IN-LB	Inch-Pound Units
SI	International System of Units

Selecting Proportions for Normal-Density and High-Density Concrete—Guide

Reported by ACI Committee 211

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This guide to concrete proportioning provides background information on, and a procedure for, selecting and adjusting concrete mixture proportions. It applies to normal-density concrete, both with and without chemical admixtures, supplementary cementitious materials, or both. The procedure uses calculations based on the absolute volumes occupied by the mixture constituents. The procedure incorporates consideration of requirements for aggregate gradation, workability, strength, and durability. Example calculations are provided, including adjustments based on the results of the first trial batch. Appendixes cover laboratory tests and proportioning of high-density concretes.

Keywords: absolute volume; admixtures; air content; durability; mixture proportioning; supplementary cementitious materials; trial batching; water-cementitious materials ratio (*w/cm*); workability; yield.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Historical background

The ability to tailor concrete properties in accordance with project requirements reflects technological developments that have taken place, for the most part, since the early 1900s. The use of the water-cement ratio (*w*/*c*)—one of the key parameters of mixture proportioning—as a tool for estimating strength was recognized in approximately 1918. In the early 1940s, improvements in durability were achieved with the use of air entrainment. These major developments in concrete technology were augmented by the development of chemical admixtures to achieve special properties, counteract possible deficiencies, and improve cost effectiveness (ACI 212.3R). The first water-reducing admixture was developed in the 1920s and was patented in Europe in 1932, and then in the United States in 1939. Slowly, water-reducing admixtures came into widespread use in the 1970s and played a major role in improving workability, thereby adjusting mixture proportions. Around this time, it was also found that some concrete characteristics could be improved with the addition of certain industrial by-products, now called supplementary cementitious materials (SCMs). The use of these materials has not only improved various concrete properties, but also played a major role in contributing to environmental sustainability. With the implementation of these technological developments, in current practice, most commercially produced concrete contains some type of chemical admixtures, SCM, or both, and their presence needs to be considered while mixture proportioning.

1.2—Introduction

Concrete is composed principally of aggregates, a portland or blended cement, and water, and may contain SCMs, chemical admixtures, or both. It will contain some amount of entrapped air and may also contain purposely entrained air created with the use of an admixture or air-entraining cement. Chemical admixtures are frequently used to accelerate or retard the time of setting, improve workability, or reduce water requirements (ACI 212.3R). Their use may affect strength and other concrete properties. Depending on the type and amount, certain SCMs such as fly ash (ACI 232.2R), natural pozzolans, slag cement (ACI 233R), and silica fume (ACI 234R) may be used in conjunction with portland or blended cement. They are added to provide specific properties such as higher strength, decreased permeability, resistance to the intrusion of aggressive solutions,

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increased resistance to alkali-aggregate reaction and sulfate attack (ACI 225R and ACI 233R), reduced heat of hydration, reduced shrinkage, improved late-age strength development, and for economic reasons.

The selection of mixture proportions involves a balance between economy and requirements for durability, strength, workability, density, and appearance. The required characteristics are determined by the intended application of concrete, and by the conditions expected to be encountered at the time of placement and beyond. These characteristics should be detailed in the job specifications. Some characteristics are governed by the concrete building code. A broad range of characteristics ranging from high strength to self-consolidation and flowable fills, from low-permeability bridge decks to pervious concrete parking lots, and many other characteristics and applications have been made possible with the use of admixtures and SCMs.

The best concrete proportions are based on previous experience with the materials that will be used on similar projects. Lacking that, numerous methods have been developed for proportioning concrete mixtures. Methods have been developed ranging from arbitrary cement:sand:rock:water proportions (that is, 1:2:3:0.5), empirical methods such as workability factors (Shilstone 1990), and methods developed from first principles such as packing models (de Larrard and Sedran 2002) and suspension methods (ACI 211.6T). It is beyond the scope of this discussion to review the background and theory behind these methods or those of the relatively simple procedures of this guide. Computer programs for concrete mixture design incorporating many of these theories are commercially available.

Frequently, existing concrete proportions are reproportioned to include chemical admixtures, SCMs, or a different material source. The performance of the reproportioned concrete should again be verified by trial batches in the laboratory or field.

Proportions calculated by any method should always be considered provisional, subject to revision based on trial batch results. Depending on circumstance, trial batches may be prepared in a laboratory. With success in the lab, the trials should move on to full-size field batches with the materials, means, and methods expected for the project. This procedure, when feasible, avoids pitfalls of assuming that data from small batches mixed in a laboratory environment will predict performance under field conditions. When using maximum-size aggregates larger than 2 in., laboratory trial batches should be verified and adjusted in the field using mixtures of the size and type to be used during construction. Trial batch procedures are discussed in Chapter 8, with additional background and details provided in the appendixes.

1.3—Scope

This guide describes a method for selecting proportions for concrete made with hydraulic cement meeting ASTM C150/C150M, C595/C595M, or C1157/C1157M with or without other cementitious materials, chemical admixtures, or both. This concrete consists of normal-density aggregates, high-density aggregates, or both (as distinguished from lightweight aggregates), with a workability suitable for normal cast-in-place construction (as distinguished from specialty concrete mixtures such as pervious or self-consolidating concretes). Proportioning with lightweight aggregates and recycled aggregates are other common options; however, they are beyond the scope of this document. Please refer to ASTM C330/C330M and ACI 213R for lightweight aggregates, and ACI 555R for recycled aggregates.

Also included are several design examples applying the procedure to a variety of situations. For proportioning with ground limestone or other aggregate mineral filler, refer to ACI 211.7R.

Information is provided on terms and concepts used in the proportioning procedure that may be unfamiliar to a novice user.

The procedure produces a first approximation for proportions of a concrete mixture. It is intended that the proportions be checked by trial batches in the laboratory, field, or both, and adjusted as necessary to produce a concrete with all the desired characteristics.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

$\%free$ = percentage of free moisture on an aggregate, %
$\%SCM$ = percentage of supplementary cementitious material to total cementitious by weight, %
$\%total$ = percentage of total evaporable moisture content, %
$A\%$ = percentage of moisture absorption of an aggregate, %
$Air\%$ = percentage of concrete volume occupied by air, %
c = cement weight, lb
cm = cementitious weight, lb
f_c' = specified compressive strength, psi
f_{cr}' = required average compressive strength, psi
$MC\%$ = percentage of moisture content of an aggregate, %
$MC\%_{free}$ = percentage of free moisture content of an aggregate, %
m_i = initial weight of sample being tested for moisture content, lb
$m_{\bullet D}$ = oven-dry weight of sample, lb
m_{SSD} = saturated surface-dry weight of sample, lb
mw_{free} = free water weight, lb
PV = paste volume, ft^3
R_Y = relative yield, %
w = water weight, lb
$w_{batched}$ = batch-ready moisture-adjusted water weight, lb
w_{free} = total free water, lb
w_{SSD} = weight of aggregate in saturated surface-dry condition, lb
Y = yield, %
Y_d = design target volume, ft^3

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2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

cement efficiency—the strength gained from each pound of cement in a cubic yard. With units of psi/lb/yd^3, it is computed by dividing the strength by the weight of cement for a cubic yard of concrete mixture.

dry-rodded unit weight—weight per unit volume of oven-dry aggregate compacted by rodding. It is also known as "dry-rodded density." In this guide, dry-rodded density is used as the preferred term.

finishability—the ability to level, smooth, consolidate, and otherwise treat surfaces of fresh or recently placed concrete to produce a desired appearance and surface.

specific gravity—the ratio of weight of a volume of a material at a stated temperature to the weight of the same volume of distilled water at that stated temperature (refer to ASTM C125 for details). It is also known as "relative density." In this guide, specific gravity is used as the preferred term.

unit weight—the weight per unit volume of a material. It is also known as "density." In this guide, density is used as the preferred term.

weight—the amount or quantity of heaviness. It is also known as "mass." In this guide, weight is used as the preferred term.

CHAPTER 3—CONCRETE PROPERTIES

The selection of concrete proportions involves matching the requirements of the project with the materials and methods available. In this chapter, some of the commonly encountered properties that go into specifying, designing, and proportioning concrete will be discussed. Concrete properties describe the way concrete behaves while being mixed, placed, cured, or in use.

Concrete proportions usually consider workability, strength, and durability needed for the specific application. Other properties may need to be considered to ensure meeting the expectations of the installed materials. These properties include pumpability, finishability, bleeding, density, heat generation, and permeability. For concrete slabs, mortar content and admixtures used can significantly affect finishing and set characteristics of the concrete materials. A project can impose the need for a particular property such as rapid strength gain, modulus of elasticity, filling of a steel-congested space, color, and architectural finish. For some of these properties, well-established relationships are known. For others, the relationship between the specific property and the mixture design can generally be described, with the details worked out through trial batches.

3.1—Water-cementitious materials ratio (*w/cm*)

It has long been known (Abrams 1918) that for a given set of materials and conditions, concrete strength and durability are directly related to the *w/cm*. This is the ratio of the weight of water, excluding that absorbed by the aggregate, divided by the weight of cementitious materials in a mixture, stated as a decimal. The abbreviation of "cm" represents cement and supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag cement, as discussed further in Chapter 7.

Differences in strength at a given *w/cm* may result from changes in placement or curing conditions; the maximum size, gradation, surface texture, particle shape, strength, and stiffness of aggregates; differences in cement types or sources; air content; and the use of chemical admixtures that affect the cement hydration process or that develop cementitious properties themselves. Because most of these factors are measurable, they are accounted for in the recommendations for quantity of water. Accurate predictions of strength and the meeting of strength targets should be based on trial batches, or experience with the project materials and requirements.

3.2—Workability

Workability is that property of freshly mixed concrete that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition. It is affected by water quantity, aggregate grading, particle shape, and proportions of aggregate, as well as by the amounts and qualities of cement and other cementitious materials, chemical admixtures, amount of entrained air, and the consistency of the mixture.

3.3—Consistency

Consistency is the degree to which a freshly mixed concrete resists deformation—that is, its ability to flow. It is measured in terms of slump (ASTM C143/C143M); the higher the slump, the more mobile the mixture will be. This ability to flow affects the ease with which the concrete can be placed. In properly proportioned concrete, the unit water content required to produce a given slump will depend on several factors. The water requirement increases as aggregates become more angular and rough-textured (but this disadvantage may be offset by improvements in other characteristics such as bond to cement paste). The required mixing water decreases as the maximum size of well-graded aggregate is increased, or the level of air entrainment increases. Mixing-water requirements usually are reduced by water-reducing admixtures (ACI 212.3R). Slump characteristics are used for developing special concretes such as self-consolidating concrete (ACI 237R), or other applications needing close control of workability (ACI 238.1R).

3.4—Strength

Conventionally, the average of two 6 x 12 in. or three 4 x 8 in. cylinders fabricated, cured, and tested at the age of 28 days is the value accepted as concrete's compressive strength (ASTM C39/C39M). It is used as a controlling value for structural design, concrete proportioning, and evaluation of concrete. Concrete is commonly specified with compressive strengths from 2500 psi to greater than 10,000 psi. The variable nature of its constituents, the effects of the placement, and curing environment all affect concrete strength. Strength is affected by variations in mixture constituents, production processes, and curing conditions, and can be expected to vary an allowable amount around a central mean value (ACI 214R). For instance, some highway pavement mixtures require reaching target strength in 6 hours, accomplished with high cementitious contents and multiple admixtures. In mass and high-strength concretes (8000 psi), mixtures are often proportioned to provide the design strength at an age greater than 28 days. However, such concrete may require a minimum early-age strength, such as 3 days, to provide for adequate early strength for operations such as form removal, form anchorage, or prestressing. The choice of strength or *w*/*cm* can be affected by early-strength or durability requirements.

3.5—Durability

Concrete is expected to have a long service life, and therefore durability is part of the specification for concrete construction (ACI 301), and concrete building codes (ACI 318) (refer to ACI 201.2R for further details). Although meeting the specified compressive strength is an essential and important characteristic of concrete, durability considerations may require a lower *w*/*cm*, resulting in strength greater than specified. A low *w*/*cm* will prolong the life of concrete by reducing permeability. Resistance to weathering, particularly freezing and thawing, and to salts used for ice removal is greatly improved by incorporation of an entrained air system. Entrained air is used in exterior concrete where freezing occurs (ACI 201.2R). The durability of concrete exposed to seawater or sulfate-bearing soils can be enhanced with the use of sulfate-resisting cement, slag cement, silica fume, or other SCMs. In some areas, aggregates should be checked for alkali-aggregate reactivity (AAR). If AAR is detected, mitigating steps should be taken. Refer to ACI 201.2R, ACI 221.1R, and ASTM C1778 for more information on the mitigation of AAR.

3.6—Density

For certain applications, concrete may be needed primarily for its density. Normal-density concrete is approximately 140 to 150 lb/ft^3 (with or without air entrainment). High-density concrete is often used for counterweights on lift bridges, weights for sinking oil pipelines, a shield from radiation, and insulation from sound. Some applications of low-density concrete are some bridge decks and elevated floors. By using special aggregates, densities as high as 350 lb/ft^3 and as low as 50 lb/ft^3 can be obtained.

3.7—Generation of heat

The hydration of cement generates heat (refer to ACI 207.1R and ACI 301 Section 8.1.3 for more information). Therefore, in many large structural elements where a high volume of concrete is placed, heat generation should be considered. A major concern in proportioning mass concrete, or for any concrete element of sufficient size and shape, is the accumulation of excessive heat and consequent expansion of volume. There can be a high thermal differential between the core and the relatively cool surface of the concrete element. The stresses induced by the thermal differential can lead to unacceptable cracks. Temperature control measures including a thermal differential of 35°F (19.4°C) or less should be considered to reduce the potential for such thermally induced cracking. Concrete placements, particularly when the minimum cross-sectional dimensions of a solid concrete member approach or exceed 2 to 3 ft, or when low *w*/*cm* are being used, may require that measures be taken to control the generation of heat. It is possible for concrete temperature to exceed 160°F (70°C), and if the temperature rise of the concrete is not minimized, and the heat is not dissipated at a reasonable rate, or if the concrete is subjected to a severe temperature differential (35°F [19.4°C] or more) or thermal gradient, cracking is likely to occur. Such cracking occurs at the surface of the concrete, typically first at the center of the large surfaces for concrete where restraint is primarily internal (refer to ACI 207.1R Section 4.3.5). Temperature control measures can include a relatively low initial placement temperature, replacement of cement with SCM, reduced quantities of cementitious materials, use of chemical admixtures, or circulation of chilled water. In some situations, insulation of concrete surfaces may be required to adjust for these various concrete conditions and exposures. It should be emphasized that mass concrete is not necessarily large-aggregate concrete and that concern about generation of an excessive amount of heat in concrete is not confined to massive dam or foundation structures.

3.8—Permeability

Low permeability is an important factor for the production of durable concrete by minimizing ingress of harmful chemicals, which is often accomplished by the addition of an SCM or using low *w*/*cm*. Chemical admixtures can also be used if low permeability is required (refer to ACI 212.3R for permeability-reducing admixtures). This is of particular interest concerning highway bridges needing to prevent chloride intrusion that ultimately corrodes the reinforcing steel. At the other end of the permeability scale, pervious concrete is used in areas where it is desirable to have water pass through the concrete for hydrological, environmental, or sustainability reasons. This is managed by the use of little or no fines with the help of chemical admixtures. Refer to ACI 522.1 for additional information regarding pervious concrete.

3.9—Shrinkage

Reducing shrinkage is critical to minimizing concrete cracking. Methods for reducing shrinkage include the reduction of paste content, usage of shrinkage-reducing admixtures, usage of shrinkage-compensating concrete, adequate curing, and control of water content (refer to ACI 209R and ACI 224R for further information). ACI 223R provides information on shrinkage-compensating concrete.

3.10—Modulus of elasticity

The modulus of elasticity is sometimes of concern in applications where deflections are considered, such as bridges, floors, and the sway of tall buildings.

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CHAPTER 4—BACKGROUND INFORMATION

4.1—Trial batching

Trial batching is a process that demonstrates that a concrete mixture with required properties can be produced with a given set of materials and tools by mixture proportioners. Shortcomings identified in the trial batches are addressed through mixture design modifications to move closer to the desired properties. The process continues until all the requirements are satisfied.

4.2—Slump

Slump is the measure of consistency of freshly mixed concrete, mortar, or stucco equal to the subsidence measured to the nearest 1/4 in. of the specimen immediately after removal of the slump cone (refer to ASTM C143/C143M for further information). The quantity of water per unit volume of concrete required to produce a given slump is dependent on the nominal maximum size, particle shape, and grading of the aggregates; the concrete temperature; the amount of entrained air; and use of chemical admixtures. Slump is not greatly affected by the quantity of cement or cementitious materials within normal use levels. Depending on aggregate texture and shape, mixing-water requirements may be somewhat above or below the tabulated values, but they are sufficiently accurate for the first estimate. The differences in water demand are not necessarily reflected in strength because other compensating factors may be involved. A rounded and an angular coarse aggregate, both well and similarly graded and of high quality, can be expected to produce concrete of approximately the same compressive strength for the same cement factor despite differences in water-cement ratio (*w*/*c*) or *w*/*cm*, resulting from the different mixing-water requirements. Particle shape is not necessarily an indicator that an aggregate will be either above or below in its strength-producing capacity. Mixtures of the stiffest consistency that can be placed efficiently should be used.

The slump values for concrete containing aggregate larger than 1-1/2 in. are based on slump tests made after removal of particles larger than 1-1/2 in. by wet screening.

4.3—Aggregates

4.3.1 *Well-graded*—A well-graded aggregate has a particle-size distribution that produces maximum density—that is, minimum void space. Such an aggregate minimizes the required paste needed to fill the aggregate voids (refer to ACI 211.6T for details on optimal grading and packing density). The aggregate combinations for this guide are assumed to be well-graded and meet ASTM C33/C33M qualities or regionally available aggregates accepted by the local state agencies.

4.3.2 *Nominal maximum aggregate size*—Used for the estimation of the initial water content, the nominal maximum aggregate size is needed in conjunction with the slump. This is because, generally, the larger an aggregate is, the less water is needed to mobilize it. The nominal maximum aggregate size is the smallest sieve opening through which the entire amount of the aggregate is permitted to pass.

Large nominal maximum sizes of well-graded aggregates have fewer voids than smaller sizes. Hence, concretes with the larger-sized aggregates require less mortar per unit volume of concrete. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure. In no case should the nominal maximum size exceed 1/5 of the narrowest dimension between sides of forms; 1/3 the depth of slabs; or 3/4 of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands (refer to ACI 318 Section 26.4.2.1(a)(5)). These limitations are sometimes waived if workability and methods of consolidation are such that the concrete can be placed without honeycombing or voids. In areas congested with reinforcing steel, post-tensioned ducts, or conduits, the proportioner should select a nominal maximum size of aggregate so concrete can be placed without excessive segregation, pockets, or voids. When high-strength concrete is desired, best results may be obtained with reduced nominal maximum sizes of aggregate because these produce higher strengths at a given *w*/*cm* (ACI 363R; ACI 211.4R).

4.3.3 *Large aggregate sizes*—In general, the largest aggregate size practical for the specific job should be used. Some special considerations are needed when using these larger sizes (above 1 in.).

Less mortar per unit volume of concrete requires a reduction when proportioning water, cement, and sand for a given mixture. Because there is less paste and generally lower slumps (1 to 2 in.), admixture dosages can be significantly different to obtain the same results as a mixture with smaller aggregates. Air-entraining admixtures may require greater dosages.

Entrained air may be proportioned into the mixture to increase workability. When using large aggregate with low-cement factors, air entrainment is not necessarily detrimental to strength. In most cases, the mixing-water requirement is reduced sufficiently to improve the *w*/*c* and to thus compensate for the strength-reducing effect of air entrainment. For concretes with large nominal maximum sizes of aggregate, air contents recommended for extreme exposure should be considered even though there may be little or no exposure to moisture or freezing.

For some applications, aggregate sizes over 6 in. are available. In the United States, projects using large aggregate sizes have been typically proportioned and placed using 3 in. nominal maximum size aggregate.

4.3.4 *Bulk volume of coarse aggregate per unit volume*—The volume of loose stone compacted to specifications of ASTM C29/C29M that will be taken up in the unit volume of the concrete mixture.

4.3.5 *Fineness modulus*—Used with the maximum aggregate size, the fineness modulus is used to estimate the bulk volume of coarse aggregate per unit volume of concrete. This value results from an ASTM C136/C136M sieve analysis. It is a factor obtained by progressively adding the cumulative sums of the percentages retained on specified sieves, then dividing that sum by 100. The sieves, halving in opening size, are 6 in. (150 mm), 3 in. (75 mm), 1-1/2 in. (37.5 mm), 3/4 in. (19 mm), 3/8 in. (9.5 mm), No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 mm), No. 50 (300 mm), and No. 100 (150 mm). It is an estimate of the position in the sieve stack where the average size particle is located. In other words, it is a measure of the average particle size that affects the way the voids between the coarse aggregate particles are filled.

4.3.6 *Dry-rodded density*—Used for determination of the weight of coarse aggregate after the bulk volume has been calculated, it is the weight per unit volume of oven-dry aggregate compacted by rodding as defined in ASTM C29/C29M.

4.3.7 *Saturated surface-dry relative density (specific gravity)*—Used for determining the absolute volume of coarse aggregate, and used to determine the weight of the fine aggregate, it is the ratio of the weight of a volume of a material (including the weight of water within the voids, but not including the voids between particles) at a stated temperature to the weight of an equal volume of distilled water at a stated temperature. Saturated surface-dry (SSD) specific gravities are measured using the procedures of ASTM C127 and C128 for coarse and fine aggregates, respectively.

4.4—Water

Water used in mixing concrete should conform to ASTM C1602/C1602M. ASTM C1602/C1602M allows the use of potable water without testing and includes methods for qualifying nonpotable sources of water with consideration of effects on setting time and strength. Testing frequencies are established to ensure continued monitoring of water quality. The standard includes optional limits for chlorides, sulfates, alkalis, and solids in mixing water that can be invoked when appropriate.

4.5—Chemical admixtures

Chemical admixtures are used to modify the properties of concrete to make it more workable, durable, or economical; increase or decrease the time of set; accelerate strength gain; or control temperature gain. Chemical admixtures should be used only after an appropriate evaluation has been conducted to show that the desired effects have been accomplished in the concrete under the conditions of intended use. Water-reducing admixtures, set-controlling admixtures, or both, conforming to the requirements of ASTM C494/C494M, when used singularly or in combination with other chemical admixtures, will significantly reduce the quantity of water per unit volume of concrete. The use of some chemical admixtures, even at the same slump, will improve such qualities as workability, finishability, pumpability, durability, and compressive and flexural strength. When only used to increase slump, chemical admixtures may not improve any other of the properties of the concrete. ASTM C1602/C1602M requires liquid admixtures, used in quantities that increase the *w*/*cm* by more than 0.01, be counted as part of the mixing water.

4.6—Air

The volume of air needs to be known because it is included in the sum of the volumes of the known ingredients when applying the absolute volume method to determine the volume of fine aggregate. Air in concrete appears in two forms: entrapped and entrained. Entrapped air bubbles are generally larger than entrained ones and irregularly shaped and dispersed. Entrained bubbles are generally smaller than 0.1 mm and are round under microscopic examination. The distribution of the bubbles measured by the spacing factor is as important as the size. Entrained air is introduced into concrete to enhance the concrete's freezing-and-thawing resistance. It is produced with the addition to the concrete mixture of air-entraining admixtures.

4.6.1 *Entrapped air*—Entrapped air is the air voids in concrete that are not purposely entrained. They are larger, irregular in shape, less useful than those of entrained air, and 0.04 in. (1 mm) or larger in size. Entrapped air is seen against the sides of the form and in broken concrete as visible voids under aggregate particles.

Table 5.3.3 approximates the amount of entrapped air to be expected in non-air-entrained concrete in the table.

4.6.2 *Entrained air*—Entrained air takes the form of microscopic air bubbles intentionally incorporated in a cementitious paste during mixing, usually by use of a surface-active agent. The air bubbles are typically between 0.0004 and 0.04 in. (10 and 1000 μm) in diameter and spherical or nearly so. As important as the size of the bubbles is their dispersion throughout the cement paste. Some water-reducing admixtures will unintentionally entrain air.

Table 5.3.3 indicates the approximate amount of entrapped air to be expected in non-air-entrained concrete and shows the recommended average air content for air-entrained concrete. If air entrainment is needed or desired, the required total air content levels are given for each aggregate size, depending on the purpose of the entrained air and the severity of exposure if entrained air is needed for durability.

The use of normal amounts of air entrainment in concrete with a specified strength of approximately 5000 psi may not be possible because each added percent of air lowers the maximum strength obtainable with a given combination of materials. In these cases, the exposure to water, deicing salts, and freezing temperatures should be carefully evaluated. If a member is not continually wet and will not be exposed to deicing salts, lower air-content values, such as those given in Table 5.3.3 for F1 exposure class, are appropriate even though the concrete is exposed to freezing-and-thawing temperatures. However, for an exposure condition where the member may be saturated prior to freezing, the use of air entrainment should not be sacrificed for strength. In certain applications, it may be found that the content of entrained air is lower than that specified, despite the use of usually satisfactory levels of air-entraining admixture. This happens occasionally—for example, when very high cement contents are involved. In such cases, the achievement of required durability may be demonstrated by satisfactory results of examination of air-void structure in the paste of the hardened concrete (Ley et al. 2012).

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When trial batches are used to establish strength relationships or verify strength-producing capability of a mixture, the least favorable combination of mixing water and air content should be used. The air content should be the maximum permitted or likely to occur, and the concrete should be designed to the highest permissible slump. This will avoid developing an over-optimistic estimate of strength on the assumption that average, rather than extreme, conditions will prevail in the field. If the concrete obtained in the field has a lower slump, air content, or both, the proportions of ingredients should be adjusted to maintain required yield. For additional information on air content recommendations, refer to ACI 201.2R, 301, and 302.1R.

4.6.3 *Effect on strength*—For normal concrete, the addition of each additional percentage point of air will reduce the strength of the concrete approximately 5% (Yurdakul et al. 2014).

4.7—Water-cementitious materials ratio (*w/cm*)

The water-cementitious materials ratio (*w/cm*) is the major parameter controlling concrete strength. For a given mixture of concrete materials, a specific *w/cm* produces a unique strength. For the same mixture, achieving a specified strength requires a particular *w/cm*.

Although it is primarily a determinant of concrete strength, *w/cm* affects other important properties such as density, elastic modulus, durability, shrinkage and cracking, and permeability. Achieving one of these properties may call for a *w/cm* lower than one that might be dictated by strength.

Once the *w/cm* is chosen, it is used to determine the weight of cementitious materials if the quantity of water is known, or vice versa.

4.7.1 w/cm *selection*—The selection of *w/cm* is made based on the strength required. However, there are several possibilities and more than one *w/cm* may be indicated, and an orderly consideration is needed. First, *w/cm* may be specified in contract documents. Next, the environmental conditions should be examined. ACI 318 Chapter 19 lists several exposure categories, with multiple classes, each calling for a particular strength and *w/cm*. The lowest *w/cm* for any of the applicable cases, or the *w/cm* required to produce the required strength needs to be considered. Finally, to account for the variability of concrete, the required average compressive strength, f_{cr}', will dictate a particular *w/cm*. The *w/cm* selected for the design will be the lowest value selected from between those required by specification, exposure class, or required average compressive strength. The relationship between *w/cm* and strength can be evaluated through *w/cm* curves that plot the strength produced by a particular set of ingredients as the *w/cm* is changed. Without such an analysis, Table 5.3.4 can be used to estimate *w/cm*.

4.7.2 w/cm *specified by contract*—When a *w/cm* is specified by contract, it should be compared to those needed for durability and strength. If another consideration produces a lower *w/cm*, the specification is considered to have been exceeded.

4.7.3 w/cm *needed for durability*—The required *w/cm* and strength for durability is dependent on the exposure.

ACI 318 Chapter 19 requires consideration of exposure to the following four categories: sulfate exposure (S), freezing-and-thawing exposure (F), exposure when in contact with water (W), and exposure to corrosion (C). ACI 301 Chapter 4 also adopts these four exposure categories described in ACI 318 Chapter 19.

Table 4.7.3a shows the requirements for Exposure Category S for sulfate exposure.

Table 4.7.3b shows the requirements for Exposure Category F for freezing-and-thawing exposure.

Table 4.7.3c shows the requirements for Exposure Category W in contact with water.

Table 4.7.3d shows the requirements for Exposure Category C for conditions requiring corrosion protection of reinforcement.

4.7.3.1 *Freezing-and-thawing exposure*—The freezing-and-thawing exposure class has four categories: F0, F1, F2, and F3. The F0 category is not exposed to freezing-and-thawing conditions, and Categories F1 through F3 are exposed from a lesser to a greater extent. The air content for freezing-and-thawing resistance is specified in Table 4.7.3.1.

Table 4.7.3a—Requirements for concrete by Exposure Category S for sulfate exposure (ACI 301-20 Table 4.2.2.6(b))

Exposure class		Maximum *w/cm*[*]	Minimum f_c', psi	Required cementitious materials[†]—types			Calcium chloride admixture
				ASTM C150/C150M	ASTM C595/C595M	ASTM C1157/C1157M	
S0		NA	2500	NA	NA	NA	No restriction
S1		0.50	4000	II[‡][§]	Types with (MS) designation	MS	No restriction
S2		0.45	4500	V[§]	Types with (HS) designation	HS	Not permitted
S3	Option 1	0.45	4500	V plus pozzolan or slag cement[‖]	Types with (HS) designation plus pozzolan or slag cement[‖]	HS plus pozzolan or slag cement[‖]	Not permitted
	Option 2	0.40	5000	V[#]	Types with (HS) designation	HS	Not permitted

[*] The maximum *w/cm* limits do not apply to lightweight concrete.

[†] Alternative combinations of cementitious materials of those listed in this table are acceptable if tested for sulfate resistance and meeting the criteria in Table 4.2.2.6(b)1.

[‡] For seawater exposure, other types of portland cements with tricalcium aluminate (C_3A) contents up to 10% are acceptable if the *w/cm* does not exceed 0.40.

[§] Other available types of cement, such as Type III or Type I, are acceptable in Exposure Classes S1 or S2 if the C_3A contents are less than 8% or 5%, respectively.

[‖] The amount of the specific source of the pozzolan or slag cement to be used shall be at least the amount determined by test or service record to improve sulfate resistance when used in concrete containing Type V cement. Alternatively, the amount of the specific source of the pozzolan or slag used shall not be less than the amount tested in accordance with ASTM C1012/C1012M and meeting the requirements of Table 4.2.2.6(b)1.

[#] If Type V cement is used as the sole cementitious material, the optional sulfate resistance requirement of 0.040% maximum expansion in ASTM C150/C150M is applicable.

Table 4.7.3b—Requirements for concrete by Exposure Category F for freezing-and-thawing exposure (ACI 301-20 Table 4.2.2.6(c))

Exposure class	Maximum *w/cm*[*]	Minimum f_c', psi	Air content	Additional requirements
F0	NA	2500	NA	
F1	0.55	3500	Table 4.2.2.6(c)1	NA
F2	0.45	4500	Table 4.2.2.6(c)1	NA
F3	0.40	5000	Table 4.2.2.6(c)1	Table 4.2.1.1(b)
F3 plain concrete	0.45	4500	Table 4.2.2.6(c)1	Table 4.2.1.1(b)

[*] The maximum *w/cm* limits do not apply to lightweight concrete.

Table 4.7.3c—Requirements for Exposure Category W in contact with water (ACI 301-20 Table 4.2.2.6(d))

Exposure class	Maximum *w/cm*[*]	Minimum f_c', psi	Additional minimum requirements
W0	NA	2500	None
W1	NA	2500	4.2.2.6(a)
W2	0.50	4000	4.2.2.6(a)

[*] The maximum *w/cm* limits do not apply to lightweight concrete.

Table 4.7.3d—Requirements for Exposure Category C for conditions requiring corrosion protection of reinforcement (ACI 301-20 Table 4.2.2.6(e))

Exposure class	Maximum *w/cm*[*]	Minimum f_c', psi	Maximum water-soluble chloride ion (Cl^-) content in concrete, % by mass of cementitious materials[†]
Non-prestressed concrete			
C0	NA	2500	1.00
C1	NA	2500	0.30
C2	0.40	5000	0.15
Prestressed concrete			
C0	NA	2500	0.06
C1	NA	2500	0.06
C2	0.40	5000	0.06

[*] The maximum *w/cm* limits do not apply to lightweight concrete.

[†] The maximum cementitious materials content used in determining chloride content shall not exceed two times the mass of portland cement.

Table 4.7.3.1—Total air content for concrete exposed to cycles of freezing and thawing (ACI 301-20 Table 4.2.2.6(c)1)

Nominal maximum aggregate size, in.	Total air content, %[*][†]	
	Exposure Classes F2 and F3	Exposure Class F1
3/8	7.5	6.0
1/2	7.0	5.5
3/4	6.0	5.0
1	6.0	4.5
1-1/2	5.5	4.5
2	5.0	4.0
3	4.5	3.5

[*] Tolerance on air content as delivered shall be ±1.5%.

[†] For f_c' equal to or greater than 5000 psi, it is acceptable to reduce air content by 1.0 percentage point.

Table 4.7.3.2—Limits on supplementary cementitious materials for concrete assigned to Exposure Class F3 (ACI 301-20 Table 4.2.1.1(b))

Supplementary cementitious material	Maximum % of total cementitious material by mass[*]
Fly ash or natural pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989/C989M	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or natural pozzolans, slag cement, and silica fume	50[†]
Total of fly ash or natural pozzolans and silica fume	35[†]

[*] Total cementitious material also includes ASTM C150/C150M, C595/C595M, and C1157/C1157M cement. The maximum percentages above shall include:

(a) Fly ash or natural pozzolans present in ASTM C1157/C1157M or C595/C595M Type IP blended cement.

(b) Slag cement present in ASTM C1157/C1157M or C595/C595M Type IS blended cement.

(c) Silica fume conforming to ASTM C1240 present in ASTM C1157/C1157M or C595/C595M Type IP blended cement.

[†] Fly ash or natural pozzolans and silica fume shall constitute no more than 25% and 10%, respectively, of the total mass of the cementitious materials.

Table 4.7.3.3—Sulfate concentration ranges for each sulfate exposure (ACI 201.2R-16 Table 6.1.4.1(a))

Sulfate exposure class	Water-soluble sulfate (SO_4) in soil (% by weight)	Sulfate (SO_4) in water (ppm)
S0, Negligible[*]	0.00 to 0.10	0 to 150
S1, Moderate[†]	0.10 to 0.20	150 to 1500
S2, Severe	0.20 to 2.00	1500 to 10,000
S3, Very severe	over 2.00	over 10,000

[*] When sulfate can be replenished by flowing water or from another exterior source, the presence of 0 to 150 ppm of sulfate should be considered moderate exposure.

[†] If the concrete will be exposed to sulfates, a maximum *w/cm* of 0.50 with a minimum f_c' of 4000 psi is needed for moderate exposure. For the severe and very severe exposures, a *w/cm* of 0.45 and a minimum strength of 4500 psi are needed.

4.7.3.2 When SCMs are used for Exposure Class F3, limits on their use are listed in Table 4.7.3.2.

4.7.3.3 *Sulfate exposure*—Table 4.7.3.3 lists the sulfate concentration ranges for each sulfate exposure class. Exposure to seawater can be considered an equivalent to moderate sulfate exposure. Sulfate concentration ranges for the sulfate exposure classes are in Table 4.7.3.3.

When sulfate exposure is anticipated, consult ACI 201.2R.

4.7.3.4 *Permeability*—There are also Permeability Categories W0 and W1 for structures in constant contact with water. In the first case, permeability is not a consideration; in the second case, it is.

In Table 4.7.3c, concrete exposed to water where permeability is not an issue has only a requirement of 2500 psi. Concrete exposed to water where permeability is an issue such as concrete used in a water barrier element—that is, the wall of a water tank—can have a maximum *w/cm* of 0.50 and minimum compressive strength of 4000 psi.

4.7.3.5 *Corrosion protection*—Finally, there is the corrosion class with Categories C0 through C2. In the C0 category, the structure is dry or protected from moisture. In the

Table 4.7.4.1—Required average compressive strength f_{cr}' if data are not available to establish standard deviation (ACI 301-20 Table 4.2.3.3(b))

Specified compressive strength f_c', psi	Required average compressive strength f_{cr}', psi
Less than 3000	$f_c' + 1000$
3000 to 5000	$f_c' + 1200$
Over 5000	$1.1f_c' + 700$

Table 4.7.4.3—*k*-factor for increasing sample standard deviation for number of strength tests considered in calculating standard deviation (ACI 301-20 Table 4.2.3.3(a)2)

Total number of tests considered	*k*-factor for increasing sample standard deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Note: Linear interpolation for intermediate number of tests is acceptable.

C1 category, there is no exposure to external chlorides, but in Category C2 there are external chlorides. In the C0 and C1 categories, a minimum compressive strength of 2500 psi is the only requirement. In the C2 category, where there is exposure to external chlorides such as deicing salts, brackish water, seawater, or spray from these sources, a maximum *w/cm* of 0.40 and minimum compressive strength of 5000 psi are required, as shown in Table 4.7.3d.

4.7.4 w/cm *from required strength*—Because of the variability of concrete, a required average compressive strength f_{cr}' is often required. The required average compressive strength should exceed the specified compressive strength f_c' by a sufficient margin to keep the number of noncompliant test results below 1% (ACI 214R; ACI 301). Several methods are used to determine the required average strength, depending on the amount of strength test data that is available.

4.7.4.1 *When no data are available*—When no data are available for determining the standard deviation, Table 4.7.4.1 can be used to determine the required average compressive strength.

4.7.4.2 *Standard deviation* s *determined from 30 strength tests*—When the standard deviation is determined from more than 30 strength tests, it is used without modification.

4.7.4.3 *Standard deviation determined from fewer than 30 strength tests*—When s is based on 15 to 29 tests, the s of those test results is multiplied by the appropriate modification factor obtained from Table 4.7.4.3.

4.7.4.4 *Required average strength when standard deviation is determined*—With an applicable value of the standard deviation s, the equations from Table 4.7.4.4 can be used to calculate f_{cr}'.

4.7.4.5 w/cm *through water-cement ratio curves*—A good way to design a concrete mixture is based on experience with the materials to be used and the results achieved in the past. It is highly desirable to have or to develop the relationship between strength and *w/cm* for the materials to be used. When such a relationship is available, the *w/cm* for the required average compressive strength can be chosen.

Table 4.7.4.4—Required average compressive strength f_{cr}' if data are available to establish a sample standard deviation, psi (ACI 301-20 Table 4.2.3.3(a)1)

f_c', psi	f_{cr}', psi Use the larger of:
5000 or less	$f_{cr}' = f_c' + 1.34ks_s$
	$f_{cr}' = f_c' + 2.33ks_s - 500$
Over 5000	$f_{cr}' = f_c' + 1.34ks_s$
	$f_{cr}' = 0.90f_c' + 2.33ks_s$

Note: f_{cr}' is required average compressive strength; f_c' is specified concrete strength; k is factor from Table 4.2.3.3(a)2; and s_s is standard deviation calculated in accordance with 4.2.3.2.

4.7.4.6 w/cm *by table*—Approximate and relatively conservative values of *w/cm* for concrete containing portland cement can be taken from Table 5.3.4. With typical materials, the tabulated *w/cm* should produce 28-day strengths close to those shown, based on tests of specimens cured under standard laboratory conditions.

4.7.5 *Cement*—Cement should meet the requirements of ASTM C150/C150M-AASHTO M 85, ASTM C595/C595M-AASHTO M 240M/M 240, or ASTM C1157/C1157M. Specific gravity for cement is generally assumed to be 3.15 for ASTM C150/C150M; all others may be slightly lower.

4.7.6 *Supplementary cementitious materials*—Supplementary cementitious materials (SCMs) are often used in concrete in combination with portland or blended cement for economy, reduction of heat of hydration, improved workability, and improved strength or durability under the anticipated service environment. These benefits depend on the amount and type of SCMs used such as fly ash, natural pozzolans (ASTM C618), slag cement (ASTM C989/C989M), and silica fume (ASTM C1240).

As defined in ASTM C618, pozzolans are "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

Fly ash is the "finely divided residue that results from the combustion of ground or powdered coal..." Fly ash used in concrete is classified into two categories: Class F, which has pozzolanic properties, and Class C, which, in addition to having pozzolanic properties, also has some cementitious properties in that this material may be self-setting when mixed with water. Class C fly ash may contain lime (CaO) amounts higher than 10%. The use of fly ash in concrete is more fully described and discussed in ACI 232.2R.

Blast-furnace slag is a by-product of the production of pig iron. When this slag is rapidly quenched and ground, it will possess latent cementitious properties. After processing, the material is known as slag cement, whose hydraulic properties vary and can be separated into grades noted in ASTM C989/C989M. The grade classification gives guidance on the relative strength potential of 50% slag cement mortars to

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the reference portland cement mortar at 7 and 28 days. Slag cement grades are 80, 100, and 120, in order of increasing strength potential. When slag cement is used in concrete with portland cement, the levels and rate of strength development will depend on the properties of the slag cement, the properties of the portland cement, and the relative and total amounts of slag cement and portland cement.

Silica fume, as used in concrete, is a by-product resulting from the reduction of high-purity quartz with coal and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys (ASTM C1240). Silica fume, which condenses from the gases escaping from the furnaces, has a very high content of amorphous silicon dioxide and consists of very fine spherical particles. Other names that have been used include silica dust, condensed or precompacted silica fume, and microsilica; the most appropriate is silica fume.

Methods for proportioning and evaluating concrete mixtures containing these SCMs should be based on trial batches using a range of ingredient proportions. By evaluating their effect on strength, water requirement, time of set, and other important properties, the optimum amount of cementitious materials can be determined. In the absence of prior information and in the interest of preparing estimated proportions for a first trial batch or a series of trial batches in accordance with ASTM C192/C192M, the following typical ranges are given based on the percentage of the ingredients by the total weight of SCM used in the batch for structural concrete:

- Class F fly ash—15 to 25%
- Class C fly ash—15 to 35%
- Natural pozzolans—10 to 20%
- Slag cement—25 to 70%
- Silica fume—5 to 10%

When using SCMs, the quantity of the materials used per cubic yard of concrete may be different from that previously shown. Often, certain special required properties such as very high strength, modulus of elasticity, or self-consolidation involve using ternary or quaternary blends using multiple SCMs.

In cases where high early strengths are required, the total weight of SCM may be greater than would be needed if portland cement were the only cementitious material. Where high early strength is not required, higher percentages of fly ash are frequently used.

Often, it is found that with the use of fly ash and slag cement, the amount of mixing water required to obtain the desired slump and workability of concrete may be lower than that used in a mixture using only portland cement. When silica fume is used, additional mixing water is usually required than when using only portland cement. In calculating the amount of chemical admixtures to dispense for a given batch of concrete, the dosage should generally be applied to the total amount of cementitious material. Under these conditions, the reduction in mixing water for conventional water-reducing admixtures (Types A, D, and E) should be at least 5%, and for high-range water-reducing admixtures (HRWRAs), at least 12%. When slag cement is used in concrete mixtures containing some HRWRA, the admixture dosage may be reduced by approximately 25% compared to mixtures containing only portland cement.

Due to differences in their specific gravities, a given weight of an SCM will not occupy the same volume as an equal weight of portland cement. The specific gravity of blended cements will be less than that of portland cement. Thus, when using either blended cements or SCMs, the yield of the concrete mixture should be adjusted using the actual specific gravities of the materials used.

Class C fly ash, normally of extremely low carbon content, usually has little or no effect on entrained air or on the air-entraining admixture dosage rate. Many Class F fly ashes may require a higher dosage of air-entraining admixture to obtain specified air contents; if carbon content is high, the dosage rate may be several times that of non-fly-ash concrete. The dosage required may also be quite variable. The entrained air content of concrete containing high-carbon-content fly ash may be difficult to obtain and maintain. Other cementitious materials may be treated the same as cement in determining the proper quantity of air-entraining admixtures per cubic yard of concrete or per 100 lb of cementitious material used.

Concrete containing a proposed blend of cement, other cementitious materials, and admixtures should be tested to determine the time required for setting at various temperatures. The use of most SCMs generally slows the time-of-setting of the concrete, and this period may be prolonged by higher percentages of these materials in the cementitious blend, cold weather, and the presence of chemical admixtures not formulated specifically for acceleration.

Because of the possible adverse effects on finishing time and consequent labor costs, in some cold climates, the proportion of other cementitious materials in the blend may have to be reduced below the optimum amount for strength considerations. Some Class C fly ashes may affect setting time whereas some other cementitious materials may have little effect on setting time. Any reduction in cement content will reduce heat generation and normally prolong the setting time.

When natural pozzolans, fly ash, slag cement, and silica fume are used in concrete, a water-cement-plus-SCM ratio or *w/cm* should be considered in place of the traditional *w/c* by weight.

4.7.7 *Absolute volume method*—In this procedure, the weights of water, air, cementitious materials, and coarse aggregate are determined either through specification, experience, or charts. Once these values are known, the absolute volumes of these materials are determined using the proper specific gravities. Then those volumes are summed along with the volume percentage of air. That sum is subtracted from the unit volume to determine the required volume of fine aggregate. The volume of fine aggregate is then converted to its equivalent weight using the specific gravity and the weight-volume relationship.

4.7.7.1 *Unit volume*—The unit volume for this procedure is 1 yd^3. The sum or the absolute volumes of all the concrete mixture ingredients will be the unit volume.

4.7.7.2 *Absolute volume*—In the case of solids, the displacement volume of particles themselves, including their permeable and impermeable voids, but excluding space between particles; in the case of fluids, their volume.

A more exact procedure for calculating the required amount of fine aggregate involves the use of volumes displaced by the ingredients. The absolute volume method presented subtracts the sum of the absolute volumes of the determined constituents from the unit volume to determine the required volume of the sand from which the weight of sand is determined. The design is checked by measuring the yield with procedures of ASTM C138/C138M, as well as testing the mixture's other required properties.

4.7.7.3 *Specific gravity-weight-volume relationship*—The volume occupied in concrete by any ingredient is equal to its weight divided by the density of that material.

The specific gravity is the ratio of the density of a substance to the density of water at a specified temperature and pressure. The density is the weight per unit volume of a substance. The weight-volume relationship defined by the specific gravity of a substance is used to determine the volume of a known substance if the weight is known, and vice versa. The density of a substance will be the specific gravity multiplied by the density of water. Once the density is known, the weight of a given volume of the substance can be found by dividing the volume by the density. If the volume is known, the weight is found by multiplying it by the density.

4.7.7.4 *Theoretical air-free density*—The sum of the weights of the constituents of a concrete mixture, divided by the sum of the absolute volumes, less the volume of air.

4.7.8 *Moisture adjustments*—Knowing the moisture content of aggregate stockpiles is variable, the net water batched to the mixture typically has to be adjusted to accommodate that variability. Moisture adjustments are not part of the design. They are adjustments to the design weights of the aggregates and water needed to achieve the concrete mixture design with respect to water. The weight of the design water should be adjusted for water on the aggregates that is free to hydrate cement. The free water is the total amount of water minus the absorbed water. When aggregates are below SSD, they will absorb water so additional water will need to be added to the batch water. When aggregates are above SSD, there is free water on the aggregate so water will be subtracted from the batch water.

4.7.8.1 *Oven dry*—Oven dry is the moisture condition achieved when an aggregate is dried to constant weight. In this state, the aggregate contains no moisture at all. If an SSD weight is known, the oven-dry weight can be found using the following equation.

$$m_{OD} = \frac{m_{SSD}}{\left(1+\frac{A\%}{100}\right)} \qquad (4.7.8.1)$$

4.7.8.2 *Saturated surface-dry*—SSD is the moisture condition achieved after a fully saturated aggregate is dried until all the surface moisture has been evaporated.

When the oven-dry weight is known, the SSD weight can be found using the following equation.

$$m_{SSD} = m_{OD}\left(1+\frac{A\%}{100}\right) \qquad (4.7.8.2)$$

4.7.8.3 *Total moisture content*—The moisture content is the amount of moisture that can be evaporated from an aggregate under controlled conditions and computed from ASTM C566. It contains both the absorbed and the surface moisture.

The total moisture content computation is

$$\%total = \frac{m_i - m_{OD}}{m_{OD}} \times 100 \qquad (4.7.8.3)$$

4.7.8.4 *Absorption*—Determined through the procedures of ASTM C127 and C128, absorption is the moisture content when the aggregate is dried from its SSD condition to its oven-dry state. At the SSD state, the aggregate has absorbed as much water as possible, but there is no moisture on the surface of the particles.

$$A\% = \frac{m_{SSD} - m_{OD}}{m_{OD}} \times 100 \qquad (4.7.8.4)$$

4.7.8.5 *Free water*—Free water is the total amount of water less the water absorbed into the aggregate. This water is on the surface of the aggregate particles and is available to hydrate cement.

$$\%free = \%total - A\% \qquad (4.7.8.5)$$

4.7.8.6 *Free water weight computation when oven-dry weight is known*—To compute the free water, the oven-dry weight of the aggregate is multiplied by the free moisture content to determine the weight of water needed to adjust the design water content.

$$mw_{free} = m_{OD} \times MC\%_{free} \qquad (4.7.8.6)$$

4.7.8.7 *Free water weight computation when* SSD *weight is known*—When the weight is given in terms of SSD weight, it is converted into oven-dry weight by dividing by $\left(1+\frac{A\%}{100}\right)$.

$$mw_{free} = \frac{m_{SSD}}{\left(1+\frac{A\%}{100}\right)} \times MC\%_{free} \qquad (4.7.8.7)$$

4.7.8.8 *Conventional method for computation of free water weight*—Because typical batch tickets give the weights of the concrete constituents in SSD terms, it is convenient to compute the free water based on these values without converting to oven-dry weight. The free water is computed as the SSD weight multiplied by the moisture content.

$$mw_{free} = m_{SSD} \times MC\%_{free} \qquad (4.7.8.8)$$

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This method produces an insignificant difference compared to the theoretical method for hard aggregates. It overestimates the free water because it overstates the oven-dry weight slightly, resulting in a little more aggregate and a little less water in the mixture than called for by the design, usually well within the weighing tolerances for water given by ASTM C94/C94M. Care should be exercised, however, when using highly absorbent aggregates at high moisture contents where it is possible to shift the *w*/*c* to the nearest 0.01.

4.7.9 *Concrete yield*

4.7.9.1 *Yield*—Yield is the volume of freshly mixed concrete produced from a known quantity of ingredients: the total weight of ingredients divided by the density of the freshly mixed concrete. It is computed based on the relationship given in ASTM C138/C138M. Concrete is produced on a volumetric basis, either as a cubic yard or a cubic meter, but it is batched on a weight basis according to a mixture design or mixture proportions. If the mixture proportions are not batched or determined properly, the combined materials may produce either more or less than the desired volume of concrete.

It is the sum of the weight of the ingredients batched divided by the fresh density, also determined by ASTM C138/C138M. The result is a volume that is compared to the volume the ingredients were supposed to produce. The target yield is 1 yd^3 or 27 ft^3 of concrete material in most cases.

4.7.9.2 *Relative yield*—Relative yield (R_Y) is the ratio of the actual volume of concrete obtained (Y) to the volume as designed (Y_d) for the batch calculated as follows

$$R_Y = Y/Y_d \qquad (4.7.9.2)$$

A value for R_Y greater than 1.00 indicates an excess of concrete being produced whereas a value less than 1.00 indicates the batch to be short of its designed volume.

Even though the concrete batching process is designed to produce 1 yd^3 (27 ft^3), variations in batch weights, specific gravity of materials, aggregate moisture conditions, and air content will result in fluctuations in the batch volume. There is no published yield tolerance in either ASTM or ACI documents, but a practical tolerance can be estimated.

4.7.9.3 *Batch tolerances*—In the field, ASTM C94/C94M batching tolerances allow the batch weights to vary ±1% for cementitious materials, and up to a maximum ±2% for aggregates when weighed in individual batchers. Entrained air tolerances allow for as much as ±1.5% of the mixture volume. If the producer decides to monitor the overall tolerance of the yield of the batching process, a 1 or 2% yield would give the numbers detailed in Table 4.7.9.3.

A 1% over batch on aggregates and a 2% additional (over target) air content can result in a yield of 1.03 on some mixtures.

As long as the R_Y is within 0.98 to 1.02, the yield is probably within acceptable tolerances; however, a contractor with a 1000 yd^3 placement might object to having to purchase an extra 20 yd^3 above what he anticipated.

Table 4.7.9.3—Overall batch tolerances for yield

Overall batch tolerances for yield					
Target	1%	R_Y	2%	R_Y	
27 ft^3	27.27	1.01	27.54	1.02	Over yield (+)
	26.73	0.99	26.46	0.98	Under yield (–)

4.7.9.4 *Benefit of verifying yield*—Typically in batching concrete materials, the weighing out of the cementitious materials is more constant than that of the aggregates due to compensation and adjustment of free moisture on the aggregate. Also, the cost difference of cement compared to aggregate puts a focus on correct tolerance for cement. For a given mixture design, the cementitious content is relatively fixed to the accuracy of the scale, from batch to batch. This relatively constant cement factor has the following effect on changing batch yields caused by a variety of factors.

If the concrete batch under-yields (produces less than the desired concrete volume), the following conditions may occur:

(a) Cementitious materials are typically weighed on a separate scale and are fairly constant for a given batched mixture design. When a load of concrete is batched and found to be in an under-yield condition, the percent of cement per volume of material is greater than that of the design, thus causing a lower *w*/*cm* (presuming original water content with similar slump) and leading to higher compressive strengths, and a more costly concrete per cubic yard.

(b) If the batch size is smaller than expected, but the water content is not changed, the concrete mixture may have a higher-than-acceptable slump.

(c) The contractor will receive less concrete than requested.

If the concrete batch over-yields (produces more than the desired concrete volume), the following conditions may occur:

(a) As stated previously, the same amount of cement is batched and the concrete is found to be in an over-yield condition. This requires the same amount of cement to cover a larger proportion of aggregates and results in less net cement per yard, thus lower strengths.

(b) The larger batch will require more water for a given slump, which will result in a higher *w*/*cm* and lower-than-anticipated strength.

(c) If the water content is not changed, the concrete mixture may have lower-than-requested slump.

Relative yield for trial batches should be reported in the field or lab report.

CHAPTER 5—PROPORTION SELECTION PROCEDURE

The procedure for selection of mixture proportions given in this section is applicable to normal-density and high-density concretes. The same basic data and procedures can also be used in proportioning concretes using multiple aggregate size fractions, multiple types of cementitious materials, or both. Sample computations for these types of concrete are given in the examples of Chapter 9.

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5.1—Background

Selection of concrete proportions should be based on test data or experience with the materials to be used. Where such background is limited or not available, estimates given herein may be employed. The intent is to produce a trial batch, which will be tested for the required fresh and hardened properties and modified as necessary to produce the required properties. The following information for available materials is useful:

(a) Sieve analyses of fine and coarse aggregates

(b) Density of coarse aggregate

(c) Bulk specific gravities, density at SSD conditions, and absorptions of aggregates

(d) Mixing-water requirements of concrete developed from experience with available aggregates

(e) Relationships between strength and the ratio of *w/c* or *w/cm* for available combinations of cements, other cementitious materials if considered, and aggregates

(f) Specific gravities of hydraulic cement and other cementitious materials, if used

Estimates from Tables 5.3.3 and 5.3.4, respectively, may be used when information from Steps (d) and (e) are not available.

5.2—Selection process

The selection process begins by estimating the required batch weights for the concrete. The estimation involves a sequence of logical, straightforward steps that, in effect, fit the characteristics of the available materials into a mixture suitable for the work. The job specifications may dictate some or all of the following:

(a) Maximum *w/cm*

(b) Minimum cementitious materials content

(c) Air content

(d) Slump

(e) Nominal maximum size of aggregate

(f) Strength

(g) Other requirements relating to required average strength, admixtures, and special types of cement, other cementitious materials, or aggregate

5.3—Estimation of batch weights

Regardless of whether the concrete characteristics are prescribed by the specifications or are left to the individual selecting the proportions, estimation of batch weights per cubic yard of concrete can be best accomplished in the following sequence.

5.3.1 *Step 1: Choice of slump*—If slump is not specified, a value appropriate for the work can be selected from Table 5.3.1. The values provided in Table 5.3.1 apply to concrete produced without a water-reducing admixture (WRA). Most structural concrete includes a WRA or high-range water-reducing admixture (refer to Chapter 6 for more information). The slumps shown in Table 5.3.1 may increase when chemical admixtures are used, providing the admixture-treated concrete has the same or lower *w/cm* and does not exhibit segregation potential and excessive bleeding. The slump ranges shown apply when vibration is used to consolidate the concrete. This table is provided as guidance for a starting point for trial batches, and slump values should be adjusted based on various conditions. It should not be applied as a specification.

Table 5.3.1—Typical slump ranges for concrete without water-reducing admixtures for various types of construction

Typical slump ranges, in.[*]	Types of construction
1 to 4	Slipformed
2 to 4	Mass concrete
2 to 5	Pavements and slabs, plain footings, caissons, substructure walls, reinforced foundation wall, and footings
3 to 5	Beams, reinforced walls, and building columns

[*] Slump may be increased when mid-range or high-range water-reducing admixtures are used, provided that the admixture-treated concrete has the same or lower *w/cm* and does not exhibit segregation or excessive bleeding.

5.3.2 *Step 2: Choice of nominal maximum size of aggregate*—Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure. The nominal maximum size should not exceed 1/5 of the narrowest dimension between sides of forms; 1/3 the depth of slabs; or 3/4 of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands (ACI 301; ACI 318).

5.3.3 *Step 3: Estimation of mixing water and air content*—The quantity of water per cubic yard of concrete required to produce a given slump is dependent on the nominal maximum size, particle shape, surface texture, and grading of the aggregates; the concrete temperature; the entrained air content; and use of chemical admixtures. Slump is not significantly affected by the quantity of cementitious materials within normal use levels. An initial estimate for the mixing-water weight can be taken from Table 5.3.3. It provides approximate mixing-water weights per cubic yard of concrete made with various nominal maximum sizes of aggregates, with and without air entrainment. The air requirements shown are those from ACI 318 Chapter 19 durability requirements.

5.3.3.1 After determining the approximate water and air contents, adjust the values for the applicable conditions provided in Table 5.3.3.1. It is recommended to withhold approximately 10% of this water initially and then add slowly to obtain proper slump for an initial first trial. The quantity of water can be further refined depending on numerous factors such as aggregate texture and shape, the type and dosage of admixtures, temperature changes, and other various factors as listed in Table 5.3.3.1.

5.3.3.1.1 *Chemical admixtures*—Chemical admixtures are used to modify various properties of concrete. Chemical admixtures should be used only after an appropriate evaluation has been conducted to show that the desired effects can be accomplished in the particular concrete under the conditions of intended use. If such admixtures are used, the slump can be increased, the water content can be adjusted following Table 5.3.3.1, or a combination of both. ASTM C94/C94M and ASTM C1602/C1602M require the weight of the water

Table 5.3.3—Approximate mixing water and air content for different slumps for concrete without water-reducing admixtures and nominal maximum sizes of aggregates

Water of concrete for indicated nominal maximum sizes of aggregates, lb/yd^3							
Slump, in.[*]	3/8	1/2	3/4	1	1-1/2	2[†]	3[†]
Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220
3 to 4	385	365	340	325	300	285	245
5 to 6	400	375	350	330	305	290	255
6 to 7	410	385	360	340	315	300	270
More than 7[‡]	—	—	—	—	—	—	—
Approximate entrapped air content in non-air-entrained concrete, %	3	2.5	2	1.5	1	0.5	0.3
Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205
3 to 4	340	325	305	295	275	265	225
5 to 6	355	335	315	300	280	270	240
6 to 7	365	345	325	310	290	280	260
More than 7[‡]	—	—	—	—	—	—	—
Required total air, %							
ACI 318 Exposure Class F1	6.0	5.5	5.0	4.5	4.5	4.0	3.5
ACI 318 Exposure Classes F2 and F3	7.5	7.0	6.0	6.0	5.5	5.0	4.5

[*] Slumps are maximum amounts for angular aggregates graded within limits of accepted specifications.

[†] The slump values are based on slump tests made after removal of particles larger than 1-1/2 in. by wet screening.

[‡] Slump values of more than 7 in. are usually obtained through the use of water-reducing admixtures. When using water-reducing admixtures, follow manufacturer's recommendations.

Note: These quantities of mixing water are for use in computing cementitious contents for trial batches at 68 to 77°F.

Table 5.3.3.1—Adjustments to estimated water content for various conditions (adapted from Bureau of Reclamation Concrete Manual, A Water Resources Technical Publication, Chapter III, Section 45)

	Adjustments[*]
Changed condition	Water content, %
Rounded aggregate	–8
Each 1% increase in air content	–3
Each 1% decrease in air content	+3
Water-reducing admixture (WRA) used	–5
High-range water-reducing admixture (HRWRA) used	–12
Each slump increase of 1 in.	+3
Each slump decrease of 1 in.	–3
Each 10°F increase in concrete temperature	+2
Each 10°F decrease in concrete temperature	–2
Each 10% increase in fly ash content as cement replacement, by weight	–3
Each 10% decrease in fly ash content as cement replacement, by weight	+3
Each 10% increase in slag cement content as cement replacement, by weight	–5
Each 10% decrease in slag cement content as cement replacement, by weight	+5
Manufactured sand is used	+5

[*] These adjustments assume the user is starting at standard laboratory temperatures of 68 to 77°F with concrete having a 3 to 4 in. slump and containing reasonably well-shaped aggregates graded within limits of accepted specifications and natural sand having a fineness modulus of 2.75. The symbol "+" represents the addition of water whereas the symbol "–" represents the reduction in water content.

in liquid admixtures be included as part of the total mixing water when it causes a change of the *w/cm* of 0.01 or more.

5.3.3.1.2 *Air content*—The section of Table 5.3.3 for non-air-entrained concrete approximates the entrapped air content to be expected in mixtures based on the nominal maximum size of aggregate. In the lower part of the table, the required total air content for Classes F1, F2, and F3 specified in ACI 318 Chapter 19 are also provided. Initial proportioning calculations should use the air content as a percent of the whole. Additional recommendations for air content and tolerances for air content control in the field are given in ACI 318. ASTM C94/C94M also provides air content limits. The requirements in other documents may not always match exactly; therefore, in proportioning, consideration should be given to selecting an air content that will meet the needs of the job as well as meet the applicable specifications.

5.3.4 *Step 4: Selection of* w/cm—The required *w/cm* is determined not only by strength requirements but also by factors such as durability. Because different aggregates and cementitious materials may produce different strengths at the same *w/cm*, it is desirable to have or to develop the relationship between strength and *w/cm* for the materials to be used.

In the absence of such data, approximate and relatively conservative values for concrete containing Type I portland cement can be taken from Table 5.3.4.

The relationship in Table 5.3.4 assumes a nominal maximum size of aggregate of approximately 3/4 to 1 in. For a given source of aggregate, strength produced at a given *w/cm* will increase as nominal maximum size of aggregate decreases.

With typical materials, the tabulated *w/cm* should produce strengths close to those shown, based on 28-day tests of specimens cured under standard laboratory conditions. Codes require that the average strength selected should exceed the specified strength by a sufficient margin to keep the number of low tests within specific limits (ACI 214R; ACI 301; ACI 318).

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Table 5.3.4—Relationship between *w/cm* and compressive strength of concrete

Compressive strength at 28 days, psi[*]	*w/cm*, by weight	
	Non-air-entrained concrete	Air-entrained concrete
7000	0.34	<0.33[†]
6000	0.41	0.33
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

[*] Values are estimated average strengths for concrete containing not more than 2% air for non-air-entrained concrete and 6% total air content for air-entrained concrete. For a constant *w/cm*, the strength of concrete is reduced as the air content is increased. Twenty-eight-day strength values may be conservative and may change when various cementitious materials are used. The rate at which the 28-day strength is developed may also change.

Compressive strength is based on 6 x 12 in. or 4 x 8 in. cylinders moist cured in accordance with ASTM C31/C31M. These are cylinders moist cured at 73.4 ± 3°F prior to testing.

[†] Concrete with a *w/cm* that is less than 0.33 may require the addition of chemical admixtures, supplementary cementitious materials, and higher cementitious materials content to achieve a 28-day compressive strength of 7000 psi.

For exposure classes of S1 through S3, F1 through F3, W2, and C2, the *w/cm* should be kept low even though strength requirements may be met with a higher value. Refer to Table 4.7.3a through Table 4.7.3d for maximum *w/cm* and minimum strength requirements. Table 4.7.3.1 additionally provides required air contents for Exposure Classes F1 through F3 as a function of nominal maximum size of aggregate.

5.3.5 *Step 5: Calculation of cementitious materials content*—The quantity of cementitious materials per unit volume of concrete is fixed by the determinations made in Steps 3 and 4. The required quantity of cementitious materials is equal to the estimated mixing-water content from Step 3 divided by the *w/cm* from Step 4. If, however, the specification includes a separate minimum limit on cementitious materials in addition to requirements for strength and durability, the mixture should be based on whichever criterion leads to the larger quantity of cementitious materials.

SCMs or chemical admixtures are often used to increase workability, strength, durability, appearance, and other factors important to the performance of concrete. Refer to ACI 234R, 232.2R, 233R, and 212.3R for more detailed information.

5.3.6 *Step 6: Estimation of coarse aggregate content*—Aggregates of essentially the same nominal maximum size and grading will produce concrete of satisfactory workability when a particular volume of coarse aggregate, on an oven-dry-rodded basis, is used per unit volume of concrete. Appropriate values for this aggregate volume are given in Table 5.3.6.

Table 5.3.6—Bulk volume of coarse aggregate per unit of volume of concrete

Nominal maximum size of aggregate, in.	Volume of oven-dry-rodded coarse aggregate[*] per unit volume of concrete for different fineness moduli of fine aggregate[†]			
	2.40	**2.60**	**2.80**	**3.00**
3/8	0.50	0.48	0.46	0.44
1/2	0.59	0.57	0.55	0.53
3/4	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1-1/2	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76

[*] Volumes are based on aggregates in oven-dry-rodded condition as described in ASTM C29/C29M. These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete, such as required for concrete pavement construction, they may be increased by approximately 10%.

[†] Refer to ASTM C136/C136M for calculation of fineness modulus.

Table 5.3.8—Design weight summary[*]

	Design weight
Mixing water	Step 3
Cementitious materials	Step 5
Coarse aggregate (SSD)	Step 6
Fine aggregate (SSD)	Step 7
Total weight	—

[*] If chemical admixtures are used, record the admixture dosage (oz/yd^3). Record the target air content percentage according to the provided values in Table 5.3.3 (Step 3).

The bulk volume of aggregate needed for a cubic yard of concrete, in cubic feet on an oven-dry-rodded basis, is equal to the value from Table 5.3.6 multiplied by 27. This volume is converted to the dry weight of coarse aggregate by multiplying the bulk volume by the oven-dry-rodded density of the coarse aggregate. The oven-dry weight is then converted to an equivalent SSD weight by multiplying by 1 plus the absorption $(1 + A)$.

5.3.7 *Step 7: Estimation of fine aggregate content*—At the completion of Step 6, the weights of all the ingredients of the concrete mixture have been estimated, except the weight of fine aggregate. Calculating the required quantity of fine aggregate involves the use of the volumes displaced by the ingredients. In concrete, the volume occupied by any ingredient is equal to its weight divided by the density of that material (the latter being the product of the density of water and the specific gravity of the material). For this calculation, the total volume displaced by the known ingredients—mixing water, air, cementitious materials, and coarse aggregate (SSD)—is subtracted from the unit volume of concrete, 27 ft^3, to obtain the required number of cubic feet of fine aggregate needed. To complete the design, that volume of sand is then converted to an SSD weight based on its SSD density by multiplying the volume by the specific gravity of the aggregate times the density of water.

5.3.8 *Step 8: Design weight summary*—Enter the constituent weights obtained from the previous steps into Table 5.3.8.

5.3.9 *Step 9: Trial batch*—Trial batches of a proposed concrete mixture are made to confirm that the combination of materials will produce the required fresh and hardened properties. The mixture design weights of Table 5.3.8 typically need adjustments to account for changes in aggregate moisture contents prior to batching. These adjustments are to accommodate changes in stockpile conditions and are not adjustments to the design of the mixture.

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Table 5.3.9.1—Batch weight summary*

	Design weight	Batch weight
Water	Step 3	—
Cementitious materials	Step 5	—
Coarse aggregate (SSD)	Step 6	—
Fine aggregate (SSD)	Step 7	—
Total weight	—	—

*If chemical admixtures are used, record the admixture dosage (oz/yd^3). Record the target air content percentage according to the provided values in Table 5.3.3 (Step 3).

5.3.9.1 *Moisture adjustments*—Typically, aggregates will have greater moisture content than their SSD condition. The amount batched will need to be increased from the design weight, expressed as SSD, by the free water on the aggregate so that the correct amount of aggregate is used. It can happen that the aggregate is so dry the amount to be weighed out needs to be decreased, with additional water added to bring it to SSD. The instructions that follow will work for both cases.

To determine the weight of aggregate to be batched, use the following formula for each aggregate and then enter these values into the batch weight summary (Table 5.3.9.1)

$$w_{batched} = \frac{(1 + MC\%)}{(1 + A\%)} \times w_{SSD} \tag{5.3.9.1}$$

The difference between the batched water and the mixing-water weight from the mixture proportions is the weight of the free water. It is subtracted from the mixing-water weight for the weight of water to be batched. Enter this value into Table 5.3.9.1. The water added to the mixture plus the free water should equal the mixing-water weight. The total batch weight after moisture adjustments should match the total mixture weight.

The total amount of materials will be needed to compute the yield. The procedure is illustrated in the examples of Chapter 9.

5.3.10 *Step 10: Post-trial batch adjustments*—The calculated mixture proportions should be checked for required performance by means of trial batches prepared and tested in accordance with ASTM C192/C192M, or full-sized field batches. Only sufficient water should be used to produce the required slump regardless of the quantity assumed in selecting the trial proportions. The concrete should be checked for density and yield (ASTM C138/C138M) and for air content (ASTM C138/C138M; ASTM C173/C173M; ASTM C231/C231M). It should also be carefully observed for workability, resistance to segregation, and finishing properties. Appropriate adjustments should be made in the proportions for subsequent batches to correct deficiencies in accordance with the following suggestions.

5.3.10.1 *Adjustment 1*—Re-estimate the quantity of the required mixing water per cubic yard of concrete by multiplying the net mixing-water content of the trial batch by 27 and dividing the product by the yield of the trial batch in cubic feet. If the slump of the trial batch was not correct, increase or decrease the re-estimated quantity of water by 10 lb for each 1 in. required increase or decrease in slump. In cases where the addition of water is undesirable, the use of water-reducing admixtures can be considered.

5.3.10.2 *Adjustment 2*—If the desired air content (for air-entrained concrete) was not achieved, re-estimate the admixture dosage for the required air content, and reduce or increase the mixing-water content of Section 5.5.1 by 5 lb for each 1% by which the air content is to be increased or decreased from that of the previous trial batch.

5.3.10.3 *Adjustment 3*—If the desired strength was not achieved, *w/cm*-versus-strength curves can be used to adjust the value. An example is shown in Chapter 9.

The measured cement efficiency can also be used to adjust the strength. Cement efficiency is the strength gained from each pound of cement in a cubic yard. With units of psi/lb/yd^3, it is computed by dividing the trial batch strength by the weight of cement for a cubic yard of the trial batch. Dividing the difference between the intended strength and the measured strength by the cement efficiency results in the weight of cement to be added to a cubic yard, to increase, or subtracted to decrease the strength. To keep the *w/cm* constant, a water adjustment will be needed. The net volume change resulting from these changes is offset by an adjustment to the weight of sand to keep the yield constant at one cubic yard. An example is shown in Chapter 9.

5.3.10.4 *Post-adjustments*—Calculate new batch weights starting with Step 5 (Section 5.3.5) and modify the volume of coarse aggregate from Table 5.3.6, if necessary, to provide proper workability.

CHAPTER 6—EFFECTS OF CHEMICAL ADMIXTURES

6.1—Background

Chemical admixtures are defined as liquids, or dispersible powders, used as ingredients in cementitious mixtures to improve their economy, properties, or both, in the plastic or hardened state.

This chapter will provide basic information needed for proportioning of concrete mixtures incorporating chemical admixtures. Although the design method presented in this guide makes only passing mention of this, very little commercial concrete is produced without chemical admixtures.

Chemical admixtures are used to tailor the properties of concrete mixtures to meet specific performance requirements of a given project such as workability, time of setting, strength, shrinkage, durability, permeability, viscosity, rheology, color, and other properties. The type and dosage of chemical admixtures are selected based on the desired performance requirements. As water-reducing admixtures (WRAs) and air-entraining admixtures (AEAs) are among the most commonly used chemical admixtures in the concrete industry, this chapter will emphasize the effects of these two admixture types on mixture proportioning. However, admixtures other than WRA and AEA such as set retarders, accelerators, and shrinkage-reducing admixtures are also used to meet various performance targets. For

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further details on admixture types and their use in concrete, refer to ACI 212.3R.

6.2—Air-entraining admixtures

Air-entraining admixtures (AEAs) are used to purposefully entrain a system of finely dispersed air bubbles primarily to increase the resistance against freezing-and-thawing damage where critically saturated exterior concrete is exposed to repeated freezing-and-thawing cycles in cold weather climates. Concrete is severely damaged when enough ice forms in the capillaries because ice creates a pressure greater than the tensile strength of the cement paste, which disrupts the capillary walls. The addition of AEAs stabilizes microscopic air bubbles (entrained air) during mixing. These bubbles provide a reservoir for water to migrate into during freezing, thereby reducing the tensile forces created in the cement paste caused by the expansion of freezing water in the smaller capillary void spaces. When thawing occurs, the water is forced back into the capillaries by compressed air in the voids, thereby freeing the voids for use again during the next freezing cycle. However, it should be noted that the air bubbles entrained by the AEA are different than the entrapped air in concrete. Entrapped air voids are incorporated into the concrete during mixing. These are mainly irregular in shape and usually 0.04 in. (1 mm) or larger in size. Entrained air bubbles are intentionally added into concrete to stabilize randomly distributed microscopic air bubbles that are typically spherical or nearly so, ranging in size between 0.0004 and 0.04 in. (0.01 and 1 mm) in diameter. Due to the large size, entrapped air bubbles do not provide the necessary protection against the cycles of freezing and thawing of the critically saturated concrete. Air-entrained voids are needed for protection and can be achieved through the use of an AEA.

AEAs may also be used to improve workability as the entrained air bubbles have a lubrication effect on the mixture. Due to the size and shape of the air voids, air-entrained concrete typically contains up to 10% less water than non-air-entrained concrete of equal workability. This reduction in the volume of mixing water as well as the volume of entrained and entrapped air must be considered in proportioning. In addition, the increase of air content may cause a reduction in strength. Therefore, mixture proportioning should be done with the consideration of the target air content's impact on strength (refer to ACI 212.3R for more information).

The quantity of AEA required to achieve an appropriate level of air entrainment in concrete is variable and depends on many mixture design characteristics. Among these are the characteristics of aggregates, type and proportions of the concrete admixtures, type and duration of mixing, consistency, temperature, cement fineness and chemistry, and the use of other cementitious materials.

6.3—Water-reducing admixtures

Water-reducing admixtures (WRAs) are used to reduce the amount of water required to achieve and maintain the target slump of freshly mixed concrete. The reduction of water in the mixture can also have other benefits such as lowering the *w*/*cm*, thereby increasing the strength. Reducing water can also improve the durability, reduce shrinkage and cracking potential, and reduce permeability. The use of a WRA permits a reduction in cementitious content when proportioning concrete mixtures due to the reduction in water content for a given *w*/*cm*. WRAs can also be used to increase slump while maintaining the original water content of the mixture.

WRAs are grouped into three general categories based on the expected amount of water reduction, although there is no standard classification indicating the amount of water reduction associated with each category. Normal-range WRAs reduce the amount of water by a minimum of 5%. Mid-range water-reducing admixtures (MRWRAs) reduce water content by between 5 and 10%. High-range water-reducing admixtures (HRWRAs) can achieve water reductions of between 12 and 40% (Kosmatka and Wilson 2016). However, the water reduction may vary (above or below) from the typical amounts listed herein. Therefore, these limits should serve only as a generic starting point that may be useful for water adjustment in mixture proportioning.

WRAs are typically used to produce slumps in the following ranges:

(a) Normal-range WRA: 0 to 6 in.
(b) MRWRA: 2 to 7 in.
(c) HRWRA: 5 to 9 in. for conventional concrete and up to 30 in. of slump flow for self-consolidating concrete (SCC)

WRAs are often formulated in combination with set retarders or accelerators. Set retarders extend the time concrete remains plastic (workable), which is useful during hot weather or extended transportation time. Set accelerators reduce the time of setting and accelerate strength gain. This can be useful in cold weather or anytime reduced time of setting or accelerated strength gain is desired.

ASTM C494/C494M specifies the characteristics for seven water-reducing and set-controlling admixtures as follows:

(1) Type A—Water-reducing
(2) Type B—Retarding
(3) Type C—Accelerating
(4) Type D—Water-reducing and retarding
(5) Type E—Water-reducing and accelerating
(6) Type F—Water-reducing, high-range
(7) Type G—Water-reducing, high-range, and retarding

ASTM C494/C494M has one additional admixture classification, Type S—Specific Performance Admixtures. Type S admixtures are designed to affect specific performance characteristics of the concrete without substantially impacting the slump, time of setting, or strength gain of the concrete.

There are many cases where more than one or two different types of chemical admixtures are added to concrete. When the use of multiple admixtures is anticipated, especially in challenging applications, chemical admixture suppliers should be consulted while still in the concrete mixture proportioning phase. In addition, the mixture proportioning phase should include a discussion on the batch water adjustment needed to account for the water in the admixtures (especially if added at high dosage rates) and their expected water-reduction levels. The compatibility of chemical admixtures with each

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other and cementitious materials as well as the combined effects of using multiple chemical admixtures on concrete performance should be assessed during the trial batching phase. Full-scale trial batches and mockups of structural elements will help identify any unexpected behaviors and allow for mixture adjustments.

CHAPTER 7—EFFECTS OF SUPPLEMENTARY CEMENTITIOUS MATERIALS

7.1—Background

Supplementary cementitious materials (SCMs) are used to improve performance and cost-efficiency of concrete mixtures while contributing to sustainability. Many of these materials are natural materials whereas others are industrial by-products, as shown in Table 7.1.

7.2—Pozzolanic versus cementitious

Fly ash, silica fume, slag cement, metakaolin, and calcined clay are some of the most commonly used SCMs. When blended with portland cement, SCMs contribute to the properties of concrete through hydraulic activity, pozzolanic activity, or both (Kosmatka and Wilson 2016). Hydraulic activity occurs when phases in the SCM chemically react with water, thereby forming cementitious hydration products similar to those formed through the hydration of portland cement. Pozzolanic activity occurs when siliceous or aluminosiliceous material in the SCM reacts with calcium hydroxide (portlandite), which in turn forms calcium silicate hydrate (C-S-H). Furthermore, pozzolans do not have any cementitious properties when used alone. However, when used in conjunction with portland cement, they react with calcium hydroxide. Considering calcium hydroxide is the most soluble of the hydration products (and thus is a weak link in concrete from porosity and durability perspectives, as opposed to C-S-H, which contributes to strength and permeability enhancement of concrete), pozzolanic activity is highly desired. Table 7.2 shows the comparison of commonly used SCMs based on their pozzolanic versus cementitious characteristics.

Table 7.1—Supplementary cementitious materials that are classified as by-products versus natural products

By-products	Natural products
Class C fly ash	Metakaolin
Class F fly ash	Calcined clay
Slag cement	Calcined shale
Silica fume	—
Rice husk ash	—

Table 7.2—Supplementary cementitious materials that are classified as pozzolanic versus cementitious

Pozzolanic	Pozzolanic + Cementitious
Class F fly ash	Class C fly ash
Silica fume	Slag cement
Metakaolin	—
Calcined clay	—
Calcined shale	—
Rice husk ash	—

Depending on the type and amount of SCMs being used, they generally:

(a) Improve the workability of concrete and decrease the tendency to bleed and segregate

(b) Reduce pore size and the porosity of both the cement matrix and the interfacial transition zone

(c) Enhance durability and service life in terms of decreasing permeability, increasing resistance to chemical attack, decreasing shrinkage, and increasing resistance to thermal cracking and alkali-aggregate expansion

(d) Increase early or ultimate strength

SCMs are added to concrete as a percentage weight basis as part of the total cementitious system, where they may be used as a partial replacement of hydraulic cement where the total cementitious materials content is increased, held constant, or decreased depending on the performance of the SCM, in the form of a hydraulic cement. The decision on the SCMs being added as a replacement or addition to the overall cementitious system as well as the selection of the total cementitious materials content should be made based on the overall performance requirements.

7.3—Types of supplementary cementitious materials

A brief summary of the impact of some of the most commonly used SCMs on concrete properties, along with the key consideration points while proportioning mixtures containing SCMs, is provided in the following.

7.3.1 *Fly ash*—Fly ash is a by-product of the combustion of ground or powdered coal. Depending on the source of the coal, characteristics of fly ash may vary, thereby differing their influence on concrete performance. There are two types of fly ash that are commonly used in concrete: Class C and Class F fly ashes (ASTM C618 also recognizes Class N natural pozzolans). Fly ash should conform to the requirements of ASTM C618.

Class F fly ashes generally contain a low amount of lime (usually less than 18% CaO), whereas it is typical for Class C fly ashes to have higher lime contents (typically more than 18% CaO). Depending on the performance requirement, fly ash is typically used within 15 to 35% of the total cementitious materials content (ACI 232.2R). However, higher and lower amounts than the typical values listed have been successfully used and can be selected depending on the project requirements.

Although the impact of fly ash on concrete properties depends on the type and amount of fly ash, the following statements are applicable for most mixtures. Fly ash tends to improve workability due to its spherical morphology that leads to the reduction of the interparticle friction. Therefore, while proportioning a mixture incorporating fly ash, depending on the selected amount and type of fly ash, slightly lower water content (up to 10%) may be needed compared to a plain concrete mixture containing portland cement only to achieve the same slump. Due to its slow pozzolanic reactivity, fly ash can increase the setting time and decrease the

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heat of hydration. Considering this retarding effect, the type and amount of fly ash should be carefully selected for projects that require early time of setting or are exposed to cold weather conditions.

Mixtures incorporating fly ash, especially when used higher than 20% of the total cementitious content, can reduce shrinkage, thereby reducing the potential for shrinkage-related cracks. Depending on the physical and chemical properties of fly ash, it also decreases permeability, enhances durability, and may increase the ultimate strength of the mixtures. However, at early ages (especially up to 3 days), mixtures with fly ash may show lower strength gain than mixtures with portland cement only. For more information on fly ash, refer to ACI 232.2R and 232.3R.

7.3.2 *Slag cement*—Slag cement is a by-product of iron production in a blast furnace. ASTM C989/C989M classifies slag cement into the following three grades based on its reactivity level: 1) Grade 80; 2) Grade 100; and 3) Grade 120. Depending on the performance requirement, slag cement is typically used to replace 20 to 50% of the total cementitious materials content. However, higher and lower amounts than the typical values listed have been successfully used and can be selected depending on the project requirements and, in some applications, up to 80% of slag cement may be used (ACI 233R).

Depending on the fineness and amount used, slag cement may increase or decrease the water demand. Mixtures containing slag cement may require slightly lower water contents (up to 5%) compared to a plain concrete mixture containing portland cement only to achieve the same slump. Slag cement typically decreases the heat of hydration; however, it has a minor impact on the time of setting depending on the amount and ambient temperature. It enhances durability and ultimate strength. For more information on slag cement, refer to ACI 233R.

7.3.3 *Silica fume*—Silica fume is the by-product of the production of elemental silicon or alloys containing silicon. Silica fume should conform to the requirements of ASTM C1240. Depending on the performance requirement, silica fume is typically used within 5 to 10% of the total cementitious materials content. However, higher and lower amounts than the typical values listed have been successfully used and can be selected depending on the project requirements.

Silica fume has a very fine particle size that is, on average, 100 times smaller than the particle size of portland cement. Due to its particles having a high specific surface area, silica fume often increases the water demand and may promote stickiness of a concrete mixture. Therefore, when all other conditions are kept the same, when proportioning a mixture containing silica fume, the use of a high-range water-reducing admixture (HRWRA), an increase in water content, or the combination of both will be needed to match the slump of a mixture containing portland cement only. Unlike most of the other SCM types, silica fume does not have a retardation effect on time of setting. In addition, it is used to increase both early-age and ultimate strength due to its very high pozzolanic reactivity. It significantly reduces the permeability; hence, it is often used in mixtures where exposure to deleterious substances such as chloride penetration is a concern. More information on silica fume can be found in ACI 234R.

7.3.4 *Metakaolin*—Metakaolin is a natural pozzolan that conforms to the requirements of ASTM C618 Type N. Metakaolin is typically used within 5 to 15% of the total cementitious materials content. However, higher and lower amounts than the typical values listed have been successfully used and can be selected depending on the project requirements.

Metakaolin is used in applications where high strength and low permeability are required. For more information on metakaolin and other natural pozzolans, refer to ACI 232.1R.

7.4—Mixture proportioning with supplementary cementitious materials

In the design method recommended by this guide, unless a preblended cement is being used, each SCM added is treated as an additional mixture component with its particular specific gravity occupying whatever volume is dictated by the quantity used (just like cement) and included in the volume calculations. Pozzolans are typically referenced in terms of percent by weight of total cementitious materials, although some locations reference them in terms of percent by volume. Where no specific reference to the contrary is included, the default reference should be as a percent by weight.

When proportioning concrete mixtures containing SCMs, the following factors should be considered while determining the desired type and amount:

(a) Pozzolanic reactivity of the SCM and its effect on concrete strength at both early and later ages

(b) Impact on the setting time and retardation

(c) Effect on the water demand needed for the desired workability and placeability

(d) Specific gravity of the SCM and its effect on the volume of concrete produced in the batch

(e) Effect on the dosage rate of chemical admixtures used in the mixture

(f) Effect of SCMs on heat of hydration, permeability, and shrinkage

(g) Amount of SCM and cement needed to meet the performance requirements

(h) Impact on bleeding rate and the need for additional curing

Table 7.4 is provided as guidance for the proportioning of mixtures containing SCMs. The relationship established in this table for a given SCM type and their corresponding impact on concrete properties is applicable only when all the other parameters are kept constant (for example, total cementitious materials content, *w/cm*, and chemical admixture dosage rate). It should be noted that there may be cases where the relationship may fall outside of the ones shown here, depending on the selected source and amount of SCM.

In the body of the table are arrows up, down, sideways, and up and down, meaning that increasing the amount of a constituent will cause the measure of the property

Table 7.4—Effects of SCM types on concrete properties (Taylor et al. 2006)

Property	Class F fly ash	Class C fly ash	Slag cement	Silica fume	Metakaolin
Workability	↑	↑	↕	↕	↓
Heat of hydration	↓	↕	↓	↔	↓
Time of setting	↑	↕	↑	↓	↔
Air content	↓	↓	↓	↓	↓
Early strength	↓	↔	↓	↑	↑
Long-term strength	↑	↑	↑	↑	↑
Permeability	↓	↓	↓	↓	↓
Chloride ingress	↓	↓	↓	↓	↓
Alkali-silica reaction	↓	↕	↓	↓	↓
Sulfate resistance	↑	↕	↑	↑	↑
Freezing-and-thawing resistance	↔	↔	↔	↔	↔
Drying shrinkage	↓	↓	↓	↓	↓

Note: ↑ Increases; ↓ Decreases; ↕ Increases or decreases; ↔ Neutral.

to go up, down, stay the same, or change could go either way, respectively.

7.5—Ternary systems

Depending on the selected type and amount of SCM, incorporating excessive amounts of a single type of SCM (binary mixtures) may have negative side effects such as extended setting time. In such cases, a possible solution is to use a ternary mixture, which is a combination of three cementitious materials that are blended to balance fresh properties, durability, and strength. For example, depending on the selected amount, combining SCMs such as fly ash and silica fume may be able to offset the adverse effects of fly ash on setting time, whereas fly ash may offset the increased water demand associated with silica fume.

7.6—Impact of SCMs on sustainability

Cement production emits approximately 5% of global carbon dioxide and consumes 5% of global energy consumption (Hendriks et al. 2004). Therefore, the replacement of cement with SCMs improves sustainability by using natural pozzolans, consuming by-products, and reducing the demand on cement clinker production considering the direct relation between the amounts of cement clinker produced and the carbon dioxide generated. In addition, the increased durability achieved with SCMs reduces the need for repair and replacement, resulting in greater sustainability.

CHAPTER 8—TRIAL BATCHING

Once the properties required of a concrete have been determined, the next step is to determine the mixture materials and proportions that will achieve those properties. Those proportions can be based on previous experience or can be developed using an assortment of design methods. Lacking those, the method recommended in this guide can be used to establish proportions for the first trial batch. Once those proportions have been determined, trial batches are conducted to demonstrate that the needed properties are indeed produced. This notion is fundamental to this guide. By whatever method the proportions are established, the trial batching should show that all the required properties are within applicable tolerances for the test. If none are given in the specification, ASTM C94/C94M gives guidance on slump and air content tolerances. Only then can it be said that the purpose of this guide has been met.

Often, the requisite properties are not achieved on the first trial. When this happens, the mixture proportions are adjusted to move the performance of the mixture in the desired direction. Sometimes, that adjustment works to improve one property, but causes another to become deficient. Another adjustment is then made, another trial batch is run, and so on until all the requirements have been met. Once the mixture produces desired results in the lab, it is recommended that it be batched at production-level amounts, using the materials, means, and methods to be used for the project to be sure the mixture works the same way when scaled up.

Trial batching is executed following the procedures of ASTM C192/C192M. This standard is used for mixture proportioning, evaluation of different mixtures and materials, correlation with nondestructive tests, and research purposes. It specifies the standard conditions, equipment, and procedures needed to test proposed mixtures for their fresh properties. Tests such as ASTM C1064/C1064M for temperature, ASTM C143/C143M for slump, ASTM C138/C138M for density and yield, and ASTM C231/C231M or ASTM C173/C173M for air content are listed among the procedures. Following proper curing procedures is very important for producing reproducible results, and for comparing with the results coming from the field. To assure reliable results, tests should be performed by an appropriately certified person.

The method of the three-point curve can be used to discover the relationship between *w/cm* and strength for a family of mixtures with similar properties but differing in strength. Such a curve can be used for the design of mixtures within the strength range of the curve, as well as strength adjustment of the mixture if needed.

Once the results of the trial batch have been gathered, Table 8 may help guide the necessary adjustments.

CHAPTER 9—SAMPLE COMPUTATIONS

9.1—Background

The following four example problems will be used to demonstrate the proportioning procedure. The conditions listed in the following apply to all examples.

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Table 8—Effect of additional constituents on various fresh properties (Kosmatka and Wilson 2016)

Property	Cement	*w/cm*	Water	Air	Fly ash	Slag cement	Silica fume
Water demand	↑	↓	N/A	↓	↓	↓	↑
Workability	↑	↑	↑	↑	↑	↑	↓
Air content	↓	↓	↓	N/A	↓	↔	↓
Bleeding and segregation	↓	↑	↑	↓	↓	↕	↓
Finishability	↕	↕	↕	↑	↑	↑	↓
Time of setting	↓	↑	↑	↔	↑	↑	↔
Heat of hydration	↑	↓	↓	↔	↓	↔	↑
Strength	↑	↓	↓	↓	↑	↑	↑
Permeability	↓	↑	↑	↔	↓	↓	↓
Cracking	↑	↑	↑	↓	↓	↑	↑

Note: ↑ Increases; ↓ Decreases; ↕ Increases or decreases; ↔ Neutral.

(a) ASTM C150/C150M Type I portland cement will be used. Its specific gravity is assumed to be 3.15.

(b) Coarse and fine aggregates in each case meet the requirements of ASTM C33/C33M.

9.2—Example 1: Mixture proportioning using portland cement only

Concrete is required for a portion of a structure that will be below ground level in a location where it will not be exposed to severe weathering, constant wetting, or sulfate attack. It is in Class F0. A strength of 2500 psi at 28 days is specified. A locally available rounded coarse aggregate with a nominal maximum size of 1.5 in. is suitable. This coarse aggregate has a saturated surface-dry (SSD) specific gravity of 2.68, absorption ($A\%$) of 0.5%, and a dry-rodded density of 100 lb/ft^3. The fine aggregate has a fineness modulus of 2.80, an SSD specific gravity of 2.64, and an absorption ($A\%$) of 0.7%. The quantities of mixture constituents per cubic yard (yd^3) of concrete are determined as outlined in the following steps.

9.2.1 *Step 1*: *Estimate slump*—On the basis of the information in Table 5.3.1 as well as previous experience, a slump of 3 to 4 in. will be targeted for the selected placement method.

9.2.2 *Step 2*: *Select nominal maximum size of aggregate*—The locally available rounded coarse aggregate with a nominal maximum aggregate size of 1.5 in. is used in this application.

9.2.3 *Step 3: Estimate mixing-water content*—Because the structure is in Class F0 exposure class, non-air-entrained concrete will be used. From the top portion of Table 5.3.3, the approximate amount of mixing water needed to produce a 3 to 4 in. slump in non-air-entrained concrete using 1.5 in. nominal maximum size aggregate is 300 lb/yd^3, and the approximate amount of entrapped air 1%.

9.2.4 *Step 4: Estimate* w/cm—The application specifies an average 28-day compressive strength (f_c') of 2500 psi. For proportioning without a standard deviation, the strength overdesign for concretes with a specified strength less than 3000 psi as required by Table 4.7.4.1 is 1000 psi. Therefore, the required average compressive strength (f_{cr}') for this mixture proportion becomes 3500 psi. Because no durability issues are indicated, strength alone can dictate the *w/cm*. Based on Table 5.3.4, the *w/cm* estimated to produce a strength of 3500 psi in non-air-entrained concrete is interpolated to be 0.62.

9.2.5 *Step 5*: *Calculate cement content*—From the information developed in Steps 3 and 4, the required cement content is calculated as: 300 lb/yd^3/0.62 = 484 lb/yd^3.

9.2.6 *Step 6*: *Calculate coarse aggregate content*—The bulk volume of coarse aggregate is estimated from Table 5.3.6. With the fine aggregate having a fineness modulus of 2.80 and the 1.5 in. nominal maximum size of coarse aggregate, the table indicates that 0.71 ft^3 of coarse aggregate, on a dry-rodded basis, is a good estimate for a cubic foot of concrete. Because its dry-rodded density is 100 lb/ft^3, each bulk cubic foot of coarse aggregate would weigh 0.71 ft^3 × 100 lb/ft^3 = 71 lb. Because a cubic yard (27 ft^3) is being proportioned, the amount will be adjusted as the following: 71 lb/ft^3 × 27 ft^3/yd^3 = 1917 lb/yd^3. Absorption ($A\%$) will be taken into account to convert the dry-rodded density to the corresponding SSD weight, as shown in the following

$$1917\ \text{lb/yd}^3 \times (1 + 0.5\%) = 1927\ \text{lb/yd}^3$$

9.2.7 *Step 7: Calculate fine aggregate content*—Concrete consists of water, air, cement, coarse aggregate, and fine aggregate. For the cubic yard being proportioned, the weights of all these except the fine aggregate have been determined. The first step necessary to determine the weight of the fine aggregate is by first calculating the absolute volumes of each of the known mixture constituents. The absolute volumes are calculated through their weight-volume relationships determined by their corresponding specific gravities (relative densities). The volume of the fine aggregate sought is determined by adding the total volume of all other mixture constituents subtracted from the total volume of one cubic yard. The weight of the fine aggregate is then calculated based on its weight-volume relationship using the known parameters—namely, its volume and specific gravity.

9.2.7.1 *Absolute volume computations*

Volume of water = 300 lb/62.4 lb/ft^3 = 4.81 ft^3

Volume of cement = 484 lb/(3.15 × 62.4 lb/ft^3) = 2.46 ft^3

Volume of coarse aggregate = 1927 lb/(2.68 × 62.4 lb/ft^3) = 11.52 ft^3

Volume of air = 1% × 27.00 ft^3 = 0.27 ft^3

Total volume except for fine aggregate = 19.06 ft^3

Volume of fine aggregate = 27.00 ft^3 – 19.06 ft^3 = 7.94 ft^3

Total volume of ingredients = 27.00 ft^3

Required SSD weight of fine aggregate = 7.94 ft^3 × 2.64 × 62.4 lb/ft^3 = 1308 lb

Table 9.2.7.2—Constituent weights

Mixture constituents	lb/yd^3	lb/ft^3
Mixing water	300	11.11
Cementitious materials	484	17.93
Coarse aggregate (SSD)	1927	71.37
Fine aggregate (SSD)	1308	48.44
Total weight	4019	148.85
Fresh density at 1% air	—	148.9
Air-free density	—	150.4

w/cm = 300 lb/484 lb = 0.62

9.2.7.2 For the first laboratory trial batch, the constituent weights, as well as the expected fresh density and the air-free density (needed for computation of yield and air content per ASTM C138/C138M), are calculated as shown in Table 9.2.7.2 prior to the moisture adjustments.

9.2.8 *Step 8: Moisture adjustment*—The constituent weights for this mixture have been established. However, moisture adjustments may be necessary at the time of batching to properly manage the amount of water required to achieve the target performance requirements. This is usually due to the presence of water on the surface of aggregates that is available to hydrate cement as opposed to water absorbed by aggregates. Free water is the difference between the total amount of water subtracted by the absorbed water. If the aggregate moisture is above SSD, an adjustment should be made to the aggregate weights with the excess moisture above SSD being subtracted from the mixture water. This assures that the total amount of water in the batch equals the amount required as stated in Table 5.3.3. These adjustments are not apparent in the initial mixture proportioning phase and can only be determined after the trial batch is completed.

For the materials available, tests indicate a total moisture content (MC%) of 2% for the coarse aggregate and 6% for the fine aggregate. Recalling that the absorptions of the coarse and fine aggregates were 0.5% and 0.7%, respectively, moisture-adjusted weights become

$$\text{Coarse aggregate: } 1927 \times \frac{1+2\%}{1+0.5\%} = 1956 \text{ lb/yd}^3$$

$$\text{Fine aggregate: } 1308 \times \frac{1+6\%}{1+0.7\%} = 1377 \text{ lb/yd}^3$$

The free water contributed by the coarse aggregate is the difference between the moisture-adjusted aggregate weight (just computed) and the SSD weight from Step 6. For coarse aggregate, free water is determined as

$$1956 \text{ lb/yd}^3 - 1927 \text{ lb/yd}^3 = 29 \text{ lb/yd}^3$$

For fine aggregate, free water is

$$1377 \text{ lb/yd}^3 - 1308 \text{ lb/yd}^3 = 69 \text{ lb/yd}^3$$

The total free water is the sum of the two amounts

$$29 \text{ lb/yd}^3 + 69 \text{ lb/yd}^3 = 98 \text{ lb/yd}^3$$

Table 9.2.8—Constituent weights

Mixture constituents	lb/yd^3	lb/ft^3
Mixing water	202	7.48
Cementitious materials	484	17.93
Coarse aggregate (SSD)	1956	72.44
Fine aggregate (SSD)	1377	51.00
Total weight	4019	148.85
Fresh density	—	148.9
Air-free density	—	150.4

Table 9.2.9—Constituent weights

Mixture constituents	Original lb/ft^3	Batched lb/ft^3
Mixing water	7.48	8.50
Cementitious materials	17.93	17.93
Coarse aggregate (SSD)	72.44	72.44
Fine aggregate (SSD)	51.00	51.00
Total weight	148.85	149.87
Fresh density	148.9	147.5
Air-free density	150.4	—

Therefore, the water required for batching is

$$300 \text{ lb/yd}^3 - 98 \text{ lb/yd}^3 = 202 \text{ lb/yd}^3$$

With aggregates adjusted to their current moisture condition, the constituent weights are shown in Table 9.2.8.

Note that after the moisture adjustments, the sum of the weights of the constituents per cubic yard (yd^3) and per cubic foot (ft^3) do not change from the original proportions.

9.2.9 *Step 9: Post-trial batch*—An initial 1 ft^3 trial batch of this mixture was prepared. Although the quantity of water for the trial batch was proportioned to be 7.48/ft^3, the amount of water added to reach the desired 3 to 4 in. slump resulted in a slump of 2 in. Therefore, to increase the slump to reach the design values of 3 to 4 in., an additional water content of 1.02 lb/ft^3 was added that increased the total water content to 8.50 lb/ft^3. The batched weights are shown in Table 9.2.9.

9.2.9.1 The trial batch produced concrete with a 2 in. slump that is below the 3 to 4 in. selected at Step 1. Even with extra water of 1.02 lb/ft^3 added, slump was too low; therefore, additional water was needed. The mixing water in the batch was not just the 7.48 lb/ft^3 that was weighed out, but also included the free water on the aggregates. The free-water weights are found by reversing the computations for determining the moist weights from the SSD proportioning weights. The aggregate batched weight is first divided by 1 + MC% to return to oven-dry condition, and then multiplied by 1 + A% to bring the aggregate to SSD. The resulting equivalent SSD weight is subtracted from the batched weights to determine the amount of free water on the aggregates in the trial batch.

Coarse aggregate

$$72.44 \text{ (moist)} \times \frac{1+0.5\%}{1+2\%} = 71.37 \text{ lb/ft}^3 \text{ (SSD)}$$

$$\text{Free water} = 72.44 \text{ lb/ft}^3 - 71.37 \text{ lb/ft}^3 = 1.07 \text{ lb/ft}^3$$

Fine aggregate

$$51.00\text{ (moist)} \times \frac{1+0.7\%}{1+6\%} = 48.45\text{ lb/ft}^3\text{ (SSD)}$$

$$\text{Free water} = 51.00\text{ lb/ft}^3 - 48.45\text{ lb/ft}^3 = 2.55\text{ lb/ft}^3$$

Therefore, the mixing water in the trial batch was

$$8.50\text{ lb/ft}^3\text{ batched} + 1.07\text{ lb/ft}^3\text{ free on coarse aggregate} + 2.55\text{ lb/ft}^3\text{ free on fine aggregate} = 12.12\text{ lb/ft}^3$$

To produce a cubic yard of concrete with the same 2 in. slump as the trial batch would use

$$12.12\text{ lb/ft}^3 \times 27.00\text{ ft}^3 = 327\text{ lb/yd}^3\text{ of water}$$

To increase the slump from the measured 2 in. to the 3 to 4 in. range selected in Step 1, the amount of water might be increased by another 15 lb for 1.5 in. additional slump, bringing the mixture water for the next trial to 342 lb/yd^3.

9.2.9.2 The density was measured to be 147.5 lb/ft^3, and the yield was

$$147.5\text{ lb/ft}^3 \times 27.00\text{ ft}^3/148.9\text{ lb/ft}^3 = 26.75\text{ ft}^3$$

Knowing the air-free density to be 150.4 lb/ft^3, the gravimetric air content was computed to be

$$Air\% = \frac{(150.4\text{ lb/ft}^3 - 147.5\text{ lb/ft}^3)}{150.4\text{ lb/ft}^3} \times 100 = 1.9\%$$

9.2.9.3 With the increased mixing water, additional cement is needed to maintain the *w*/*cm* of 0.62. The cement content for the next trial becomes

$$342\text{ lb/yd}^3/0.62 = 552\text{ lb/yd}^3$$

9.2.9.4 As workability was found to be satisfactory, the weight of coarse aggregate will remain as originally proportioned.

9.2.9.5 With these changes made, Step 6 is reapplied to determine the amount of fine aggregate needed for the next trial batch.

Volume of water = 342 lb/62.4 lb/ft^3 = 5.48 ft^3

Volume of cement = 552 lb/(3.15 × 62.4 lb/ft^3) = 2.81 ft^3

Volume of SSD coarse aggregate = 1927 lb/(2.68 × 62.4 lb/ft^3) = 11.52 ft^3

Volume of air (using measured air from trial) = 1.9% × 27.00 ft^3 = 0.51 ft^3

Total volume of ingredients except fine aggregate = 20.32 ft^3

Volume of SSD fine aggregate required = 27.00 ft^3 – 20.32 ft^3 = 6.68 ft^3

Required weight of SSD fine aggregate = 6.68 ft^3 × 2.64 × 62.4 lb/ft^3 = 1100 lb

9.2.9.6 Prior to trial batch moisture adjustments, the constituent weights for the next trial batch per cubic yard and per cubic foot are determined, as shown in Table 9.2.9.6.

Table 9.2.9.6—Constituent weights

Mixture constituents	lb/yd^3	lb/ft^3
Mixing water	342	12.67
Cementitious materials	552	20.44
Coarse aggregate (SSD)	1927	71.37
Fine aggregate (SSD)	1100	40.74
Total weight	3921	145.22
Fresh density	—	145.2
Air-free density	—	148.0

The *w*/*cm* is maintained to be 0.62 (342 lb/552 lb).

9.2.9.7 The results of the next trial batch will be evaluated for its properties, and if found deficient again, further adjustments to the proportioning will be made until the desired properties are achieved. However, it should be noted that an adjustment to correct one property may adversely affect another property. The process continues until all the required properties of the mixture are achieved.

9.3—Example 2: Mixture proportioning of binary mixture containing fly ash

A concrete mixture is needed for several ponds on a lobster farm located in Northern Maine. The ponds will be operated in such a way as to be fully influenced by the tides, but not the direct impact of the waves. For durability, this application is classed as S1, F3, and W1. For additional durability, fly ash at 20% by weight as cement replacement is specified. A local rounded coarse aggregate with nominal maximum size of 1.5 in. with suitable gradation, SSD specific gravity of 2.66, a dry-rodded density of 101 lb/ft^3, and absorption (A%) of 0.8% is available. A local natural sand, having a fineness modulus of 2.80, an SSD specific gravity of 2.65, and an absorption (A%) of 1.0% will be used. A sample standard deviation (S_s) of 300 psi has been determined from similar mixtures.

9.3.1 *Step 1*: *Estimate slump*—A slump of 5 to 6 in. is specified.

9.3.2 *Step 2*: *Select nominal maximum size of aggregate*—The locally available rounded coarse aggregate with a nominal maximum aggregate size of 1.5 in. is used in this application.

9.3.3 *Step 3: Estimate water content*—Severe saltwater and freezing-and-thawing exposures place this application into Exposure Class F3. The level of air entrainment for F3 is found in Table 5.3.3. Given the nominal maximum aggregate size of 1.5 in., a total air content of 5.5% is required. To entrain 5.5% air, an air-entraining agent (AEA) will be used.

For these exposure considerations, along with the 5 to 6 in. slump and the 1.5 in. nominal maximum size of aggregate, an approximate mixing-water weight of 280 lb is recommended for concrete without a water-reducing admixture (WRA) based on Table 5.3.3. However, a WRA within the manufacturer's recommended dose will be used. Therefore, Table 5.3.3.1 suggests water reduction of 5% when using a WRA, which yields a 14 lb water reduction.

The use of 20% fly ash replacement allows for a further water reduction of 6%, which yields to 17 lb based on Table 5.3.3.1.

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Furthermore, Table 5.3.3.1 suggests a water reduction of 8% for the use of rounded aggregates, which yields to an additional 22 lb.

The estimated mixing water then becomes

$$280 \text{ lb} - 14 \text{ lb (due to WRA)} - 17 \text{ lb (due to fly ash)} - 22 \text{ lb (due to rounded aggregates)} = 227 \text{ lb}$$

These water reductions are estimates and should be evaluated with a trial batch.

9.3.4 *Step 4: Estimate* w/cm—The selection of *w/cm* requires consideration of both the durability and strength requirements. Based on Table 4.7.3a through Table 4.7.3d, F3 freezing-and-thawing exposure allows only a maximum *w/cm* of 0.40 and minimum f_c' of 5000 psi. In the tidal splash zone for seawater exposure, S1 permits only a maximum *w/cm* of 0.50 and minimum f_c' of 4000 psi. For water tightness, W1 has a minimum f_c' of 2500 psi. Based on this, the F3 requirements for freezing-and-thawing exposure governs durability considerations.

The strength needs to comply with specifications for the required average compressive strength (f_{cr}'). The local supplier anticipated f_c' in the 5000 psi range. For these mixtures, a sample standard deviation (*s*) of 300 psi was computed. Applying the formula from Table 4.7.4.4, the required average strength will need to be the larger of

$$f_{cr}' = f_c' + 1.34s = 5000 \text{ psi} + (1.34 \times 300 \text{ psi}) = 5400 \text{ psi}$$

or

$$f_{cr}' = f_c' + 2.33s - 500 = 5000 \text{ psi} + (2.33 \times 300 \text{ psi}) - 500 = 5200 \text{ psi}$$

As it is higher, 5400 psi is selected for f_{cr}'. From Table 5.3.4, interpolating between 5000 and 6000 psi values for air-entrained concrete, a *w/cm* of 0.37 is chosen. Because 0.37 is lower than the *w/cm* of 0.40 required for resistance to freezing and thawing, 0.37 is the *w/cm* selected for proportioning.

9.3.5 *Step 5: Calculate cementitious materials content*—Because the *w/cm* selected for proportioning is 0.37, the cementitious materials content is the water content divided by 0.37. Mixing-water weight of 227 lb is divided by the selected *w/cm* of 0.37 to calculate the cementitious materials content, which is 614 lb. Fly ash at 20% replacement level will yield 123 lb while the remaining amount (491 lb) will constitute portland cement. The local fly ash, with specific gravity of 2.40, will have a volume of 0.82 ft^3. The cement volume will be 2.50 ft^3. When fly ash is used, Table 5.3.3.1 suggests a water reduction of 3% for each additional 10% fly ash replacement. This water adjustment was already accounted for in Step 3.

9.3.6 *Step 6: Calculate coarse aggregate content*—Based on Table 5.3.6, a dry-rodded volume of 0.71 ft^3 per unit volume is recommended for a nominal maximum size of aggregate of 1.5 in. and a fineness modulus of sand of 2.80. Considering the dry-rodded density being 101 lb/ft^3, a dry-rodded volume of 0.71 ft^3 results in the oven-dry weight of coarse aggregate to be 71.7 lb. The corresponding weight per yard is calculated by multiplying 71.7 lb × 27.00 ft^3, which produces an oven-dry coarse aggregate weight of 1936 lb/yd^3. Absorption (*A*%) will be taken into account to convert the dry-rodded density to the corresponding SSD weight, as shown in the following

$$1936 \text{ lb/yd}^3 \times (1 + 0.8\%) = 1951 \text{ lb/yd}^3$$

Table 9.3.7.2—Constituent weights

Mixture constituents	lb/yd^3	lb/ft^3
Mixing water	227	8.41
Cement	491	18.19
Fly ash	123	4.56
Coarse aggregate (SSD)	1951	72.26
Fine aggregate (SSD)	1124	41.63
Total weight	3916	145.04
Fresh density at 5.5% air	—	145.0
Air-free density	—	153.4

9.3.7 *Step 7: Calculate fine aggregate content*—Using the calculated volume of each mixture constituent, the weight of fine aggregate is calculated as shown in 9.3.7.1.

9.3.7.1 Absolute volume computations:

Volume of water = 227 lb/62.4 lb/ft^3 = 3.64 ft^3

Volume of cement = 491 lb/(3.15 × 62.4 lb/ft^3) = 2.50 ft^3

Volume of fly ash = 123 lb/(2.40 × 62.4 lb/ft^3) = 0.82 ft^3

Volume of coarse aggregate = 1951 lb/(2.66 × 62.4 lb/ft^3) = 11.75 ft^3

Volume of air = 5.5% × 27.00 ft^3 = 1.49 ft^3

Total volume of ingredients except fine aggregate = 20.20 ft^3

Volume of fine aggregate required = 27.00 ft^3 – 20.20 ft^3 = 6.80 ft^3

Required weight of SSD fine aggregate = 6.80 ft^3 × 2.65 × 62.4 lb/ft^3 = 1124 lb

Air-free volume = 25.51 ft^3

w/cm = 227 lb/(491 lb + 123 lb) = 0.37

9.3.7.2 For the first laboratory trial batch, the constituent weights, as well as the expected fresh density and the air-free density (needed for computation of yield and air content per ASTM C138/C138M), are calculated as shown in Table 9.3.7.2 prior to the moisture adjustments.

9.3.8 *Step 8: Moisture adjustment*—For the materials available, tests indicate a total moisture content (*MC*%) of 1% for the coarse aggregate and 3% for the fine aggregate. Recalling that the absorptions of the coarse and fine aggregates were 0.8% and 1.0%, respectively, moisture-adjusted weights become

$$\text{Coarse aggregate: } 1951 \times \frac{1+1\%}{1+0.8\%} = 1955 \text{ lb/yd}^3$$

$$\text{Fine aggregate: } 1124 \times \frac{1+3\%}{1+1.0\%} = 1146 \text{ lb/yd}^3$$

The free water contributed by the coarse aggregate is the difference between the moisture-adjusted aggregate weight

Table 9.3.8—Constituent weights

Mixture constituents	lb/yd^3	lb/ft^3
Mixing water	201	7.44
Cement	491	18.19
Fly ash	123	4.56
Coarse aggregate (SSD)	1955	72.41
Fine aggregate (SSD)	1146	42.44
Total weight	3916	145.04
Fresh density	—	—
Air-free density	—	—

(just computed) and the SSD weight from Step 6. For coarse aggregate, free water is determined as

$$1955 \text{ lb/yd}^3 - 1951 \text{ lb/yd}^3 = 4 \text{ lb/yd}^3$$

and for fine aggregate, free water is

$$1146 \text{ lb/yd}^3 - 1124 \text{ lb/yd}^3 = 22 \text{ lb/yd}^3$$

The total free water is the sum of the two amounts

$$4 \text{ lb/yd}^3 + 22 \text{ lb/yd}^3 = 26 \text{ lb/yd}^3$$

Therefore, the water required for batching is

$$227 \text{ lb/yd}^3 - 26 \text{ lb/yd}^3 = 201 \text{ lb/yd}^3$$

With aggregates adjusted to their current moisture condition, the constituent weights are shown in Table 9.3.8.

Note that after the moisture adjustments, the sum of the weights of the constituents per cubic yard (yd^3) and per cubic foot (ft^3) do not change from the original proportions.

9.3.9 *Step 9: Post-trial batch*—The trial batch produced the following results:

The slump was measured to be 5.5 in. Therefore, no adjustment on the WRA dose is needed. However, the fresh density was measured to be 146.0 lb/ft^3, and the yield was 146.0 lb/ft^3 × 27.00 ft^3/145.0 lb/ft^3 = 27.19 ft^3. Knowing the air-free density to be 153.4 lb/ft^3, the gravimetric air content was computed as follows

$$Air\% = \frac{(153.4 - 146.0)}{153.4} \times 100 = 4.8\%$$

The air content was 0.7% lower than the target air content of 5.5%, and the mixture over-yielded slightly. The results are generally good. A slight increase in AEA dosage will slightly increase the air content into the acceptable range and increase the slump slightly as well. Consider doing the next trial batch of a couple yards in a mixer of the type (for example, central-mixed, truck-mixed) to be used on the project.

9.4—Example 3: Mixture proportioning using cementitious efficiency factor

The cementitious efficiency factor is the compressive strength achieved divided by the amount of cementitious material used (psi/lb). This factor is often used to compare the performance of different mixtures. A rational way to adjust the strength of a concrete mixture is by using the cementitious efficiency factor. It can be used to either increase or decrease the strength of a mixture by several hundred psi. Because strength is affected by *w/cm*, when the cementitious efficiency factor is used to adjust the strength of a mixture, it is important to ensure the *w/cm* is not kept the same to see an impact on the strength. This can be achieved by keeping the water content the same while adjusting the cementitious material content.

9.4.1 *Step 1: Calculate cementitious efficiency factor*—The use of this factor for strength adjustment will be demonstrated starting with the following mixture proportions for a cubic yard targeting 4500 psi that, when trial batched, only reached 4200 psi. In this mixture, a coarse aggregate with nominal maximum size of 1 in. with suitable gradation, saturated surface-dry (SSD) specific gravity of 2.73 and absorption (*A*%) of 0.7% was used. The fine aggregate having an SSD specific gravity of 2.64 and an absorption (*A*%) of 0.6% will be used.

Weight, per yd^3
Cement: 564 lb
Fine aggregate: 1550 lb
Coarse aggregate: 1600 lb
Water: 300 lb
Total weight: 4014 lb
Density: 148.7 lb/ft^3

The *w/cm* was calculated to be 300 lb/564 lb = 0.53.

The cementitious material efficiency factor was calculated as 4200 psi/564 lb = 7.45 psi/lb.

9.4.2 *Step 2: Adjust mixture constituents based on the desired strength gain*—The slump was found to be satisfactory. However, because 300 psi of strength gain is needed, the *w/cm* was reduced by increasing the cementitious material content while keeping the water content the same.

(1) The cementitious material efficiency factor is 7.45 psi/lb.

(2) The strength gain needed is 4500 psi – 4200 psi = 300 psi.

(3) The additional cementitious weight needed to be added is determined by dividing the strength increase needed by the cementitious efficiency factor: 300 psi/7.45 psi/lb = 40 lb.

(4) The new cementitious weight is 564 lb + 40 lb = 604 lb.

(5) The water content is kept constant as 300 lb. Therefore, the new *w/cm* is 300 lb/604 lb = 0.50.

(6) Because the *w/cm* is reduced from 0.53 to 0.50, a WRA within the manufacturer's recommended dose is used to maintain the target slump.

(7) The yield is kept constant by removing a volume of fine aggregate equal to the volume of the additional cementitious material.

(8) The volume of additional cementitious material is 40 lb/(3.15 × 62.4 lb/ft^3) = 0.20 ft^3.

(9) The volume of fine aggregate is reduced by 0.20 ft^3. The corresponding fine aggregate weight is calculated as 0.20 ft^3 × (2.64 × 62.4 lb/ft^3) = 33 lb. Hence, the fine aggregate weight is reduced by 33 lb.

(10) The new fine aggregate weight is 1550 lb – 33 lb = 1517 lb.

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9.4.3 *Step 3: Calculate the new mixture proportions*—The proportions for the next trial batch are shown in the following:

Weight, per yd^3
Cement: 604 lb
Fine aggregate: 1517 lb
Coarse aggregate: 1600 lb
Water: 300 lb
Total weight: 4021 lb
Density: 148.9 lb/ft^3

9.5—Example 4: Mixture proportioning using target paste volume

The paste volume (*PV*) is defined as the sum of volumes of the cementitious materials and water expressed as a percent of the total concrete volume. A lower paste volume can lead to lower concrete shrinkage, lower concrete temperature due to lower heat of hydration, lower materials cost, and lower carbon footprint of concrete. AASHTO PP 84 lists a paste volume of 25% as one of the approaches to reduce unwanted slab warping and cracking due to shrinkage (if cracking is a concern).

9.5.1 *Step 1: Calculate paste volume*—A concrete mixture has been designed for concrete piles exposed to aggressive seawater in Florida. The exposure class for the concrete is F0, C2, S1, and W1. According to Tables 4.7.3a through 4.7.3d, the concrete needs to have a *w/cm* of 0.40 and have a minimum compressive strength of 5000 psi. Due to the desired resistance to chloride penetration, a mixture containing slag cement at 50% replacement level (by weight) is used. The following mixture, which has been found to attain the strength, resistance to chloride penetration, and workability levels, is designed.

Cement = 350 lb/yd^3 with a specific gravity of 3.15

Slag cement = 350 lb/yd^3 with a specific gravity of 2.90

Total cementitious materials content = 350 lb/yd^3 + 350 lb/yd^3 = 700 lb/yd^3

Water = 280 lb/yd^3

w/cm = 280 lb/yd^3/700 lb/yd^3 = 0.40

Coarse aggregate = 1800 lb/yd^3 with a specific gravity of 2.80

Fine aggregate = 1200 lb/yd^3 with a specific gravity of 2.60

Fine-to-coarse aggregate ratio is 40%/60%

The percent paste volume of the above mixture is shown in the following:

Cement = 350 lb/(3.15 × 62.4 lb/ft^3) = 1.78 ft^3

Slag cement = 350 lb/(2.90 × 62.4 lb/ft^3) = 1.93 ft^3

Water = 280 lb/(1 × 62.4 lb/ft^3) = 4.49 ft^3

Total paste volume = 8.20 ft^3

Percent paste volume = 8.20 ft^3/27.00 ft^3 = 30.4%

9.5.2 *Step 2: Adjust mixture constituents to achieve the target paste volume of 25%*—Because the mixture already attains the target strength and resistance to chloride penetration, it was decided to maintain the same *w/cm* of 0.40 and 50% replacement level of slag cement. A lower water content along with the target *w/cm* (for attaining target strength and resistance to chloride penetrability) will lead to a lower paste volume.

25% paste volume in 1 yd^3 of concrete is 25% × 27.00 ft^3 = 6.75 ft^3, which will be the new paste volume.

The new cement weight is calculated as follows

$$\text{Cement} = \frac{(PV \times 62.4 \times (1 - \%SCM))}{\left(w/cm + \dfrac{(1 - \%SCM)}{3.15} + \dfrac{\%SCM}{SCM_{RD}}\right)}$$

Inserting the appropriate values, the new cement weight is determined as shown in the following

$$\text{Cement} = \frac{(6.75 \times 62.4 \times (1 - 50\%))}{\left(0.40 + \dfrac{(1 - 50\%)}{3.15} + \dfrac{50\%}{2.9}\right)} = 288 \text{ lb}$$

$$\text{Slag} = \frac{\text{Cement} \times \%SCM}{(1 - \%SCM)} = \frac{288 \times 50\%}{(1 - 50\%)} = 288 \text{ lb}$$

Therefore, total cementitious material content is calculated as 288 lb + 288 lb = 576 lb.

Because the *w/cm* is kept constant as 0.40, water content is calculated as 0.40 × 576 = 230 lb.

9.5.3 *Step 3: Calculate the new paste volume for verification*

New paste volume

$$(230 \text{ lb}/62.4 \text{ lb/ft}^3 + 288 \text{ lb}/3.15/62.4 \text{ lb/ft}^3 + 288 \text{ lb}/2.90/62.4 \text{ lb/ft}^3) = 6.75 \text{ ft}^3$$

New percent paste volume

$$6.75 \text{ ft}^3/27.00 \text{ ft}^3 = 25\%$$

Reduction in paste volume compared to original mixture

$$(8.20 \text{ ft}^3 - 6.75 \text{ ft}^3) = 1.45 \text{ ft}^3$$

This reduction will need an increase in total aggregate volume to produce the cubic yard. Dividing this aggregate volume by the fine-to-coarse aggregate ratio of 40%/60% yields the following adjustments

$$\text{Increase in coarse aggregate} = 60\% \times 1.45 \text{ ft}^3 \times 2.80 \times 62.4 \text{ lb/ft}^3 = 152 \text{ lb}$$

$$\text{Increase in fine aggregate} = 40\% \times 1.45 \text{ ft}^3 \times 2.60 \times 62.4 \text{ lb/ft}^3 = 94 \text{ lb}$$

9.5.4 *Step 4: Calculate the new mixture proportions*

Cement = 288 lb
Slag cement = 288 lb
Water = 230 lb
Coarse aggregate = (1800 lb + 152 lb) = 1952 lb
Fine aggregate = (1200 lb + 94 lb) = 1294 lb

Because the new mixing-water content is 230 lb, which is 18% lower than before (280 lb), the mixture should be designed with a high-range water-reducing admixture

(HRWRA) to attain the target workability. It should be noted that very low mixing-water contents (particularly below 200 lb/yd^3) will result in difficulty in finishing in the field. The equations provided in this example can be used for any target paste volume, *w*/*cm*, SCM%, and specific gravity.

CHAPTER 10—REFERENCES

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AASHTO PP 84-2020—Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures

American Concrete Institute (ACI)

ACI 201.2R-16—Guide to Durable Concrete

ACI 207.1R-05(12)—Guide to Mass Concrete

ACI 209R-92(08)—Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures

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ACI 211.6T-14—Aggregate Suspension Mixture Proportioning Method

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ACI 212.3R-16—Report on Chemical Admixtures for Concrete

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APPENDIX A—LABORATORY TESTS

A.1—Need for laboratory testing

Several basic physical properties of ingredient materials used for concrete need to be known or determined from laboratory tests prior to the selection of concrete mixture proportions. The physical properties of the ingredient materials are used in the proportioning calculations to determine and report the *w*/*cm*; air content; quantities of coarse, fine, and intermediate aggregates; and quantities of cementitious materials and admixtures. The mixture proportioning procedure is used to establish initial proportions for trial batches and then fine-tune and optimize the proportions to provide

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the desired workability, *w/cm*, air content, cement content, strength, and durability requirements for the specific materials that will be used in the proposed concrete mixture. The extent of laboratory testing for any given job will depend on the project size and importance and on the service conditions involved.

A.2—Prequalification of materials

Tests on concrete materials and mixtures can serve the purpose of prequalification of ingredient materials and desired concrete performance properties for the purpose of establishing data required for a mixture submittal. Many of these tests may only need to be conducted annually, or less often when their purpose is for prequalification of materials and mixtures. These prequalification data can then be used for several jobs. For example, test data that establishes the potential of alkali-silica reactivity of an aggregate does not need to be tested for every job if the sources of materials and the mixture proportions do not change significantly.

A.3—Properties of cementitious materials

A.3.1 Physical and chemical characteristics of cementitious materials influence the properties of freshly mixed and hardened concrete. The laboratory should obtain records of material certifications from the supplier and other data on the uniformity of material characteristics from that source, such as reports for portland cement (ASTM C917/C917M). The only property of cementitious materials used directly in computation of concrete mixture proportions is specific gravity. The specific gravity of portland cements of the types covered by ASTM C150/C150M may usually be assumed to be 3.15 without introducing appreciable error in computations of mixture proportions. For other types such as blended hydraulic cements (ASTM C595/C595M; ASTM C1157/C1157M), slag cement (ASTM C989/C989M), fly ash or natural pozzolan (ASTM C618), or silica fume (ASTM C1240), the specific gravity for use in volume calculations can be obtained from the material certification provided by the supplier of the material or should be determined by test (ASTM C188; ASTM C311/C311M; ASTM C989/C989M).

A.3.2 Samples of cementitious materials should be obtained from the concrete producer or the materials supplier who will supply materials for the job. The sample should be of sufficient quantity for tests contemplated with a liberal margin for additional tests that might later be considered desirable. Samples of cementitious materials should be shipped in airtight and moisture-proof containers. Depending on the nature of the job and specifications, samples of the cementitious materials used for determining mixture proportions and from subsequent shipments may be saved in airtight containers for a reasonable period after the job has been completed to verify mixture characteristics if necessary.

A.3.3 The concrete producer might choose to conduct a variety of tests of cementitious materials for quality-control purposes. The intent of these tests may be for the purpose of optimizing mixtures for specific applications and seasonality and for ensuring compatibility of material ingredients for producing consistent concrete with predictable performance. These tests may be nonstandard tests (such as those for monitoring color or foam generation), or standard tests (such as making mortar cubes with concrete sand or full-fledged laboratory concrete mixtures in accordance with ASTM C192/C192M where setting characteristics, slump, entrained air content, strength, and other properties are monitored). The concrete producer should retain material certifications for all shipments of cementitious materials and uniformity reports of the predominant cement from a source (ASTM C917/C917M) and monitor changes in the reported characteristics such as compressive strength and material fineness.

A.4—Properties of aggregates

A.4.1 Sieve analyses, specific gravity, absorption, and moisture content of both fine and coarse aggregates (ASTM C127; ASTM C128) and bulk density by rodding (ASTM C29/C29M) of coarse aggregate are physical properties necessary for mixture proportioning computations. Other tests that may be desirable for large or special types of work include petrographic examination (ASTM C295/C295M) and tests for chemical reactivity (ASTM C1260; ASTM C1293), soundness (ASTM C88/C88M), durability, resistance to abrasion (ASTM C535), and various deleterious substances. Such tests yield information of value in judging the serviceability of concrete.

A.4.2 Aggregate grading determined by sieve analysis (ASTM C136/C136M) can influence water requirements, proportions of coarse and fine aggregate, and quantity of cementitious materials for satisfactory workability. Numerous aggregate grading curves have been proposed, and these, tempered by practical considerations, can be used as a tool for mixture proportioning optimization. ASTM C33/C33M provides a selection of sizes and gradings suitable for most concrete. Additional workability realized by use of air entrainment or supplementary cementitious materials (SCMs) such as fly ash and slag cement may permit, to some extent, the use of less-restrictive aggregate gradings and may accommodate the use of locally available material.

A.4.3 Aggregate samples for tests to determine characteristics for proportioning concrete mixtures should be representative of aggregate available for use in the work. For laboratory tests, the coarse aggregates should be separated into size fractions and recombined at the time of mixing to assure representative grading for the small test batches. Under some conditions, for work of important magnitude, laboratory investigations may involve efforts to overcome grading deficiencies of the available aggregates.

Undesirable sand grading may be corrected by:

(a) Separation of the sand into two or more size fractions and recombining in suitable proportions

(b) Increasing or decreasing the quantity of certain sizes to balance the grading

(c) Reducing excess coarse material by grinding or crushing

Undesirable coarse-aggregate gradings may be corrected by:

(a) Crushing excess coarser fractions

Table A.5.1—Typical test program to establish concrete-making properties of local materials

Batch quantities, lb/yd^3								Concrete characteristics				
Mixture No.	Cement	Sand	Coarse aggregate	Est. water	Used water	Total weight	*w/c*	Slump, in.	Density, pcf	Yield, ft^3	28-day compressive strength, psi	Work-ability
1	500	1375	1810	325	350	4035	0.70	4	147.0	27.45	—	Oversanded
2	500	1250	1875	345	340	3965	0.68	3	147.0	26.97	3350	OK
3	400	1335	1875	345	345	3955	0.86	4.5	145.5	27.18	2130	OK
4	450	1290	1875	345	345	3960	0.77	4	146.2	27.09	2610	OK
5	550	1210	1875	345	345	3980	0.63	3	147.5	26.98	3800	OK
6	600	1165	1875	345	345	3985	0.58	3.5	148.3	26.87	4360	OK

(b) Wasting sizes that occur in excess

(c) Supplementing deficient sizes with another intermediate aggregate

(d) A combination of these methods

Whatever grading adjustments are made in the laboratory should be practical and economically justified from the standpoint of full-size production and job operation. Aggregate grading requirements in specifications should be consistent with that of economically available materials.

Besides the aggregate grading, the particle shape and texture, particularly of manufactured fine aggregate, will have an important effect on the mixing-water requirements for target slump. Testing a graded sand to quantify changes in the particle shape and texture and relate these back to changes in mixing-water requirements for a target slump of a concrete mixture may prove useful (ASTM C1252).

A.5—Trial batch series

A.5.1 The tabulated and graphical relationships in the body of this document may be used to make preliminary estimates of batch quantities for trial batches. Optional steps to obtain a quick estimate of preliminary mixture proportions may be skipped, thereby proceeding more rapidly to trial batch evaluation, or the optional steps may be used to implement a more detailed procedure that incorporates more principles of concrete technology and potentially reduces the number of trial batches required. However, even when using the more detailed approach, the mathematical calculations that provide mixture proportions are still too generalized to apply with a high degree of accuracy to a specific set of materials. It is therefore necessary to make a series of concrete tests to establish quantitative relationships for the materials to be used. An illustration of such a test program is shown in Table A.5.1.

A.5.2 In the test program of Table A.5.1, a batch of medium cement content and usable consistency is proportioned by the described methods. In preparing Mixture No. 1, an amount of water is used that will produce the desired slump even if this differs from the targeted requirement. The freshly mixed concrete is tested for slump and density and observed closely for workability and finishing characteristics. In the example, the yield is too high, and the concrete is judged to contain an excess of fine aggregate.

A.5.3 Mixture No. 2 is prepared, adjusted to correct the material proportions in Mixture No. 1, and the testing and evaluation repeated. In this case, the desired fresh concrete properties are achieved within acceptable tolerances and cylinders are molded to check the compressive strength. The information derived so far can now be used to select proportions for a series of additional mixtures—No. 3 through 6—with cement contents above and below that of Mixture No. 2, encompassing the range likely to be needed.

A.5.4 Mixture No. 2 through 6 provide the background, including the relationship of strength to *w/c* for the particular combination of ingredients needed to select proportions for a range of specified requirements.

A.5.5 In laboratory tests, it seldom will be found, even by experienced operators, that desired adjustments will develop as smoothly as indicated in Table A.5.1. Furthermore, it should not be expected that full-size production batches and field results will compare exactly with laboratory results. Concrete producers will have a general idea, based on experience, on the difference in strength level and other characteristics between mixtures from laboratory batches and full-size production batches of similar mixture proportions. An adjustment of the selected laboratory trial batch, when moving to full-size production, is usually necessary. Another important aspect is to make adjustments for anticipated delivery time and jobsite adjustments, which are not generally simulated in laboratory batches. Closer agreement between laboratory and field results is more likely if machine mixing is employed in the laboratory. This is especially desirable for air-entrained concrete because the type of mixer, type of air-entraining admixture, and duration of mixing influence the amount of air entrained in the mixture. Before mixing the first batch, the laboratory mixer should be "buttered" or the mixture "over-mortared," as described in ASTM C192/C192M. Similarly, any processing of materials in the laboratory should simulate as closely as practicable the corresponding treatment in the field, such as the moisture conditioning of the aggregates.

A.5.6 The series of tests illustrated in Table A.5.1 may be expanded as the size and special requirements of the work warrant. Variables that may require investigation include alternative aggregate sources; maximum sizes and gradings; different types and brands of cement; the use of other cementitious materials; admixtures; and considerations of concrete durability, volume change, temperature rise, thermal properties, and time of set.

A.6—Test methods

A.6.1 In conducting laboratory tests to provide information for selecting concrete proportions, the latest revisions of the following methods should be used.

A.6.1.1 For tests of ingredients:

(a) Density of hydraulic cement—ASTM C188

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(b) Sampling stone, slag, gravel, and sand—ASTM D75/D75M

(c) Reducing samples of aggregate to testing size—ASTM C702/C702M

(d) Sieve analysis and fineness modulus of fine and coarse aggregates—ASTM C136/C136M

(e) Relative density (specific gravity) and absorption of coarse aggregates—ASTM C127

(f) Relative density (specific gravity) and absorption of fine aggregates—ASTM C128

(g) Surface moisture in fine aggregate—ASTM C70

(h) Total moisture content of aggregate by drying—ASTM C566 or a nonstandardized test such as the speedy moisture meter—ASTM D4944

(i) Bulk density (unit weight) and voids in aggregate—ASTM C29/C29M

(j) Uncompacted void content of fine aggregate (as influenced by particle shape, surface texture, and grading)—ASTM C1252

A.6.1.2 For tests of concrete:

(a) Air content of freshly mixed concrete by the volumetric method—ASTM C173/C173M

(b) Air content of freshly mixed concrete by the pressure method—ASTM C231/C231M

(c) Slump of hydraulic cement concrete—ASTM C143/C143M

(d) Density (unit weight), yield, and air content (gravimetric) of concrete—ASTM C138/C138M

(e) Temperature of freshly mixed portland-cement concrete—ASTM C1064/C1064M

(f) Making and curing concrete test specimens in the laboratory—ASTM C192/C192M

(g) Compressive strength of cylindrical concrete specimens—ASTM C39/C39M

(h) Flexural strength of concrete (simple beam with third-point loading)—ASTM C78/C78M

(i) Flexural strength of concrete (simple beam with center-point loading)—ASTM C293/C293M

(j) Splitting tensile strength of cylindrical concrete specimens—ASTM C496/C496M

(k) Capping cylindrical concrete specimens—ASTM C617/C617M

(l) Use of unbonded caps in determination of compressive strength of hardened concrete cylinders—ASTM C1231/C1231M

A.7—Mixtures for small jobs

A.7.1 For small jobs where time and personnel are not available to determine proportions in accordance with the recommended procedure, mixtures in Table A.7.1 will usually provide concrete that is of adequate strength and durability if the amount of water added at the mixer is not large enough to make the concrete with an excessively high slump. These mixtures have been predetermined in conformity with the recommended procedure by assuming conditions applicable to the average small job, and for aggregate of medium density. Three mixtures are given for each nominal maximum size of coarse aggregate. For the selected size of coarse aggregate, Mixture B is intended for initial use. If this mixture proves to be oversanded, change to Mixture C; if it is undersanded, change to Mixure A. It should be noted that the mixtures listed in the table are based on surface-dry sand. If the fine aggregate is moist or wet, make appropriate corrections in batch weights. Unless the lightweight aggregate is in fully saturated surface-dry (SSD) condition, consideration should be taken that lightweight aggregate might absorb water and water should be adjusted accordingly.

Table A.7.1—Concrete mixtures for small jobs

Procedure: Select the proper nominal maximum size of aggregate. Use Mixture B, adding just enough water to produce a workable consistency. If the concrete appears to be undersanded, change to Mixture A, and if it appears oversanded, change to Mixture C.						
		Approximate weights of solid ingredients per ft^3 of concrete, lb				
			Sand (SSD)[*]		Coarse aggregate (SSD)	
Nominal maximum size of aggregate, in.	Mixture designation	Cement	Air-entrained concrete[†]	Concrete without air entrainment	Gravel or crushed stone	Lightweight aggregate
1/2	A	25	48	51	54	47
	B	25	46	49	56	49
	C	25	44	47	58	51
3/4	A	23	45	49	62	54
	B	23	43	47	64	56
	C	23	41	45	66	58
1	A	22	41	45	70	61
	B	22	39	43	72	63
	C	22	37	41	74	65
1-1/2	A	20	41	45	75	65
	B	20	39	43	77	67
	C	20	37	41	79	69
2	A	19	40	45	79	69
	B	19	38	43	81	71
	C	19	36	41	83	72

[*] If damp sand is used, increase tabulated weights of sand 2 lb, and if very wet sand is used, 4 lb.

[†] Air-entrained concrete should be used in all structures exposed to alternate cycles of freezing and thawing. Air entrainment can be obtained by the use of an air-entraining cement or by adding an air-entraining admixture. If an admixture is used, the amount recommended by the manufacturer will, in most cases, produce the desired air content.

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A.7.2 The approximate cement content of concrete listed in the table will be helpful in estimating cement requirements for the job. These estimates apply to the use of portland cement only. These requirements are based on concrete that has just enough water to allow for a consistency that facilitates working into forms without objectionable segregation. An index of a good consistency is when the concrete slides, not runs, off a shovel.

APPENDIX B—HIGH-DENSITY CONCRETE MIXTURE PROPORTIONING

B.1—General

Concrete of normal placeability and workability can be proportioned for densities as high as 350 lb/ft^3 by using high-density aggregates such as iron ore, iron shot, steel shot, barite, iron punchings, and steel punchings. Although each of the materials has its own special characteristics, they can be processed to meet the standard requirements for grading, soundness, cleanliness, and other relevant aggregate properties. ACI 304.3R addresses high-density concrete in detail and should be consulted before attempting to proportion high-density concrete.

B.2—Aggregate selection

The selection of the aggregate should depend on the intended use of the concrete. For example, in the case of radiation shielding, trace elements within the material that may become reactive when subjected to radiation should be avoided. In the selection of materials and proportioning of high-density concrete, the data needed and procedures used are similar to those required for normal-density concrete. Aggregate density and composition for high-density concrete should meet requirements of ASTM C637 and ASTM C638. Typical materials used as high-density aggregates are listed in Table B.2.

B.3—Adjustment in anticipation of drying

If the concrete will be exposed to an environment that causes a significant loss of weight due to drying, it should be proportioned so that the fresh density is higher than the required density by the amount of the anticipated density loss due to drying. A conservative estimate of this density loss may be obtained by measuring the wet density and the oven-dry density of concrete cylinders as follows.

Cast three cylinders and determine the wet density in accordance with ASTM C138/C138M. After 72 hours of standard curing, dry the cylinders to a constant weight in an oven at 211 to 230°F and measure the average density. Calculate the density loss due to drying by subtracting the oven-dry density from the wet density.

Add this difference to the required dry density when calculating mixture proportions to allow for this loss. Less conservative methods of determining density loss may be appropriate depending on the application. Normally, a freshly mixed density (wet density) is 8 to 10 lb/ft^3 higher than the oven-dry density.

B.4—Adjustment for entrained air

If entrained air is required to resist conditions of exposure, allowance should be made for the loss in weight due to the volume occupied by the air. To compensate for the loss of entrained air as a result of vibration, the concrete mixture should be proportioned with higher air content.

B.5—Handling of high-density aggregates

Handling of high-density aggregates should be in accordance with ACI 304.3R (ASTM C637 and ASTM C638). Typical proportions are shown in ACI 304.3R.

B.6—Preplaced aggregate

High-density preplaced aggregate concrete should be proportioned in the same manner as normal-density preplaced aggregate concrete. Example mixture proportions for the preplaced aggregate method and for typical grout proportions can be found in ACI 304.3R.

B.6.1 *Example*—Concrete is required for counterweights on a lift bridge that will not be subjected to freezing-and-thawing conditions. An average 28-day compressive strength of 3500 psi will be required. Placement conditions permit a slump of 2 to 3 in. and a nominal maximum size aggregate of 1 in. The design of the counterweight requires

Table B.2—Typical high-density aggregates

Material	Description	Specific gravity	Resulting concrete density, lb/ft^3
Limonite and goethite	Hydrous iron ores	3.4 to 3.8	180 to 195
Barite	Barium sulfate	4.0 to 4.4	205 to 225
Ilmenite, hematite, and magnetite	Iron ores	4.2 to 5.0	215 to 240
Steel and iron	Shot, pellets, and punchings	6.5 to 7.5	310 to 350

Table B.6.1—Properties of selected aggregates

Property	Coarse aggregate	Fine aggregate
Material	Ilmenite	Specular hematite
Fineness modulus	N/A	2.30
Specific gravity	4.61	4.95
Absorption	0.08%	0.05%
Bulk density	165 lb/ft^3	N/A
Nominal maximum size	1 in.	N/A
Gradation	Well-graded	—
Particle shape	Cubical crushed	—

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an oven-dry density of 225 lb/ft^3 (the oven-dried condition is specified and is a more conservative value than that of the air-dried condition). An investigation of economically available materials has indicated the following:

(a) Cement: ASTM C150/C150M Type I

(b) Fine aggregate: specular hematite

(c) Coarse aggregate: ilmenite

(d) A high-range water-reducing admixture (HRWRA) will be used

Table B.2 indicates that this combination of materials may result in an oven-dry density of 215 to 240 lb/ft^3. As shown in Table B.6.1, the following properties of the aggregates have been obtained from laboratory tests.

The quantities of ingredients are calculated as follows.

B.6.1.1 *Step 1*—The detailed approach will be used.

B.6.1.2 *Step 2*—From Table 5.3.3, a concrete with a 2 to 3 in. slump and a 1 in. nominal maximum size aggregate requires a water content of approximately 315 lb/yd^3. As the aggregate is of normal particle shape and expected bulk densities, no adjustment in water content is made. No pozzolans are to be used, so no adjustment is made for their effects. Non-air-entrained concrete will be used because the concrete will not be exposed to severe weather and high air content would reduce the dry density of the concrete. Therefore, no reduction in water demand for air entrainment is made. After consulting the manufacturer of the HRWRA, a reduction of 25% in water demand is expected, so the water content is adjusted

$$w = \left(\frac{100\% - 25\%}{100\%}\right) \times 315 = 236 \text{ lb/yd}^3$$

and the volume of water is estimated as

$$V_{water} = \frac{w}{\rho_w} = \frac{236}{62.4} = 3.78 \text{ ft}^3\text{/yd}^3$$

B.6.1.3 *Step 3*—Because neither freezing-and-thawing exposure or sulfate exposure is anticipated, there are no recommended maximum values on *w/cm* for this concrete. There are no production records relevant to the concrete being proportioned; therefore, Table 4.7.4.1 is used to determine f_{cr}'

$$f_{cr}' = f_c' + 1200 \text{ psi} = 3500 + 1200 = 4700 \text{ psi}$$

From Table 5.3.4, interpolating between the aggregate size lines, *w/c* needed to produce this f_{cr}' in non-air-entrained concrete is found to be approximately 0.48. Thus, the required cement content is calculated to be

$$\text{Cement content } (c) = 236/0.48 = 492 \text{ lb/yd}^3$$

and the volume of cement is estimated to be

$$V_{cm} = \frac{\text{cement content}}{\text{specific gravity of cement} \times \text{ density of water}}$$

$$= \frac{492}{3.15 \times 62.4} = 2.50 \text{ ft}^3\text{/yd}^3$$

B.6.1.4 *Step 4*—The volume of air:

The estimated entrapped air from Table 5.3.3 is 1.5%.

V_{air} = 27 ft^3/yd^3 × % air in mixture

The cubic feet of air entrainment is 27.0 ft^3/yd^3 × 1.5% = 0.41 ft^3/yd^3

B.6.1.5 *Step 5*—The volume of aggregate to be provided is

$$V_{aggregate} = \frac{27 \text{ ft}^3}{\text{yd}^3} - (V_{water} + V_{cement} + V_{air}) =$$

$$27 - (3.78 + 2.50 + 0.41) = 20.31 \text{ ft}^3\text{/yd}^3$$

The fractional volume of coarse aggregate is estimated from Table 5.3.6 for a fine aggregate having a fineness modulus of 2.30 and found to be 0.72. Therefore, the oven-dry weight of coarse aggregate will be

$$\text{Fractional volume of coarse aggregate} \times \text{bulk density} \times 27 \text{ ft}^3\text{/yd}^3 = 0.72 \times 165 \times 27 = 3208 \text{ lb/yd}^3$$

The SSD weight of the coarse aggregate will be

$$\left(1 + \frac{A\%}{100\%}\right) \times m_{OD} = \left(1 + \frac{0.08}{100\%}\right) \times 3208 = 3211 \text{ lb/yd}^3$$

The volume fraction of the coarse aggregate will be

$$\frac{3211}{4.61 \times 62.4} = 11.16 \text{ ft}^3\text{/yd}^3$$

The volume fraction of the fine aggregate will be:

$$V_{aggregate} - V_{coarse\ aggregate} = 20.31 - 11.16 = 9.15 \text{ ft}^3\text{/yd}^3$$

The SSD weight of the fine aggregate will be

$$M_{SSD} = V_{fine\ aggregate} \times RD_{SSD} \times 62.4 \text{ lb/ft}^3 = 9.15 \times 4.95 \times 62.4 = 2826 \text{ lb/yd}^3$$

The anticipated wet density of the concrete will then be the weight of water, cement, coarse aggregate, and fine aggregate divided by the unit volume or

$$\frac{w + c + M_{SSD,coarse\ aggregate} + M_{SSD,\ fine\ aggregate}}{27 \text{ ft}^3\text{/yd}^3}$$

$$= \frac{236 + 492 + 3211 + 2826}{27} = 251 \text{ lb/ft}^3$$

The actual test results indicated the concrete possessed the following properties:

(a) Density (freshly mixed): 249 lb/ft^3

(b) Oven-dry density: 242 lb/ft^3

(c) Air content: 2.2%

(d) Slump: 2.5 in.

(e) Strength: 5000 psi at 28 days

Note: Oven-dry density of the concrete having a combination of hematite and ilmenite aggregates was 7 lb/ft^3 less than the freshly mixed density.

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