CHAPTER 19—CONCRETE: DESIGN AND DURABILITY REQUIREMENTS

CODE

19.1—Scope

19.1.1 This chapter shall apply to concrete, including:

(a) Properties to be used for design

(b) Durability requirements

19.1.2 This chapter shall apply to durability requirements for grout used for bonded tendons in accordance with 19.4.

19.2—Concrete design properties

19.2.1 *Specified compressive strength*

19.2.1.1 The value of f_c' shall be in accordance with (a) through (d):

(a) Limits for f_c' in Table 19.2.1.1. Limits apply to both normalweight and lightweight concrete.

(b) Durability requirements in Table 19.3.2.1

(c) Structural strength requirements

(d) f_c' for lightweight concrete in special moment frames and special structural walls, and their foundations, shall not exceed 5000 psi, unless demonstrated by experimental evidence that members made with lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normalweight concrete of the same strength.

Table 19.2.1.1—Limits for f_c'

Application	Minimum f_c', psi
General	2500
Foundations for structures assigned to SDC A, B, or C	2500
Foundations for Residential and Utility use and occupancy classification with stud bearing wall construction two stories or less assigned to SDC D, E, or F	2500
Foundations for structures assigned to SDC D, E, or F other than Residential and Utility use and occupancy classification with stud bearing wall construction two stories or less	3000
Special moment frames Special structural walls with Grade 60 or 80 reinforcement	3000
Special structural walls with Grade 100 reinforcement	5000
Precast-nonprestressed driven piles Drilled shafts	4000
Precast-prestressed driven piles	5000

19.2.1.2 The specified compressive strength shall be used for proportioning of concrete mixtures in 26.4.3 and for testing and acceptance of concrete in 26.12.3.

19.2.1.3 Unless otherwise specified, f_c' shall be based on 28-day tests. If other than 28 days, test age for f_c' shall be indicated in the construction documents.

COMMENTARY

R19.1—Scope

R19.2—Concrete design properties

R19.2.1 *Specified compressive strength*

Requirements for concrete mixtures are based on the philosophy that concrete should provide both adequate strength and durability. The Code defines a minimum value of f_c' for structural concrete. There is no limit on the maximum value of f_c' except as required by specific Code provisions.

Concrete mixtures proportioned in accordance with 26.4.3 should achieve an average compressive strength that exceeds the value of f_c' used in the structural design calculations. The amount by which the average strength of concrete exceeds f_c' is based on statistical concepts. When concrete is designed to achieve a strength level greater than f_c', it ensures that the concrete strength tests will have a high probability of meeting the strength acceptance criteria in 26.12.3. The durability requirements prescribed in Table 19.3.2.1 are to be satisfied in addition to meeting the minimum f_c' of 19.2.1. Under some circumstances, durability requirements may dictate a higher f_c' than that required for structural purposes.

Available test data do not include lower strength concrete with Grade 100 reinforcement in special structural walls (refer to R18.2.6).

For design of special moment frames and special structural walls used to resist earthquake forces, the Code limits the maximum f_c' of lightweight concrete to 5000 psi. This limit is imposed primarily because of a paucity of experimental and field data on the behavior of members made with lightweight concrete subjected to displacement reversals in the nonlinear range.

Minimum concrete strengths are increased for special seismic systems with $f_y > 80{,}000$ psi to enhance bar anchorage and reduce the neutral axis depth for improved performance.

The Code also limits f_c' for design of anchors to concrete. The requirements are in 17.3.1.

CODE

19.2.1.4 For pretensioned members, f'_{ci} shall be at least 3000 psi.

19.2.2 *Modulus of elasticity*

19.2.2.1 It shall be permitted to calculate E_c in accordance with (a) or (b):

(a) For values of w_c between 90 and 160 lb/ft^3

$$E_c = w_c^{1.5} 33\sqrt{f_c'} \text{ (in psi)} \quad (19.2.2.1.a)$$

(b) For normalweight concrete

$$E_c = 57{,}000\sqrt{f_c'} \text{ (in psi)} \quad (19.2.2.1.b)$$

19.2.2.2 It shall be permitted to specify E_c based upon testing of concrete mixtures to be used in the Work in accordance with (a) through (c):

(a) Specified E_c shall be used for proportioning concrete mixtures in accordance with 26.4.3.

(b) Testing to verify that the specified E_c has been achieved shall be conducted, and results shall be provided with the mixture submittal.

(c) Test age of measurement of E_c shall be 28 days or as indicated in the construction documents.

COMMENTARY

R19.2.2 *Modulus of elasticity*

R19.2.2.1 Equations in 19.2.2.1 provide an estimate of E_c for general design use. Studies leading to the expression for E_c of concrete are summarized in Pauw (1960), where E_c is defined as the slope of the line drawn from a stress of zero to 45 percent of the compressive strength using the stress-strain curve of the concrete. This definition is slightly different than the definition in ASTM C469. ASTM C469 defines E_c using 40% of the compressive strength.

The modulus of elasticity is sensitive to a number of variables including aggregate type, concrete constituents, mixture proportions, bond between paste and aggregate, and the age of the concrete. This sensitivity, coupled with the inherent variability in the properties of the constituent materials and quality control exercised during construction, can result in differences between measured and calculated values for deflection, drift, periods of vibration, and other quantities that depend on E_c. Refer to ACI PRC-435 for more information on the use of E_c, especially when used in deflection calculations.

Modulus of elasticity determined by calculation using the Code equations has been shown to be appropriate for most applications based on many years of use. For some applications, however, these equations may not provide sufficiently accurate estimates of actual values. Larger differences between measured and calculated values of E_c have been observed for high-strength concrete ($f_c' > 8000$ psi), lightweight concrete, and for mixtures with low coarse aggregate volume, as can occur with self-consolidating concrete. Refer to ACI PRC-363, ACI PRC-213, and ACI PRC-237 for more information.

R19.2.2.2 For any project, E_c used for design may be specified and verified by testing. Design conditions that are sensitive to the value of E_c may warrant testing. Examples include applications where deflections are critical, tall buildings or similar structures for which axial deformation or lateral stiffness impact performance, and where estimation of E_c is important to acceptable vibration or seismic performance.

In cases where an unintended change of stiffness may have an adverse effect on the design, such as for some seismic applications, the licensed design professional may choose to specify a range of acceptable values of E_c at a specified test age. If a range of values of E_c is specified, details of a testing program and acceptance criteria should be provided in the construction documents.

The licensed design professional may choose to specify laboratory testing of E_c at multiple ages. It should be recognized that the development of E_c over time cannot be controlled with precision.

CODE

19.2.3 *Modulus of rupture*

19.2.3.1 Modulus of rupture, f_r, for concrete shall be calculated by:

$$f_r = 7.5\lambda\sqrt{f_c'} \tag{19.2.3.1}$$

where the value of λ is in accordance with 19.2.4.

19.2.4 *Lightweight concrete*

19.2.4.1 Except as required in Table 25.4.2.5, the value of λ shall be determined using Table 19.2.4.1(a) based on the equilibrium density, w_c, of the concrete mixture used in design, or Table 19.2.4.1(b) based on the composition of the aggregate in the concrete mixture assumed in the design.

Table 19.2.4.1(a)—Values of λ for lightweight concrete based on equilibrium density

w_c, lb/ft^3	λ	
≤ 100	0.75	(a)
$100 < w_c \leq 135$	$0.0075w_c \leq 1.0$	(b)
>135	1.0	(c)

Table 19.2.4.1(b)—Values of λ for lightweight concrete based on composition of aggregates

Concrete	Composition of aggregates	λ
All-lightweight	Fine: ASTM C330 Coarse: ASTM C330	0.75
Lightweight, fine blend	Fine: Combination of ASTM C330 and C33 Coarse: ASTM C330	0.75 to 0.85[1]
Sand-lightweight	Fine: ASTM C33 Coarse: ASTM C330	0.85
Sand-lightweight, coarse blend	Fine: ASTM C33 Coarse: Combination of ASTM C330 and C33	0.85 to 1[2]

[1]Linear interpolation from 0.75 to 0.85 is permitted based on the absolute volume of normalweight fine aggregate as a fraction of the total absolute volume of fine aggregate.
[2]Linear interpolation from 0.85 to 1 is permitted based on the absolute volume of normalweight coarse aggregate as a fraction of the total absolute volume of aggregate.

19.2.4.2 It shall be permitted to take λ as 0.75 for lightweight concrete.

19.2.4.3 The value of λ shall be taken as 1.0 for normalweight concrete.

COMMENTARY

R19.2.4 *Lightweight concrete*

The modification factor λ is used to account for the reduced mechanical properties of lightweight concrete compared with normalweight concrete of the same compressive strength. For design using lightweight concrete, shear strength, friction properties, splitting resistance, bond between concrete and reinforcement, and development length requirements are not taken as equivalent to normalweight concrete of the same compressive strength. The methodology for determining λ was changed in the 2019 Code to include a new method that is based on the equilibrium density of the lightweight concrete. The new method allows the designer to select a value for λ based on the equilibrium density of the lightweight concrete that is used in design. Laboratory testing on the specific mixture to be used in the structure can be accomplished if the designer desires to determine a more accurate value of λ (Ivey and Buth 1967; Hanson 1961). Table 19.2.4.1 is based on data from tests (Graybeal 2014; Greene and Graybeal 2013, 2015) of concrete made with many types of structural lightweight aggregate and having a wide range of mixture proportions that resulted in equilibrium densities over a range of 90 to 135 lb/ft^3.

The second method for determining λ, which is retained from the previous code, is based on the composition of aggregates. In most cases, local concrete and aggregate suppliers have standard lightweight concrete mixtures and can provide the volumetric fractions to determine the value of λ. In the absence of such data, it is permissible to use the lower-bound value of λ for the type of lightweight concrete specified. This method is based on the assumption that, for equivalent compressive strength levels, the tensile strength of lightweight concrete is a fixed fraction of the tensile strength of normalweight concrete (Ivey and Buth 1967). The multipliers used for λ are based on data from tests on concrete made with many types of structural lightweight aggregate.

A previously included method to calculate λ based on splitting tensile strength and the corresponding value of measured compressive strength was removed from the Code in 2019.

In editions of the Code prior to 2019, the upper limit on the equilibrium density for lightweight concrete was 115 lb/ft^3. With the lower limit for normalweight concrete established at 135 lb/ft^3, a 20 lb/ft^3 range remained that was undefined. In practice, to achieve an equilibrium density in the range of 115 to 135 lb/ft^3, the use of some amount of light-

CODE

COMMENTARY

weight aggregate is required. The 2019 Code removes this undefined range by defining lightweight concrete as having an equilibrium density from 90 to 135 lb/ft^3.

19.3—Concrete durability requirements

R19.3—Concrete durability requirements

The Code addresses concrete durability on the basis of exposure categories and exposure classes as defined in Table 19.3.1.1. The licensed design professional assigns members in the structure to the appropriate exposure category and class. The assigned exposure classes, which are based on the severity of exposure, are used to establish the appropriate concrete properties from Table 19.3.2.1 to include in the construction documents.

The Code does not include provisions for especially severe exposures, such as acids or high temperatures.

19.3.1 *Exposure categories and classes*

R19.3.1 *Exposure categories and classes*

The Code addresses four exposure categories that affect the requirements for concrete to ensure adequate durability:

Exposure Category F applies to concrete exposed to moisture and cycles of freezing and thawing.

Exposure Category S applies to concrete in contact with soil or water containing deleterious amounts of water-soluble sulfate ions.

Exposure Category W applies to concrete in contact with water.

Exposure Category C applies to concrete exposed to conditions that require additional protection against corrosion of reinforcement because of exposure to moisture, with or without exposure to external sources of chlorides.

Severity of exposure within each category is defined by classes with increasing numerical values representing increasingly severe exposure conditions. A classification of 0 is assigned if the exposure severity has negligible effect (is benign) or the exposure category does not apply to the member.

The following discussion provides assistance for selecting the appropriate exposure class for each of the exposure categories. Members are required to be assigned to four exposure classes, one for each exposure category, and are also required to meet the most restrictive requirements of all of these exposures. For example, an exterior elevated slab subject to deicing salt application in a cold climate might be assigned to Exposure Classes F2, S0, W2, and C2.

Exposure Category F: Whether concrete is damaged by cycles of freezing and thawing depends on the amount of water in the pores of the concrete at the time of freezing (Powers 1975). The amount of water present may be described in terms of the degree of saturation of the concrete. If the degree of saturation is high enough, there will be sufficient water in the concrete pores to produce internal tensile stresses large enough to cause cracking when the water freezes and expands. The entire member need not be

CODE

COMMENTARY

saturated to be susceptible to damage. For example, if the top 3/8 in. of a slab or outer 1/4 in. of a wall is saturated, those portions are vulnerable to damage from freezing and thawing, regardless of how dry the interior may be.

For any portion of a member to be resistant to freezing and thawing, that portion of the concrete needs to have sufficient entrained air and adequate strength. Adequate strength is obtained by requiring a low *w/cm*, which also reduces the pore volume and increases resistance to water penetration. Entrained air makes it more difficult for the concrete to become saturated and allows for expansion of the water when it freezes.

Exposure class varies with degree of exposure to water, as this will influence the likelihood that any portion of the concrete will be saturated when exposed to cyclic freezing and thawing. Conditions that increase the potential for saturation include longer-duration or more-frequent contact with water without intervening drainage or drying periods. The likelihood that concrete in a member will be saturated depends on project location, member location and orientation in the structure, and climate. Records of performance of similar members in existing structures in the same general location can also provide guidance in assigning exposure classes. Various deicing chemicals can increase water absorption and retention (Spragg et al. 2011), which would enable the concrete to become saturated more readily, increasing the risk of freezing and thawing damage and scaling.

Plain concrete with minimal reinforcement and metallic embedments subjected to deicing chemical application assigned to Exposure Class F2 should also be assigned to Exposure Class C2.

Exposure Category F is subdivided into three exposure classes:

(a) Exposure Class F0 is assigned to concrete that will not be exposed to cycles of freezing and thawing.

(b) Exposure Class F1 is assigned to concrete that will be exposed to cycles of freezing and thawing and that will have limited exposure to water. Limited exposure to water implies some contact with water and water absorption; however, it is not anticipated that the concrete will absorb sufficient water to become saturated. The licensed design professional should review the exposure conditions carefully to support the decision that the concrete is not anticipated to become saturated before freezing. Even though concrete in this exposure class is not expected to become saturated, a minimum entrained air content of 3.5 to 6% is required to reduce the potential for damage in case portions of the concrete member become saturated.

(c) Exposure Class F2 is assigned to concrete that will be exposed to cycles of freezing and thawing and that will have frequent exposure to water. Frequent exposure to water implies that some portions of the concrete will absorb sufficient water such that over time they will have the potential to be saturated before freezing. If there is doubt about whether to assign Exposure Classes F1 or F2

CODE

COMMENTARY

to a member, the more conservative choice, F2, should be selected. If scaling is a concern, Exposure Class F2 is appropriate. Exposure Class F3 has been deleted in the 2025 edition of the Code as redundant because it is equivalent to a combination of Exposure Classes F2 and C2. Furthermore, Exposure Class F3 incorrectly implied that scaling is only possible in the presence of deicing chemicals.

Table R19.3.1 provides examples of concrete members for each of these exposure classes.

Table R19.3.1—Examples of structural members in Exposure Category F

Exposure class	Examples
F0	• Members in climates where freezing temperatures will not be encountered • Members inside structures and not exposed to freezing • Foundations not exposed to freezing • Members buried in soil below the design frost depth
F1	• Members not subject to ponding of water or snow and ice accumulation, such as exterior walls, beams, girders, and slabs not in direct contact with soil • Foundation walls likely to be saturated
F2	• Members subject to ponding of water or snow and ice accumulation, such as exterior elevated slabs • Foundation or basement walls extending above grade that have snow and ice buildup against them • Horizontal and vertical members in contact with soil above the design frost depth

Exposure Category S is subdivided into four exposure classes:

(a) Exposure Class S0 is assigned for conditions where the water-soluble sulfate concentration in contact with concrete is low and injurious sulfate attack is not a concern.

(b) Exposure Classes S1, S2, and S3 are assigned for structural concrete members in direct contact with soluble sulfates in soil or water. The severity of exposure increases from Exposure Class S1 to S3 based on the more critical value of measured water-soluble sulfate concentration in soil or the concentration of dissolved sulfate in water. Seawater exposure is classified as Exposure Class S1.

Exposure Category W is subdivided into three exposure classes:

(a) Members are assigned to Exposure Class W0 if they are dry in service.

(b) Members are assigned to Exposure Class W1 if they may be exposed to continuous contact with water, to intermittent sources of water, or can absorb water from surrounding soil. Members assigned to W1 do not require concrete with low permeability.

(c) Members are assigned to Exposure Class W2 if they may be exposed to continuous contact with water, to intermittent sources of water, or can absorb water from surrounding soil,

CODE

COMMENTARY

and if the penetration of water through the concrete might reduce durability or serviceability. Members assigned to W2 require concrete with low permeability.

Exposure Category C is subdivided into three exposure classes:

(a) Exposure Class C0 is assigned to concrete members not exposed to moisture in service.

(b) Exposure Class C1 is assigned to concrete members requiring protection against reinforcement corrosion due to exposure to moisture, but not to external sources of chlorides in service. Because of the potential exposure to moisture, the limits on water-soluble chloride ions in the concrete materials are more stringent for this exposure class than for Exposure Class C0.

(c) Exposure Class C2 is assigned to concrete members requiring additional protection against reinforcement corrosion or concrete degradation due to exposure to moisture and external sources of chlorides in service. Examples of exposure to external sources of chlorides include concrete in direct contact with deicing chemicals, salt, industrial chloride solutions, salt water, brackish water, seawater, spray from these sources, and airborne chlorides. Depending on prevailing winds, humidity, and geography, it is possible for airborne chlorides to reach inland up to 1 mile from the source, and sometimes farther. In cases of intracoastal or intercoastal waterways, salt lakes, and other chloride-containing bodies of water, there may not be significant quantities of airborne chlorides that would require Exposure Class C2. In cases such as islands surrounded by salt water or low-lying coastal regions with strong onshore winds, chloride exposure at greater distances may need to be addressed. ACI PRC-362.1 provides guidance for the consideration of exposure to external chlorides that extend up to 3 miles from the source. The licensed design professional should consider local conditions and the long-term chloride penetration and corrosion performance of existing structures to at least 1 mile from the source, and sometimes farther when establishing the corrosion exposure class.

19.3.1.1 The licensed design professional shall assign exposure classes in accordance with (a) and (b) and the severity of the anticipated exposure of members for each category in Table 19.3.1.1.

(a) Plain concrete exposed to freezing and thawing shall be assigned to Exposure Class F2 or Exposure Classes F2 and C2 depending on potential exposure to chlorides and the presence of reinforcement, embedments, or both.

(b) Concrete potentially susceptible to freezing and thawing scaling shall be assigned to Exposure Class F2 or Exposure Classes F2 and C2 depending on potential exposure to chlorides.

R19.3.1.1

(b) Scaling is local flaking or peeling away of the near-surface portion of hardened concrete or mortar. Horizontal concrete members that are subject to wetting are most susceptible to scaling. If exposed to an external source of chlorides from deicing or other chemicals, salts, brackish water, seawater, spray, or airborne chlorides from these sources, scaling will be exacerbated. Resistance to freezing

CODE

Table 19.3.1.1—Exposure categories and classes

Category	Class	Condition	
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles	
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water	
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water	
Sulfate (S)		Water-soluble sulfate (SO_4^{2-}) in soil, percent by mass[1]	Dissolved sulfate (SO_4^{2-}) in water, ppm[2]
	S0	$SO_4^{2-} < 0.10$	$SO_4^{2-} < 150$
	S1	$0.10 \leq SO_4^{2-} < 0.20$	$150 \leq SO_4^{2-} <$ 1500 or seawater
	S2	$0.20 \leq SO_4^{2-} \leq 2.00$	$1500 \leq SO_4^{2-} \leq$ 10,000
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10{,}000$
In contact with water (W)	W0	Concrete dry in service	
	W1	Concrete in contact with water where low permeability is not required	
	W2	Concrete in contact with water where low permeability is required	
Corrosion protection of reinforcement (C)	C0	Concrete dry or protected from moisture	
	C1	Concrete exposed to moisture but not to an external source of chlorides	
	C2	Concrete exposed to moisture and an external source of chlorides from deicing or other chemicals, salt, brackish water, seawater, spray, or airborne chlorides from these sources.	

[1]Percent sulfate by mass in soil shall be determined by ASTM C1580.

[2]Concentration of dissolved sulfates in water, in ppm, shall be determined by ASTM D516.

COMMENTARY

and thawing scaling requires appropriate selection of materials, proper finishing, and proper curing. Causes and prevention of scaling are discussed in ACI PRC-302.1 and ACI PRC-201.2.

19.3.2 *Requirements for concrete mixtures*

R19.3.2 *Requirements for concrete mixtures*

For the Exposure Classes addressed by the Code, durability is impacted by the resistance of the concrete to fluid or ion (chloride or sulfate) penetration. This resistance is primarily affected by the *w/cm* and the types of cementitious and supplementary cementitious materials used in the concrete. The Code provides limits on *w/cm* in Table 19.3.2.1 to achieve the intended durability. Combinations of the materials listed in Table 26.4.1.1.1(a) are also commonly used to improve durability. Refer to ACI PRC-201.2 for guidance on appropriate concrete mixtures for specific exposure conditions.

Because *w/cm* of concrete cannot be accurately verified in the field using standard test methods, strength tests are used as a surrogate. Representative values for minimum f_c' have been assigned to each *w/cm* limit in Table 19.3.2.1. The acceptance criteria for strength tests in 26.12 establish a basis to indicate that the maximum *w/cm* has not been exceeded. For this approach to be reliable, the values of f_c' specified in construction documents should be consistent with the maximum *w/cm*. Considering the wide range of

CODE | COMMENTARY

materials and concrete mixtures possible, including regional variations, the minimum f_c' limit in Table 19.3.2.1 associated with the maximum *w*/*cm* should not be considered absolute. The average strength of concrete mixtures for a given *w*/*cm* can in some cases be considerably higher than the average strength expected for the representative value of f_c'. For a given exposure class, the licensed design professional may choose to specify a higher value of f_c' than listed in the table to obtain better consistency between the maximum *w*/*cm* and f_c'. This improves the confidence that concrete complies with the *w*/*cm* limit if the strength acceptance criteria are satisfied.

As stated in the footnote to Table 19.3.2.1, maximum *w*/*cm* limits are not specified for lightweight concrete because the amount of mixing water that is absorbed by the lightweight aggregates makes calculation of *w*/*cm* uncertain. Therefore, only a minimum f_c' is specified to achieve the required durability.

Table 19.3.2.1 provides the requirements for concrete on the basis of the assigned exposure classes. The most restrictive requirements are applicable. For example, a member assigned to Exposure Class W1 and Exposure Class S2 would require concrete to comply with a maximum *w*/*cm* of 0.45 and a minimum f_c' of 4500 psi because the requirement for Exposure Class S2 is more restrictive than the requirement for Exposure Class W1.

Exposure Classes F1 and F2: In addition to complying with a maximum *w*/*cm* limit and a minimum f_c', strength for durability, concrete for members subject to freezing-and-thawing exposures is required to be air entrained in accordance with 19.3.3.1.

Exposure Classes S1, S2, and S3: Table 19.3.2.1 lists the appropriate types of cement and the maximum *w*/*cm* and minimum f_c' for various sulfate exposure conditions. In selecting cement for sulfate resistance, the principal consideration is its tricalcium aluminate (C_3A) content.

The use of fly ash (ASTM C618, Class F), natural pozzolans (ASTM C618, Class N), silica fume (ASTM C1240), or slag cement (ASTM C989) has been shown to improve the sulfate resistance of concrete (Li and Roy 1986; ACI PRC-233; ACI PRC-234). Therefore, Footnote [7] to Table 19.3.2.1 provides a performance option to determine the appropriate amounts of these materials to use in combination with the specific cement types listed. ASTM C1012 is permitted to be used to evaluate the sulfate resistance of mixtures using combinations of cementitious materials in accordance with 26.4.2.2(c).

Some ASTM C595 and ASTM C1157 blended cements can meet the testing requirements of 26.4.2.2.(c) without addition of pozzolans or slag cement to the blended cement as manufactured.

Note that sulfate-resisting cement will not increase resistance of concrete to some chemically aggressive solutions—for example, sulfuric acid. The construction documents should explicitly cover such cases.

CODE

COMMENTARY

In addition to the proper selection of cementitious materials, other requirements for durable concrete exposed to water-soluble sulfates are essential, such as *w/cm*, strength, consolidation, uniformity, cover of reinforcement, and moist curing to develop the potential properties of the concrete.

Exposure Class S1: ASTM C150 Type II cement is limited to a maximum C_3A content of 8 percent and is acceptable for use in Exposure Class S1. Blended cements under ASTM C595 with the MS designation, which indicates the cement meets requirements for moderate sulfate resistance, are also appropriate for use. Under ASTM C1157, the appropriate designation for moderate sulfate exposure is Type MS.

Seawater is listed under Exposure Class S1 (moderate exposure) in Table 19.3.1.1, even though it generally contains more than 1500 ppm SO_4^{2-}. Less expansion is produced by a given cement in seawater compared with freshwater with the same sulfate content (ACI 201.2R). Therefore, seawater is included in the same exposure class as solutions with lower sulfate concentrations. Portland cement with C_3A up to 10 percent is allowed in concrete mixtures exposed to seawater if the maximum *w/cm* is limited to 0.40 (refer to the footnote to Table 19.3.2.1).

Exposure Class S2: ASTM C150 Type V cement is limited to a maximum C_3A content of 5 percent and is acceptable for use in Exposure Class S2. The appropriate binary and ternary blended cements under ASTM C595 include the suffix (HS) as part of their designation, which indicates the cement conforms to requirements for high sulfate resistance. Under ASTM C1157, the appropriate designation for severe sulfate exposure is Type HS.

Exposure Class S3 (Option 1): The benefit of the addition of pozzolan or slag cement allows for a greater *w/cm* than required for Option 2. The amounts of supplementary cementitious materials are based on records of successful service or testing in accordance with 26.4.2.2(c).

Exposure Class S3 (Option 2): This option allows the use of ASTM C150 Type V portland cement meeting the optional limit of 0.040 percent maximum expansion, ASTM C595 binary and ternary blended cements with the (HS) suffix in their designation, and ASTM C1157 Type HS cements without the use of additional pozzolan or slag cement, but it instead requires a lower *w/cm* than that required for Option 1. This lower *w/cm* reduces the permeability of the concrete and thus increases sulfate resistance (Lenz 1992). Use of this lower *w/cm* permits a shorter testing period to qualify the sulfate resistance of a cementitious system in accordance with 26.4.2.2(c).

In addition to the proper selection of cementitious materials, other requirements for durable concrete exposed to water-soluble sulfates are essential, such as low *w/cm*, strength, adequate consolidation, uniformity, adequate cover of reinforcement, and sufficient moist curing to develop the potential properties of the concrete.

Exposure Class W1: This exposure class does not have specific requirements for low permeability. However,

CODE

COMMENTARY

because of the exposure to water, the Code (26.4.2.2(d)) has a requirement to demonstrate that aggregates used in concrete are not alkali reactive according to ASTM C1778. If the aggregates are alkali-silica reactive, the Code (26.4.2.2(d)) also requires submission of proposed mitigation measures. The Code (26.4.2.2(d)) prohibits the use of aggregates that are alkali-carbonate reactive.

Exposure Class W2: This exposure class requires low concrete permeability. The primary means to obtain a concrete with low permeability is to reduce *w/cm*. For a given *w/cm*, permeability can be reduced by optimizing the cementitious materials used in the concrete mixture. In addition, because of the exposure to water, the Code (26.4.2.2(d)) has a requirement to demonstrate that aggregates used in concrete are not alkali reactive according to ASTM C1778. If the aggregates are alkali-silica reactive, the Code (26.4.2.2(d)) also requires submission of proposed mitigation measures. The Code (26.4.2.2(d)) prohibits the use of aggregates that are alkali-carbonate reactive.

Exposure Class C2: For concrete in Exposure Class C2, the maximum *w/cm*, minimum specified compressive strength, and minimum cover are the basic requirements to be considered. Conditions should be evaluated for structures exposed to chlorides, such as in parking structures where chlorides may be tracked in by vehicles, or in structures near seawater. Coated reinforcement, corrosion-resistant steel reinforcement, corrosion-inhibiting admixtures, sealers, membranes, and cover greater than the minimum required in 20.5 can provide additional protection under such conditions. Use of slag cement meeting ASTM C989 or fly ash meeting ASTM C618 and higher values of specified compressive strength provide increased protection. Use of silica fume meeting ASTM C1240 with an appropriate high-range water reducing admixture conforming to ASTM C494, Types F and G, can also provide additional protection (Ozyildirim and Halstead 1988). The use of ASTM C1202 to test concrete mixtures proposed for use will provide additional information on their resistance to chloride ion penetration.

Chloride limits for Exposure Category C: For Exposure Classes C0, C1, and C2, the chloride ion limits apply to the chlorides contributed from the concrete materials, not from the environment surrounding the concrete. Even for Exposure Class C0, water-soluble chlorides introduced from the concrete materials can potentially induce corrosion of the reinforcement and must be limited for both nonprestressed and prestressed concrete, regardless of external exposure. For nonprestressed concrete, the permitted maximum amount of water-soluble chloride ions incorporated into the concrete, depends on the degree of exposure to an anticipated external source of moisture and chlorides. For prestressed concrete, the same limit of 0.06% chloride ion by mass of cementitious material applies regardless of exposure. The limits on chloride ion content for prestressed concrete are reduced from those for nonprestressed concrete because corrosion of prestressed reinforcement generally has more severe conse-

CODE

COMMENTARY

quences than corrosion of nonprestressed reinforcement. Corrosion-induced reduction in the cross-sectional area of the prestressed reinforcement may result in fracture of the steel (ACI PRC-222).

Some admixtures contain intentionally added chlorides, and many admixtures contain trace or background amounts of chlorides as an impurity in the ingredients. The Code does not impose limits on chloride ion content for admixtures. The total chloride ion content of admixtures measured by the supplier should be used when calculating the chloride ion content of concrete to meet the requirements of Table 19.3.2.1.

The presence of chloride ions may increase the corrosion rate of embedded aluminum such as conduits, especially if the aluminum is in contact with embedded steel and the concrete is in a humid environment (Woods 1966). Requirements for protecting aluminum embedments from corrosion are given in 20.6.3 and 26.8.2.

Allowable chloride limits are based on the mass of total cementitious materials rather than portland cement alone. This change was made in ACI CODE-318-19 to reflect findings that demonstrate the beneficial effects of supplementary cementitious materials (SCMs) in reducing permeability and binding chlorides, thus helping to inhibit corrosion (Wilson and Tennis 2021). Because there are diminishing chloride binding effects with increasing amounts of SCMs, the Code (26.4.2.2(d)) limits the mass of SCMs that can be used to calculate the allowable amount of chloride ions in concrete (Tepke et al. 2016).

Additional information on the effects of chlorides on the corrosion of steel reinforcement is given in ACI PRC-201.2, which provides guidance on concrete durability, and ACI PRC-222, which provides guidance on factors that impact corrosion of metals in concrete. Requirements for the evaluation of chloride ion content are provided in 26.4.2.2.

19.3.2.1 Based on the exposure classes assigned from 19.3.1, concrete mixtures shall conform to the requirements given in Table 19.3.2.1, and as indicated in (a) through (c):

(a) Specified compressive strength, f_c', shall be the greater of that required for structural design of the member and the greatest minimum f_c' in Table 19.3.2.1 assigned for durability considering all Exposure Categories.

(b) The chloride ion content of concrete mixtures shall meet the requirements of Table 19.3.2.1 as determined in accordance with 26.4.2.2(d).

(c) For plain concrete assigned to Exposure Class C2, the licensed design professional shall assign concrete requirements according to (i) through (iii) depending on potential exposure to chlorides and the presence of reinforcement, embedments, or both.

(i) Limit on water-soluble chloride ion content in concrete from those in Table 19.3.2.1

(ii) Maximum w/cm of 0.45

(iii) Minimum f_c' of 4500 psi

R19.3.2.1

(c) The requirements for plain concrete members in Exposure Class C2 may be relaxed because of the reduced likelihood of problems caused by reinforcement or embedment corrosion. The licensed design professional should consider the details of the minimal reinforcement and embedments to be included in plain concrete members to ensure that the less restrictive requirements are appropriate for the specific project.

CODE

Table 19.3.2.1—Requirements for concrete by exposure class

Exposure class	Maximum w/cm[1,2]	Minimum f_c', psi	Additional requirements			
			Air content			
F0	N/A	2500	N/A			
F1	0.55	3500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			
F2	0.45	4500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			
			Cementitious materials[3] — Types			
			ASTM C150	ASTM C595	ASTM C1157	Calcium chloride admixture
S0	N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1	0.50	4000	II[4][5]	Types with (MS) designation	MS	No restriction
S2	0.45	4500	V[5]	Types with (HS) designation	HS	Not permitted
S3 Option 1	0.45	4500	V plus pozzolan or slag cement[6]	Types with (HS) designation plus pozzolan or slag cement[6]	HS plus pozzolan or slag cement[6]	Not permitted
S3 Option 2	0.40	5000	V[7]	Types with (HS) designation	HS	Not permitted
W0	N/A	2500	None			
W1	N/A	2500	26.4.2.2(d)			
W2	0.50	4000	26.4.2.2(d)			
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by mass of cementitious materials			
			Nonprestressed concrete	Prestressed concrete		
C0	N/A	2500	1.00	0.06		
C1	N/A	2500	0.30	0.06		
C2[8]	0.40	5000	0.15	0.06		

[1]The *w/cm* is calculated on all cementitious and supplementary cementitious materials in the concrete mixture.
[2]The maximum *w/cm* limits do not apply to lightweight concrete.
[3]Alternative combinations of cementitious materials to those listed are permitted for all sulfate exposure classes when tested for sulfate resistance and meeting the criteria in 26.4.2.2(b).
[4]For seawater exposure, other types of portland cements with tricalcium aluminate (C_3A) contents up to 10 percent are permitted if the ***w/cm*** does not exceed 0.40.
[5]Other available types of cement such as Type I or Type III are permitted in Exposure Classes S1 or S2 if the C_3A contents are less than 8 percent for Exposure Class S1 or less than 5 percent for Exposure Class S2.
[6]The amount of the specific source of the pozzolan or slag cement to be used shall be at least the amount that has been determined by 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 cement to be used shall be at least the amount tested in accordance with ASTM C1012 and meeting the criteria in 26.4.2.2(b).
[7]If Type V cement is used as the sole cementitious material, the optional sulfate resistance requirement of 0.040 percent maximum expansion in ASTM C150 shall be specified.
[8]Concrete cover shall be in accordance with 20.5.1.4.

19.3.3 *Additional requirements for freezing-and-thawing exposure*

19.3.3.1 Concrete assigned to freezing-and-thawing Exposure Classes F1 and F2 shall be air entrained. Except as permitted in 19.3.3.6, air content shall conform to Table 19.3.3.1.

COMMENTARY

R19.3.3 *Additional requirements for freezing-and-thawing exposure*

R19.3.3.1 A table of required air contents for concrete to resist damage from cycles of freezing and thawing is included in the Code, based on guidance provided for proportioning concrete mixtures in ACI PRC-211.1. Entrained air will not protect concrete containing coarse aggregates that undergo disruptive volume changes when frozen in a saturated condition.

CODE

Table 19.3.3.1—Total air content for concrete exposed to cycles of freezing and thawing

Nominal maximum aggregate size, in.	Target air content, %	
	F1	F2
3/8	6.0	7.5
1/2	5.5	7.0
3/4	5.0	6.0
1	4.5	6.0
1-1/2	4.5	5.5
2	4.0	5.0
3	3.5	4.5

19.3.3.2 Concrete shall be sampled in accordance with ASTM C172, and air content shall be measured in accordance with ASTM C231 or ASTM C173.

19.3.3.3 Wet-mix shotcrete assigned to freezing-and-thawing Exposure Classes F1 or F2 shall be air entrained. Dry-mix shotcrete assigned to freezing-and-thawing Exposure Class F2 and corrosion protection Exposure Class C2 shall be air entrained. Except as permitted in 19.3.3.6, air content shall conform to Table 19.3.3.3.

Table 19.3.3.3—Total air content for shotcrete exposed to cycles of freezing and thawing

Mixture type	Sampling location	Target air content, %		
		F1	F2	F2 and C2
Wet-mix shotcrete	Before placement	5.0	6.0	6.0
Dry-mix shotcrete	In-place	N/A[1]	N/A[1]	4.5

[1]Entrained air is not required in dry-mix shotcrete for these exposure classes.

COMMENTARY

R19.3.3.2 The sampling of fresh concrete for acceptance based on air content is usually performed as the concrete is discharged from a mixer or a transportation unit (for example, a ready mixed concrete truck) to the conveying equipment used to transfer the concrete to the forms. ASTM C172 primarily covers sampling of concrete as it is discharged from a mixer or a transportation unit, but recognizes that specifications may require sampling at other points such as discharge from a pump. Table 19.3.3.1 was developed for testing as-delivered concrete. ASTM C231 is applicable to normalweight concrete and ASTM C173 is applicable to normalweight or lightweight concrete.

If the licensed design professional requires measurement of air content of fresh concrete at additional sampling locations, such requirements should be stated in the construction documents, including the sampling protocol, test methods to be used, and the criteria for acceptance.

R19.3.3.3 Adding air-entraining admixtures improves freezing-and-thawing resistance of wet-mix shotcrete (ACI PRC-506). Having air contents before placement as specified in Table 19.3.3.3 will provide required performance in freezing and thawing. Air contents greater than those specified will not improve shotcrete performance because once adequate air content for durability is achieved, there is no further benefit. As in all concrete, too much in-place air will reduce strength.

Dry-mix shotcrete without air entrainment has performed well in freezing-and-thawing environments with no exposure to saltwater or deicing salts (ACI PRC-506; Seegebrecht et al. 1989). For exposure to saltwater or deicing salts, air-entraining admixtures, in either a wet or dry form, can be added to dry-mix shotcrete to provide the required air content for durability in these exposures (Bertrand and Vezina 1994). The higher air content of wet-mix shotcrete sampled at the point of delivery accounts for expected air losses during shooting.

CODE

19.3.3.4 Wet-mix shotcrete shall be sampled in accordance with ASTM C172, and air content shall be measured in accordance with ASTM C231 or ASTM C173.

19.3.3.5 Dry-mix shotcrete shall be sampled and air content shall be measured as directed by the licensed design professional.

19.3.3.6 For $f_c' \geq 5000$ psi, reduction of air content indicated in Table 19.3.3.1 and 19.3.3.3 by 1.0 percentage point is permitted.

19.3.4 *Additional requirements for chloride ion content*

19.3.4.1 Nonprestressed concrete that will be cast against stay-in-place galvanized steel forms shall comply with the chloride ion limits for Exposure Class C1 unless a more stringent limit is required by other project conditions.

COMMENTARY

R19.3.3.5 If the licensed design professional requires measurement of air content of fresh dry-mix shotcrete, such requirements are to be stated in the construction documents, including the sampling frequency, sampling protocol, test methods to be used, and the criteria for acceptance.

The air content required for dry-mix shotcrete is for sampling of in-place shotcrete. This air content can be verified by taking cores from shotcrete test panels for analysis in accordance with ASTM C457. During the mixture development process, shotcrete test panels may be prepared with different amounts of air-entraining admixture and cored to determine a dosage that will provide the required amount of air after placement.

The use of ASTM C457 for quality control during construction is not practical. Although there are no standard tests for air content of dry-mix shotcrete during construction, there are industry accepted methods for testing. These methods involve obtaining samples of dry-mix shotcrete and performing standard tests such as ASTM C231 to determine air content.

Field measurements of air content of dry-mix shotcrete have been obtained by shooting the material directly into a bowl of an air meter (Betrand and Vezina 1994). Samples for air content testing can also be taken from material shot into test panels, into a wheelbarrow, or onto the ground. These samples can then be used for testing in accordance with ASTM C231 (Zhang 2015).

R19.3.3.6 This section permits a 1.0 percentage point lower air content for concrete with f_c' equal to or greater than 5000 psi. Such higher-strength concretes, which have a lower *w*/*cm* and porosity, have greater resistance to cycles of freezing and thawing.

R19.3.4 *Additional requirements for chloride ion content*

R19.3.4.1 Corrosion of galvanized steel sheet or stay-in-place galvanized steel forms may occur, especially in humid environments or where drying is inhibited by the thickness of the concrete, coatings, or impermeable coverings. If stay-in-place galvanized steel forms are used, the maximum chloride limit of 0.30% is required. For more severe environments, such as for concrete in Exposure Class C2, a more stringent limit of 0.15% would be required.

At the time of design, the licensed design professional may not know if aluminum embedments or stay-in-place galvanized steel forms will be used. Use of aluminum embedments is covered in 26.8.2. Use of stay-in-place galvanized steel forms is covered in 26.4.2.2.

CODE

19.4—Grout durability requirements

19.4.1 Water-soluble chloride ion content of grout for bonded tendons shall not exceed 0.06% when tested in accordance with ASTM C1218, measured by mass of chloride ion to mass of cementitious materials.

COMMENTARY

R19.4—Grout durability requirements