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Inch-Pound Units

SI

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

Reported by ACI Committee 211

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

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

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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 infiltration of aggressive solutions,

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 reportioned to include chemical admixtures, SCMs, or a different material source. The performance of the reportioned 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 light-

weight 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_{OD}	= oven-dry weight of sample, lb
m_{SSD}	= saturated surface-dry weight of sample, lb
$m_{w_{free}}$	= 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

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 $\text{psi}/\text{lb}/\text{yd}^3$, 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/ft³ (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/ft³ and as low as 50 lb/ft³ 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.

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 sieve nominal maximum 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 μ m), No. 50 (300 μ m), and No. 100 (150 μ m). 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 μ m) 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 concrete of the intended concrete (Ley et al. 2012).

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 $f_c', \text{ psi}$	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	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	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 $f_c', \text{ psi}$	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 $f_c', \text{ psi}$	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 $f_c', \text{ psi}$	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 $\pm 1.5\%$.

[†]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

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.

used. When such a relationship is available, the w/cm for the required average compressive strength can be chosen.

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