/2 in.)	72 to 93
9.5 mm (3/8 in.)	66 to 85
4.75 mm (No. 4)	51 to 69
2.36 mm (No. 8)	38 to 56
1.18 mm (No. 16)	28 to 46
600 µm (No. 30)	18 to 36
300 µm (No. 50)	11 to 27
150 µm (No. 100)	6 to 18
75 µm (No. 200)	2 to 8

given compactive effort over a range of moisture content. It is similar to the method used to determine the relationship between the moisture content and dry density of soils and soil-aggregate mixtures. The compaction equipment used includes a 4.54 kg (10 lb) compaction hammer having an 457 mm (18 in.) drop and a 152 mm (6.0 in.) diameter steel mold having a height of 116 mm (4.6 in.). Both are described in ASTM D 1557. The method is suited to those mixtures that have a NMSA of 19 mm (3/4 in.) or less and cementitious material contents greater than typically used in RCC mixtures for massive sections. It should generally be considered for use in proportioning RCC mixtures for relatively thin section such as pavements or slabs. The compactive effort to be applied to the moisture-density specimens corresponds to that described in ASTM D 1557.

A3.7.2 *Cementitious materials content*—The cementitious materials content is determined by the compressive or flexural strength at the optimum water content for different mixtures. The cementitious material content is expressed as a percentage of the dry mass of aggregate. The cementitious material content for RCC pavements generally ranges from 10 to 17%, depending on the strength and durability requirements. This range corresponds to approximately 210 to 360 kg/m^3 or 350 to 610 lb/yd^3 of cementitious material.

A3.7.3 *Fine and coarse aggregate content*—Fine and coarse aggregate should be blended to create a dense-graded combined aggregate. Recommended grading limits for 19 mm (3/4 in.) NMSA to be used in RCC pavement mixtures are given in Table A3.2. The volume of fine and coarse aggregate per unit volume of concrete are determined after the optimum water content of the aggregate-cementitious material mixture is determined.

A3.7.4 *Water content*—For a given compactive effort, the optimum moisture content of the mixture is depends upon the properties of the aggregates used and the cementitious material content. Strength loss will occur with a moisture content below the optimum. This is due to insufficient paste and the presence of voids between aggregate particles. Strength loss will also occur if the moisture content is significantly above the optimum due to an increase in the *w/cm*. The moisture content (by mass) is expressed as a percent of the dry mass of the aggregate-cementitious material mixture and should be determined in accordance with ASTM C 566. After completion of compaction tests conducted at incremental moisture contents, the moisture-density data points are plotted, and a smooth curve is drawn through them. The peak of the parabolic curve establishes the optimum moisture content (Fig 3.3).

A3.7.5 *Proportioning steps*—

Step 1—Combine dry coarse and fine aggregate to produce a grading within the limits of Table A3.2. Approximately 9 kg (20 lb) of the combined aggregate are needed for each moisture-density test.

Step 2—Select a cementitious materials content according to the compressive or flexural strength. For RCC pavements having specified flexural strengths as determined in accordance with ASTM C 78, of 4 to 5 MPa or 600 to 700 psi, the amount of cementitious materials used should range between 12 and 16% by mass of dry aggregate. The value selected will depend partially on the type and amount of pozzolan used.

Step 3—Using the combined aggregate and the selected cementitious materials content, determine the optimum moisture content of the RCC in accordance with ASTM D 1557. A minimum of four moisture-density specimens should be molded, and each specimen should be prepared from a separate batch of RCC to avoid excessive cement hydration. Each successive batch should contain a higher moisture content than previous ones. This is done by adding sufficient water to the batch so as to increase the RCC moisture content, as a percentage of the dry mass of RCC by 0.75 to 1.0%.

Step 4—Determine the optimum moisture content by plotting the dry mass of each specimen versus its respective moisture content and drawing a smooth curve through these plotted points (Fig. A3.3). The moisture content and dry density corresponding to the peak of this curve is the optimum moisture.

Step 5—Assume an entrapped air content of 2.0%. (The actual value can be calculated from compaction test results and the zero air-voids curve.)

Step 6—Using the optimum moisture content, the selected cementitious materials content, and the value for the air content, calculate the absolute volumes and masses of the materials for the required unit volume of concrete.

Step 7—Follow Steps 2 through 6 using a higher and lower cementitious materials content. After trial batches are produced at the optimum moisture content for each cementitious materials content, plot strength versus cementitious materials content to determine the value needed for the final mixture proportions. Follow Steps 2 through 6 again with the selected cementitious materials content to determine the optimum moisture content and recalculate the material absolute volumes and mass.

A3.7.6 *Example problem*—Concrete pavement is required for a large storage terminal located in a moderate climate. The specified flexural strength is 4.5 MPa (650 psi) at 28 days age. Local aggregate sources are capable of producing ample supplies of aggregate fractions which, when properly blended, will be well-graded. A nominal maximum-size aggregate of 19 mm (3/4 in.) is selected based on the type of modified paving equipment that is anticipated for use. Type I portland cement and Class F fly ash are available and will be specified. Proportion an RCC mixture which may be compacted such that it contains not more than 2% voids and will achieve the required strength.

Step 1—Aggregates for the project are supplied in two size groups—4.75 to 19 mm (No. 4 to 3/4 in.) and 75 µm to 4.75 mm (No. 200 to No. 4). Sieve analysis tests indicate that if 46% of the coarse aggregate is combined with 54% of the fine aggregate, a well-graded combined aggregate grading within the limits of Table A3.2 is produced. Four 9 kg or 20 lb batches of the combined dry aggregate are batched in preparation for the production of compaction test specimens.

Step 2—A cementitious materials content of 14% by dry mass of aggregates is initially selected for use. A fly ash content of 25% by absolute volume of cementitious materials is also selected. Varying cementitious materials contents and fly ash contents should be considered, depending on specification requirements during the mixture proportioning study.

Steps 3 and 4—Compaction tests are conducted in accordance with ASTM D 1557, Method D, at regularly spaced RCC moisture contents. The moisture-dry density curve indicates the optimum moisture content is 5.8% and the maximum dry density of 2348 kg/m^3 or 146.5 lb/ft^3.

Steps 5 and 6—The bulk densities (dry basis) of the materials are:

cement	=	3150 kg/m^3 (197 lb/ft^3)
fly ash	=	2450 kg/m^3 (153 lb/ft^3)
4.75 to 19 mm (No. 4 to 3/4 in.)	=	2716 kg/m^3 (169.5 lb/ft^3)
75 µm to 4.75 mm No. 200 to No. 4)	=	2624 kg/m^3 (163.7 lb/ft^3)
water	=	1000 kg/m^3 (62 lb/ft^3)

Calculations are given herein for SI units and the corresponding inch-pound values are in the framed text. The proportions of materials (dry basis) used in a batch prepared at the optimum moisture content are (in SI units):

75 µm to 4.75 mm	=	9 kg × 0.54	=	4.86 kg (0.00185 m^3)
4.75 to 19 mm	=	9 kg × 0.46	=	4.14 kg (0.00152 m^3)
cementitious material volume	=	(9 kg × 0.14)/ 3150	=	0.0004 m^3
cement	=	(0.0004 m^3 × 0.75) × 3150 kg/m^3	=	0.945 kg (0.0003 m^3)
fly ash	=	(0.0004 m^3 × 0.25) × 2450 kg/m^3	=	0.245 kg (0.0001 m^3)
water	=	9 kg × 0.058	=	0.522 kg (0.000522 m^3)
total air-free batch volume			=	0.004292 m^3

For 1 m^3 of concrete, multiply the volume of each material by:
(1 – 0.02)/0.004292 = 228.33

75 µm to 4.75 mm = 0.422 m^3 (1110 kg)

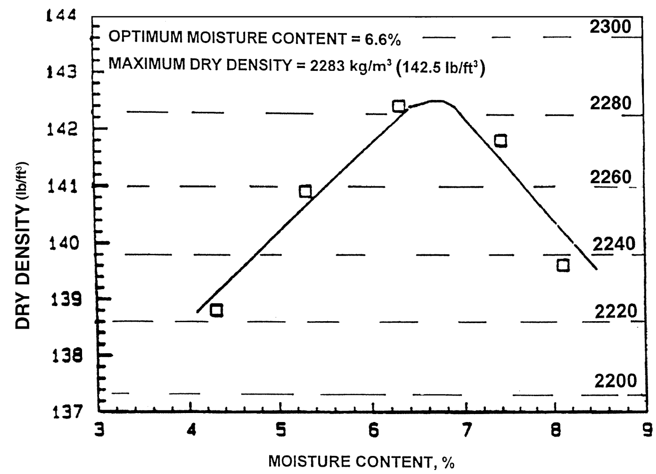


Fig. A3.3—Typical moisture-dry density relationship.

4.75 to 19 mm	= 0.347 m^3 (945 kg)
cement	= 0.069 m^3 (216 kg)
fly ash	= 0.023 m^3 (56 kg)
water	= 0.119 m^3 (119 kg)
air	= 0.02 m^3

The proportions of materials (dry basis) used in a batch prepared at the optimum moisture content are (in inch-pound units):

No. 200 to No. 4	=	20 lb × 0.54	=	10.80 lb (0.0660 ft^3)
No. 4 to 3/4-in.	=	20 lb × 0.46	=	9.20 lb (0.0543 ft^3)
cementitious material volume	=	(20 lb × 0.14)/196.56	=	0.01425 ft^3
cement	=	(0.1425 ft^3 × 0.75) × 196.56 lb/ft^3	=	2.10 lb (0.01069 ft^3)
fly ash	=	(0.01425 ft^3 × 0.25) × 152.88 lb/ft^3	=	0.54 lb (0.00356 ft^3)
water	=	20 lb × 0.058	=	1.16 lb (0.0186 ft^3)
total air-free batch volume			=	0.1532 ft^3

For 1 yd^3 of concrete, multiply the volume of each material by
(27 – 0.54)/0.1532 = 172.72

No. 200 to No. 4 (dry)	= 11.40 ft^3 (1866.3 lb)
No. 4 to 3/4-in. (dry)	= 9.38 ft^3 (1589.7 lb)
cement	= 1.85 ft^3 (363.6 lb)
fly ash	= 0.61 ft^3 (93.3 lb)
water	= 3.21 ft^3 (200.3 lb)
air	= 0.54 ft^3

Step 7—Follow Steps 2 through 6 using a higher and lower cementitious materials content. After trial batches are produced and flexural strength specimens molded and tested at the optimum moisture content for each cementitious

materials content, plot flexural strength versus cementitious materials content to determine the value needed for the final mixture proportions. Follow Steps 2 through 6 again with the selected cementitious materials content to determine the optimum moisture content and recalculate the material absolute volumes and weights masses.

APPENDIX 4—CONCRETE ROOF TILE MIXTURE PROPORTIONING

A4.1—General

Concrete roof tiles are generally produced by an extrusion process, although some manufacturers incorporate a vibration and compaction process similar to that for producing masonry units and paving stones. The extrusion process requires a mixture incorporating only fine aggregate, whereas the vibration and compaction process incorporates both fine and coarse aggregates. This guide deals only with the manufacture of concrete roof tiles by the extrusion process.

Roof tiles are produced by extruding a concrete mixture into a specific shape (profile) and cutting the extruded section to the proper length. The freshly extruded roof tiles are transported by conveyor to storage racks and subsequently placed into kilns for air, mist, or low-pressure steam curing. The proportioning of materials for the concrete mixture will vary depending on the type of materials, the specific tile profile being produced, and the desired density.

Material properties most critical for concrete roof tiles are strength, absorption, durability, density, texture, and aesthetics. The strength of roof tiles is determined by measuring the flexural load capacity.

A low-absorption value of concrete roof tiles is a major factor in the design of a roof-framing system due to the effect of increased dead load under inclement weather conditions. Low-absorption values are also thought to improve the durability aspects of roof tiles; however, further studies on this subject are warranted.

The density of roof tiles determines the load per unit area that a structure must support. This can influence the feasibility of using concrete roof tile instead of asphaltic shingles for a proposed reroofing operation.

Texture and aesthetics are important for providing the purchaser with an architecturally desirable product that can be manufactured to match pigmented stucco walls or other building elements.

A4.2—Selection of materials

A.4.2.1 *Portland cement*—Type I and Type III portland cement (ASTM C 150) are typically used in the production of concrete roof tile depending upon the climate, availability, and production schedule for the particular manufacturing facility.

A4.2.2 *Mineral admixtures*—Pozzolans are sometimes used as partial replacement of portland cement. Typically, either Class F or Class C fly ash (ASTM C 618) is used. Class C fly ash is often used because it provides faster strength gain than Class F. Class C fly ash can be used as a partial replacement for cement in the range of 20 to 25%. The cement replacement percentage should be determined so that sufficient early strength is obtained for production and handling.

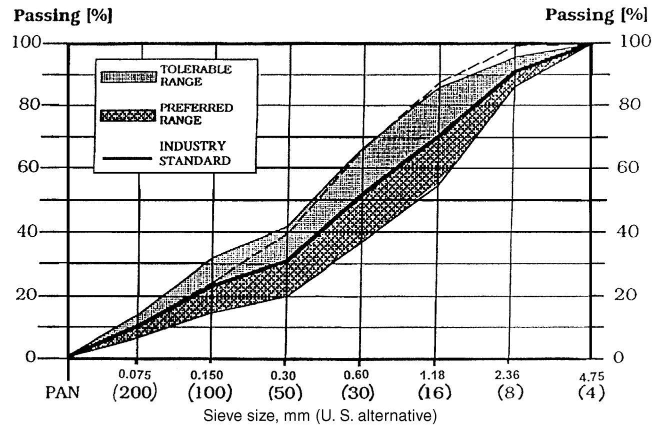


Fig. A4.1—Aggregate grading ranges for concrete roof tiles.

A4.2.3 *Normalweight and lightweight aggregates*—Most roof tiles are produced using only normalweight aggregates; however, some production incorporates lightweight aggregate. Lightweight roof tiles are produced mainly for the reroofing market where structures are not designed for normalweight roof tile dead loads. Considering that patents for lightweight roof tile production are held by certain manufacturing companies, this guide deals exclusively with the manufacture of roof tiles using normalweight aggregates.

A4.2.4 *Grading and fineness modulus*—Fine aggregate only is used in the production of extruded concrete roof tile to facilitate cutting of the extrudate and producing smooth ends. The fineness modulus of the aggregate should range between 2.2 and 3.0, with a typical value being 2.5. The grading limits that have been recommended by one an international supplier to the roof tile industry are shown in Fig. A4.1.

A4.2.5 *Admixtures*—

Accelerators—Depending on the climate, production schedule, and type of cement, accelerating admixtures are used in the production of roof tiles.

Water repellents—Integral water repellents can be used to decrease water absorption of roof tile. Use of low *w/cm*, pozzolans and low-absorption aggregates typically decrease water absorption as well.

Plasticizers (wetting agents, water reducers)—Plasticizers can be used to increase the flow of material while improving the texture of the roof tile during extrusion and cutting.

A4.2.6 *Pigments*—Pigments are added integrally to the concrete mixture, or placed in a cement slurry, or both, and applied to the roof tile after extrusion. This is done to obtain the desired aesthetics with the roof tile, either by producing a single color or applying a mottled color to the exposed surface for a specific effect.

A4.3—Proportioning procedure

A4.3.1 *Water-cementitious materials ratio*—The *w/cm* can range from 0.32 to 0.45 depending on the fineness of the aggregate and the profile of the roof tile being produced. When the amount of cementitious materials is held constant, the *w/cm* will increase with decreasing aggregate fineness modulus (due to increased surface area), but it may not be clear how the type of roof tile profile being produced influences the *w/cm*.

For a given concrete roof tile mixture, the flexural load capacity of a convoluted roof tile will be greater than that of a flat roof tile due to a greater moment of inertia for the convoluted tile. Therefore, to achieve the same flexural load capacity, the concrete mixture for flat roof tile must be stronger than the mixture for convoluted roof tile. This is accomplished by increasing the cement content of the mixture, which in turn, decreases the water-cementitious materials content.

Cement-aggregate ratio by weight mass—The cement to aggregate ratio varies from 1:2.5 to 1:4.5, with a typical cement to aggregate ratio for flat and convoluted roof tile being 1:3 and 1:4, respectively.

Example 1—An example of a convoluted roof tile mixture using Type III portland cement and no admixtures is:

1200 kg (2600 lb) sand (FM = 2.60, SSD)
285 kg (620 lb) cement (cement-aggregate ratio = 1:4.2)
123 kg (267 lb) water (*w/c* = 0.43)
10 kg (22 lb) pigment (3.5% by mass of cement)

Example 2—An example of a flat roof tile mixture using Type III portland cement and no admixtures is:

1200 kg (2600 lb) sand (FM = 2.60, SSD)
387 kg (840 lb) cement (cement-aggregate ratio = 1:3.1)
123 kg (267 lb) water (*w/c* = 0.32)
13 kg (29 lb) pigment (3.5% by mass of cement)

APPENDIX 5—CONCRETE MASONRY UNIT MIXTURE PROPORTIONING

A5.1—General

This guide contains methods for selecting mixture proportions for standard CMU (less than no-slump mixtures) manufactured on conventional vibrating block machines. Covered are the selection of cementitious materials, blending and proportioning aggregates for both normalweight and lightweight units, and curing conditions as they affect mixture proportioning. Mixture proportioning for decorative CMU is not covered due to its highly specialized nature.

A5.2—Cementitious materials

A5.2.1 *Portland cement*—Portland cement should conform to ASTM C 150. In certain areas, block cement is used, but this type of cement does not have a corresponding ASTM specification. This is a proprietary product and its performance characteristics should be discussed with the cement supplier. Types III and III-A portland cements are frequently used to achieve early strengths and to facilitate handling and storage.

A5.2.2 *Supplementary cementitious materials*—commonly used supplementary cementitious materials are ground granulated blast-furnace slag (GGBFS), fly ash (ASTM C 618, Class F and C) and silica fume. Common additions by mass of cement for GGBFS are 20 to 50%. Fly ash is normally used at a rate of 15 to 25% by mass of cement.

A5.2.3 *Quantity of cementitious materials*—Cementitious materials content of CMU mixtures can be expressed as kilograms (kg) or pounds (lb) of material per batch or per CMU (200 mm [8 in.] standard unit). Also, cement content can be calculated as a percent of the total mass of the aggregates. Cement content can vary depending on design strength, aggregate grading and quality, and expected curing condition. For ASTM C 90, CMU produced with normalweight aggregates, a cement content of 7 to 10% by mass of aggregate is the normal range. Obviously, higher cement factors are needed for high-strength CMU and these may exceed 20% by mass of aggregates.[9]

A5.3—Aggregates

Aggregates for CMU may be made from either normalweight or lightweight materials. The normalweight materials are generally considered to be gravel, crushed limestone, and unprocessed blast-furnace slag. Normalweight aggregates should conform to the requirements of ASTM C 33.

Lightweight aggregates may be classified into three general types as follows:

- Aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate;
- Aggregates prepared by processing natural materials, such as pumice, scoria, or tuff; or
- Aggregate consisting of end products of coal or coke combustion.

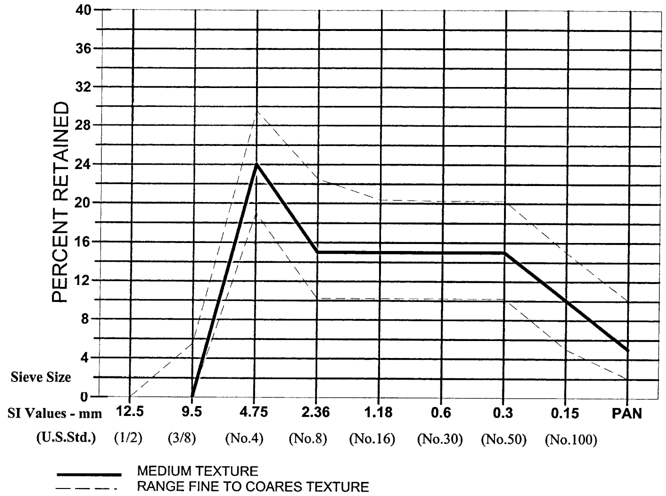
Lightweight aggregates should conform to ASTM C 331.

Grading of aggregates—Generally, in CMU manufacture, material passing the 9.5 mm (3/8 in.) sieve and remaining on the 4.75 mm (No. 4) sieve is designated as coarse aggregate. A coarser grading of normalweight aggregate results in less surface area and less inter-particle voids; therefore, less cement paste is needed. If the volume of cementitious materials is held constant, a lower *w/cm* can be used resulting in increased strength. Therefore, the ideally graded aggregate is that mixture that contains as much coarse material as can be used, short of producing harshness in the mixture and an excessively rough-textured CMU.

Fine aggregates consist of natural sand, lightweight fines or stone screenings, which pass the 4.75 mm (No. 4) sieve. The grading of each aggregate to be used in the mixture should be determined in accordance with ASTM C 136.

Fineness modulus—The specific gravity for natural aggregates is essentially constant for all sieve sizes and, as a result, the fineness modulus on a mass basis will directly reflect the volumes occupied by each particular size. In contrast, the specific gravities measured on each sieve size in a typical commercial lightweight aggregate blend reveal a progressive increase in specific gravity as the particle size decreases. It is the volume occupied by each size fraction, not the mass of material retained on each sieve, that ultimately determines the void structure, paste requirements, and workability characteristics. An example is included and shown in Table A5.1 to further demonstrate this difference between the mass and volume occupied by particles on each sieve for a particular lightweight aggregate.

From Table A5.1 it can be seen that the fineness modulus by volume of 3.36 indicates a considerably coarser gradation than the fineness modulus by mass, 3.15. Therefore, because of their unique characteristics, lightweight aggregates require a



SUGGESTED GRADING

SIEVE SIZE mm	US Std.	PERCENT RETAINED	CUMUL.% RETAINED
12.5	(1/2)	—	—
9.5	(3/8)	—	—
4.75	(No.4)	25	25
2.38	(No.8)	15	40
1.18	(No.16)	15	55
0.6	(No.30)	15	70
0.3	(No.50)	15	85
0.15	(No.100)	10	95
PAN		5	—
FM = 3.70			

Fig. A5.1—Aggregate analysis graph: normal weight.

Table A5.1—Fineness modulus (FM) by mass and volume

Sieve size, mm or U.S. alternative	Percent retained by mass	Cumulative percent retrained by mass	Specific gravity (SSD)	Percent retained by volume	Cumulative percent retained by volume
9.5 (3/8 in.)	0	0	—	—	—
4.75 (No. 4)	5	5	1.5	5.9	5.9
2.36 (No. 8)	25	30	1.6	27.8	33.7
1.18 (No. 16)	25	55	1.7	26.1	59.8
0.60 (No. 30)	10	65	1.8	9.9	69.7
0.30 (No. 50)	10	75	1.9	9.3	79.0
0.15 (No. 100)	10	85	2.0	8.9	87.9
Pan/FM	15	FM by mass	2.2	12.1	FM by volume
	Total 100	3.15	—	Total 100	3.36

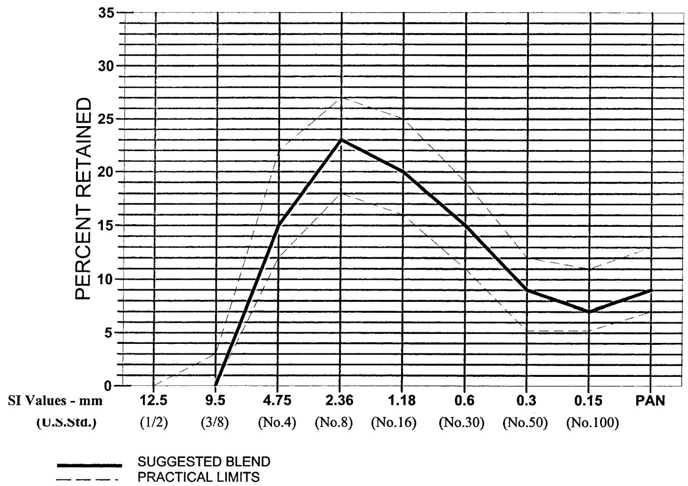
significantly larger percentage of material retained on the finer sieves, when computed on a mass basis, than normalweight aggregates to provide a comparable void system. Furthermore, pyroprocessed lightweight aggregate particles passing the 150 µm (No. 100) sieve are extremely beneficial because they serve a dual role as both aggregate and pozzolan.

It is important to recognize that the fineness modulus is a single number index that suggests an average particle size, and identical fineness moduli may be obtained from fundamentally differing gradings. The fineness modulus can be useful as an overall qualitative index or for quality control of an individual supplier providing a specific standard gradation, but it is not a reliable index for comparing alternative aggregate sources. From the data shown in Table A5.2, it can be seen that an aggregate producer could supply three different grading textures that have identical fineness modulus that would produce CMUs with three significantly different textures. Because fineness modulus methodology reflects an average particle size, by keeping the percent retained constant on the 1.18 mm (No. 16) sieve for all gradings, one can manipulate numbers and arrive at the same fineness modulus for all three fundamentally different products that satisfy the grading limits in ASTM C 331.

Figure A5.1 illustrates the ideal grading and range for a blend of normalweight aggregates. A blend of intermediate-weight aggregate shown in Fig. A5.2 and A5.3 illustrates the ideal grading for 100% lightweight CMU. Although the curves are empirical, they can be modified to fit local market preferences for surface texture. The optimum fineness modulus for normalweight aggregates is generally considered to be 3.70.

Menzel[8] showed that the influence of grading (expressed in terms of fineness modulus) on the strength-making characteristics of CMU molded with structural grade lightweight aggregate (LWA CMU) differed from units incorporating rounded sand and gravel. The compressive strength of the CMUs made with expanded shales was essentially constant over a wide range of fineness modulus up to approximately 3.5, after which there was a rapid decline in strength levels with coarser gradings. This behavior was opposite to the sand and gravel CMUs, which showed an increase of strength, ultimately reaching a maximum at a fineness modulus above 4. Compressive strength levels for LWA CMUs significantly greater than ASTM C 90 minimums are best achieved when finer gradings of structural grade lightweight aggregate are used. Systematically eliminating large particles that have an inherently higher porosity, and as a consequence a lower particle strength, will significantly increase the strength. Lowering of the nominal maximum size of aggregate also reduces bridging of particles within the mass and improves the compactability of the mixture.

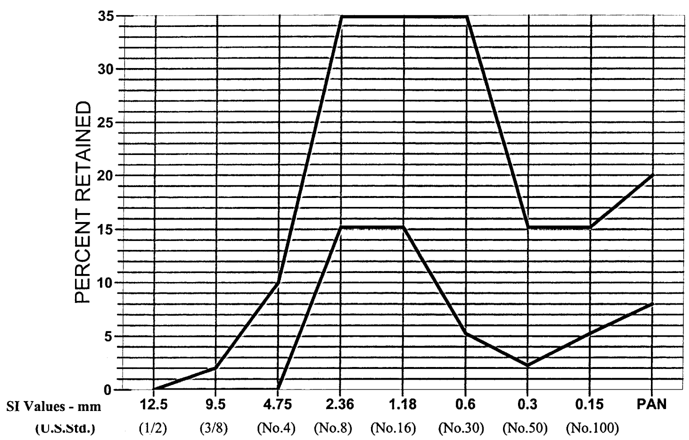
Use of optimized gradings will result in a balance of qualities that include production characteristics (smooth feeding,



SUGGESTED GRADING

SIEVE SIZE mm	US Std.	PERCENT RETAINED	CUMUL.% RETAINED
12.5	(1/2)	—	—
9.5	(3/8)	—	—
4.75	(No.4)	17	17
2.38	(No.8)	23	40
1.18	(No.16)	20	60
0.6	(No.30)	18	75
0.3	(No.50)	9	84
0.15	(No.100)	7	91
PAN		9	—
FM = 3.70			

Fig. A5.2—Aggregate analysis graph: fine texture intermediate weight.



SUGGESTED GRADING

SIEVE SIZE mm	US Std.	PERCENT RETAINED	CUMUL.% RETAINED
12.5	(1/2)	0	0
9.5	(3/8)	0-2	0-2
4.75	(No.4)	0-10	0-10
2.38	(No.8)	15-35	20-40
1.18	(No.16)	15-35	45-85
0.6	(No.30)	5-20	60-75
0.3	(No.50)	5-15	70-85
0.15	(No.100)	5-15	80-92
PAN		8-20	100

Fig. A5.3—Aggregate analysis graph: lightweight.

Table A5.2—Comparison of gradings for aggregates with equal fineness modulus

Sieve size, mm or U.S. alternative	ASTM C 331 limits for combined aggregates, % retained	Texture			ASTM C 331 limits for combined aggregates, % retained
		Fine	Medium	Coarse	
9.5 (3/8 in.)	(0)	0	0	0	(0-10)
4.75 (No. 4)	(0-15)	5	10	15	(10-35)
2.36 (No. 8)	—	35	40	45	(35-65)
1.18 (No. 16)	(20-60)	55	55	55	—
0.60 (No. 30)	—	75	70	65	—
0.30 (No. 50)	(65-90)	85	80	75	(75-90)
0.15 (No. 100)	(75-95)	90	90	90	(85-95)
FM	—	3.45	3.45	3.45	—

compactability, green strength) as well as superior hardened concrete properties. What is truly important in achieving the consistent quality standards required of high-quality LWA CMUs is close attention to specific individual sieve sizes of aggregate, and in particular, the material retained on the 4.75 and 2.36 mm (No. 4 and No. 8) sieves (essential for texture control) and that passing the 150 μm (No. 100) (critical for molding and handling characteristics). Following the gradings recommendations shown in Fig. A5.3 will result in a uniform, fine-textured surface with an optimum interstitial void system within the block concrete. This will, in turn, maximize the thermal, acoustical, and fire resistance as well as the strength-making properties of the finished product.

A5.4—Proportioning procedure

Calculation of aggregate proportions—The percentage of coarse and fine aggregate by volume to achieve an optimum fineness modulus grading is calculated as follows

$$FA\% = \frac{FM_{CA} - FM_{COMB}}{(FM_{CA} - FM_{FA}) \times 100} \quad \text{(A5.1)}$$

where FM_{CA} and FM_{FA} are the fineness modulus of coarse and fine aggregate, respectively; and FM_{COMB} is the recommended combined fineness modulus.

Example—

Given: FM_{CA} = 5.48; FM_{FA} = 2.57

Desired combined FM_{COMB} = 3.70

$$FA\% = \frac{5.48 - 3.70}{(5.48 - 2.57) \times 100} = 61\% \quad \text{(A5.2)}$$

Therefore, the blend would consist of 39% coarse aggregate and 61% fine aggregate, by volume.

NOTE: Fineness modulus determinations are normally based on mass retained on given sieve sizes rather than volumes. Volume-based gradings can be developed for use in designing block mixtures; however, experience has shown that mass-determined fineness moduli provide a satisfactory basis for preliminary block mixtures because production adjustments are almost always needed. Block machine compaction and vibration will affect the surface texture of the masonry units as will the moisture content of the mixture at time of use.

Calculation of batch quantities—To determine batch quantities, the volume capacity of the mixer to be used and the dry mass of the aggregates must be determined. For design purposes, the full-rated volume of the mixer is used, yet, total batch size may need adjusting as trial batches are run.

Trial batch example:

Mixer volume = 2.27 m^3 (80 ft^3)

CA density (dry-rodded) =1218 kg/m^3 (76 lb/ft^3)

FA density (dry-rodded) = 1522 kg/m^3 (95 lb/ft^3)

The paste volume is only a little greater than the voids between the aggregate particles so that the dry-rodded volume is close to the concrete volume. A batch volume of 2.21 m^3 or 78 ft^3 will be used.

Mass calculations in SI units:

Mass of CA = 2.21 m^3(0.39)1218 kg/m^3 = 1050 kg

Mass of FA = 2.21 m^3(0.61)1522 kg/m^3 = 2052 kg

Total mass of aggregate = 3102 kg

Cement factor: assume 10% by mass of aggregate

Cement content = 3102(0.10) = 310 kg

Mass calculated in inch-pound units:

Mass of CA = 78 ft^3 (0.39) (76 lb/ft^3) = 2312 lb

Mass of FA = 78 ft^3 (0.61) (95 lb/ft^3) = 4520 lb

Total mass of aggregate = 6832 lb

Cement factor: assume 10% by mass of aggregate

Cement content = 6832 (0.10) = 683 lb

The water content is adjusted until the mixture will "ball" in the hand. It will have sufficient cohesion to hold its shape when squeezed but will not exhibit any free moisture.

This method is more of a trial-and-error approach than the volumetric approach and therefore, is for trial designs only. Test batches must be run through the machine to be used in production to verify such characteristics as compressive strength, surface texture, absorption, and green strength (the ability of a freshly molded block to withstand machinery and pallet movement without cracking).

APPENDIX 6—PERVIOUS CONCRETE MIXTURE PROPORTIONING

A6.1—General

This guide provides a method for proportioning no-slump pervious concrete that is used for pavements and other applications where drainage and percolation are needed. Pervious concrete is an open-graded material that is bound by cement paste. The structure of the material allows the passage of water, yet provides moderate structural strength. Because of the high percentage of voids, pervious concrete has been used also as an insulating material.

A6.2—Materials

Pervious concrete is composed of cement or a combination of cement and pozzolan, coarse aggregate, and water. Occasionally, a small amount of fine aggregate has been incorporated to increase compressive strength and to reduce percolation through the concrete. The most common gradings of coarse aggregate used in pervious concrete meet the requirements of ASTM C 33 sieve sizes 9.5 to 2.36 mm (Size No. 8), 12.5 to 4.75 mm (Size No. 7), and 19.0 to 4.75 mm (Size No. 67). Portland cement should conform to ASTM C 150 or a combination of cementitious materials can be used that conform to the appropriate ASTM specifications.

A6.3—Water-cementitious materials ratio

The *w/cm* is an important consideration for maintaining strength and the void structure of the concrete. A high *w/cm* reduces the adhesion of the paste to the aggregate and causes the paste to flow and fill the voids even when lightly compacted. A low *w/cm* will tend to cause balling in the mixer and prevent an even distribution of materials. Experience has shown a range of 0.35 to 0.45 will provide the best aggregate coating and paste stability. Higher values of *w/cm* should only be used if the concrete is lightly tamped or compacted. The *w/cm* versus compressive strength relationship, which is normally used with conventional concrete, does not apply to pervious concrete.

A6.4—Durability

Freezing-and-thawing tests of pervious concrete indicate poor durability if the void system is filled with water. Tests have indicated that durability is improved when the void structure is permitted to drain and the cement paste is air-entrained. No research has been conducted on resistance of pervious concrete to the aggressive attack by sulfate-bearing or acidic water that can percolate through the concrete. Therefore, caution should be used in applications where aggressive water may exist.

A6.5—Percent voids

Compressive strength versus percolation—To ensure that water will percolate through pervious concrete, the percent voids, calculated as percent air by the gravimetric method (ASTM C 138), should be 15% or greater as shown on

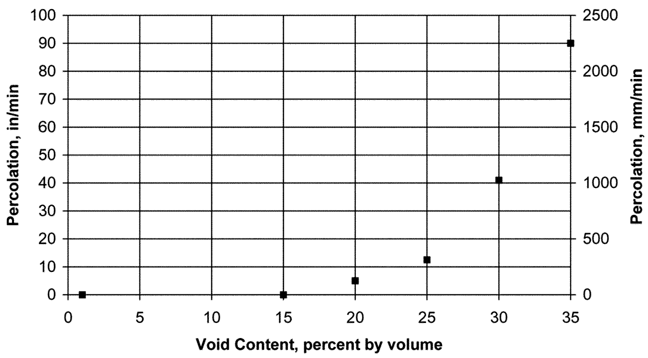


Fig. A6.1—Minimum void content for percolation based on NAA-NRMCA tests and test method.

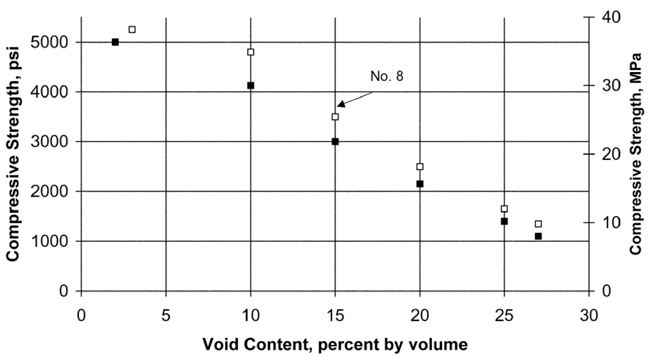


Fig. A6.2—Relationship between void content and 28-day compressive strength for No. 67 and No. 8 aggregate size.

Fig. A6.1.[6] At this void content, the compressive strength of the concrete as shown in Fig. A6.2 would be approximately 24 MPa (3500 psi) at 28 days. The higher the percent voids, the higher the percolation rate and the lower the compressive strength. The lower the percent voids, the lower the percolation rate and the higher the compressive strength. Also, the compressive strength increases as the nominal maximum size aggregate decreases.

A6.6—Amount of coarse aggregate

Coarse aggregate, b/b_o, dry-rodded density tests made by the National Aggregates Association-National Ready Mixed Concrete Association (NAA-NRMCA)[6] show that the dry-rodded density of coarse aggregate, as determined by ASTM C 29/C 29M, can be effectively used in proportioning pervious concrete, where:

b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete;

b = solid volume of coarse aggregate in a unit volume of concrete; and

b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate.

The b/b_o value automatically compensates for the effects of different coarse aggregate particle shape, grading, and specific gravity. Furthermore, the b/b_o values for a range of nominal maximum-size aggregates normally used in pervious concrete, 10 to 20 mm (3/8 to 3/4 in.), are very similar. Table A6.1 gives the b/b_o values for coarse aggregate sizes No. 8 and No. 67 for fine aggregate contents of 0, 10, and 20% of the total aggregate.

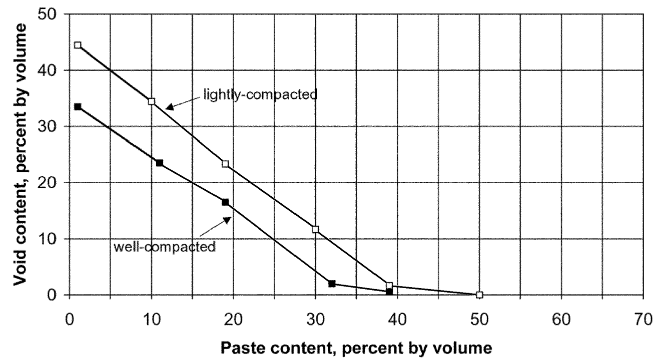


Fig. A6.3—Relationship between paste and void content for No. 8 aggregate size designations.

Table A6.1—Effective b/b_o values

Percent fine aggregates	b/b_o ASTM C 33 Size No. 8	b/b_o ASTM C 33 Size No. 67
0	0.99	0.99
10	0.93	0.93
20	0.85	0.86

A6.7—Proportioning procedure

The proportioning procedure for pervious concrete is based on the volume of paste necessary to bind the aggregate particles together while maintaining the necessary void content, as shown in Fig. A6.3. The quantity of aggregate depends on the dry-rodded density and the b/b_o values selected from Table A6.1. Once the paste volume is determined from Fig. A6.3 and the desired w/cm is selected, the cement and water quantities can be determined from the relationship:

Paste volume (V_P) = cement volume + water volume, or

$$V_P = c/3150 + w/1000 \text{ (m}^3\text{)}$$

In inch-pound units

$$V_P = c/(3.15 \times 62.4) + w/62.4 \text{ (ft}^3\text{)}$$

where c is the mass of cement and w is the mass of water. If the water-cement ratio is (w/c) then

$$w = (w/c)c\text{; and}$$

$$V_P = c/3150 + [(w/cm)c/1000] \text{ (m}^3\text{)}$$

In inch-pound units

$$V_p = c/(3.15 \times 62.4) + [(w/c)c/62.4] \text{ (ft}^3\text{)}$$

Therefore, once the paste volume is determined from Fig. A6.3 and the w/cm is selected, the mass of cement can be calculated. When fine aggregate is used, the paste volume should be reduced by 2% for each 10% fine aggregate of the total aggregate for well-compacted pervious concrete, and by 1% for each 10% fine aggregate of the total aggregate for lightly compacted pervious concrete. These reductions are necessary to maintain the same percent voids by volume.

Example—Proportion a well-compacted pervious concrete mixture with a No. 8 coarse aggregate (ASTM C 33) that has a dry-rodded density of 1742 kg/m^3 (108.7 lb/ft^3), a bulk specific gravity (saturated surface dry) of 2.75, and an absorption of

1.2%. The mixture should have a void content of at least 20% and a compressive strength of 14 MPa or 2000 psi at 28 days. The pervious concrete will be proportioned for w/c = 0.38, which has been selected as a stable paste for this example. No fine aggregate will be used in the mixture.

Mass of aggregate (M_a) per m^3 (yd^3);

M_a = 1742 × 0.99 = 1725 kg (dry)
= 1725 × 1.012= 1746 kg (SSD)
M_a = 108.7 × 0.99 × 27 = 2906 lb (dry)
= 2906 × 1.012 = 2941 lb (SSD)

Solid volume of aggregate per m^3 (yd^3)(V_a);

V_a = 1746/2750 = 0.635 m^3
V_a = 2941/(2.75 × 62.4) = 17.14 ft^3

From Fig. A6.3, the percent paste by volume is 16.5 when the voids equal 20% and the material is well-compacted. Figure A6.1 indicates a percolation rate of approximately 125 mm/min (5 in./min) Figure A6.2 indicates a compressive strength of approximately 17 MPa (2500 psi).

Solid volume of paste per m^3(V_P);

V_P = 16.5/100 = 0.165 m^3, and
0.165 = c/3150 + ((0.38) c/1000), therefore;

c = 237 kg/m^3
w = 237(0.38) = 90 kg/m^3
V_C = 237/3150 = 0.075 m^3
V_W = 90/1000 = 0.090 m^3

In inch-pound units

V_P = (16.5/100) × 27 = 4.46 ft^3; and
4.46 = c/(3.15 × 62.4) + 0.38(c/62.4) = 2.03 + 2.42, therefore;

c = 399 lb/yd^3
V_C = 399/(3.15 × 62.4) = 2.03 ft^3
w = (0.38)399 = 152 lb
V_W = 152/62.4 = 2.43 ft^3

The batch quantities, per m^3, are as follows:

Cement		237 kg/m^3
Water		90 kg/m^3
No. 8 aggregate		1745 kg/m^3 (SSD)
Total mass	=	2072 kg/m^3
Density	=	2072 kg/m^3

Check solid volume, per m^3:

Cement	0.075 m^3
Water	0.090 m^3
No. 8 aggregate	0.635 m^3
Total	0.800 m^3

Volume of voids = 1.000 – 0.800 = 0.200 m^3

The batch quantities, per yd^3, are as follows:

Cement		399 lb/yd^3
Water		152 lb/yd^3
No. 8 aggregate		2941 lb/yd^3 (SSD)
Total mass	=	3492 lb/yd^3
Density	=	129.3 lb/yd^3

Check solid volume, per lb/yd^3:

Cement	2.03 ft^3
Water	2.43 ft^3
No. 8 aggregate	17.14 ft^3
Total	21.60 ft^3

Volume of voids = (27 – 21.60) = 5.4 ft^3
Percent voids = 20.00

The calculated mixture proportions should be checked in the laboratory by trial batch and adjusted as required. In addition, it is recommended that trial batches include two additional mixtures with 30 kg/m^3 (50 lb/yd^3) more and 30 kg/m^3 (50 lb/yd^3) less cement. These mixtures should also include the appropriate adjustments in: 1) water to produce the required w/cm; and in 2) aggregate to maintain the required percent voids. Generally, achieving the required void content and percolation rate with a stable paste are of greater importance than compressive strength of the mixture.