Selecting Exposure Classes and Requirements for Durability

Prescriptive and performance requirements

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For any concrete construction project, specifications may be overly conservative or not applicable to the project's exposure conditions—either of which could adversely impact sustainability, cost, constructability, serviceability, or service life. With the goal of maximizing value for project owners and society, this article provides guidance to help designers generate concrete specifications that minimize environmental impacts and result in economical, buildable, and durable structures.

Chapter 26 of ACI CODE-318-19(22)[1] requires that designers assign exposure classes for durability and specify applicable requirements for concrete mixtures for structural members in buildings. ACI SPEC-301-20[2] incorporates these Code requirements in the ACI reference specification. This article summarizes those requirements and also offers performance alternatives to the water-cementitious materials ratio (*w/cm*) requirements in the Code.

If the designer chooses to use performance requirements, these must be specified as substitutions rather than additions to the prescriptive limits. In some cases, the designer should determine the process of validating that proposed mixtures comply with the intent and may need to establish acceptance criteria. The article provides two case examples to clarify the process. An Excel spreadsheet that can help designers select the appropriate exposure class and the corresponding concrete requirements has been recently developed.[3]

Exposure and Concrete Requirements

ACI CODE-318-19(22) covers requirements for concrete materials and mixtures in Chapter 19. This chapter defines the exposure categories and classes for durability and the requirements for concrete. Details that the designer must address in the construction documents are covered in Chapter 26.

The primary intent of the durability requirements for concrete is to minimize the permeability of concrete to water and dissolved chemicals that can cause durability problems. This is addressed by requiring a maximum *w/cm* and a minimum specified strength. Because *w/cm* cannot be reliably verified, the strength requirement serves as an acceptance criterion. If durability requires a higher strength than that needed for structural capacity, this higher strength can be used to advantage when designing a member.

Assigning durability exposure classes is part of the design process, and it is the responsibility of the Licensed Design Professional (LDP) to assess the severity of exposure for each type of concrete member. The LDP can opt for a performance alternative for concrete mixtures that meet the intent of the Code such as a performance test to measure the permeability of concrete instead of the *w/cm* and specified strength. Section 1.10 of the Code addresses the consideration of alternate systems of design, construction, or construction materials and tests not covered by the Code.

Exposure classes must be assigned for each of the four categories specified in the Code:

- F for exposure to freezing-and-thawing cycles;
- S for exposure to water-soluble sulfates in soil;
- W for concrete members in contact with water; and
- C for concrete members requiring protection from corrosion of reinforcement.

Typically, the most benign exposure classes are assigned for interior concrete members. Some interior members can require consideration for durability, most commonly related to an exposure to moisture. For example, boiler rooms, textile plants, plating facilities, or food-manufacturing facilities can be impacted by the corrosion of embedded steel. Kitchens, shower areas, laundries, or other similar areas exposed to moisture in service may be susceptible to alkali-silica reaction (ASR). An interior slab-on-ground that is placed on a goodquality vapor retarder can be considered to be isolated from the ground and moisture but may be exposed to freezing and thawing during construction. Requiring air content for such slabs can cause delamination problems, if slabs are troweled, and the content of cementitious material may need to be increased to achieve the required strength detracting from sustainability goals. Instead, these concrete surfaces should be protected from exposure to cycles of freezing and thawing during construction.

Freezing and thawing

The Code requires that concrete members expected to be exposed to cyclic freezing and thawing be air-entrained. The required air content depends on the severity of the exposure and the aggregate size. Larger-size aggregate requires a lower air content because the cementitious paste volume is lower. Concrete that has a higher potential for saturation when subject to freezing-and-thawing cycles (more severe) requires a higher air content. Requiring a higher air content than that stated does not improve durability and typically leads to increases in cement content to meet structural requirements. If the specified strength is equal to or greater than 5000 psi, the specified air content can be reduced from those in Table 19.3.1.1 in the Code by 1%. Maximum limits on *w/cm* are intended to reduce the potential for concrete to become saturated.

Exposure classes for Exposure Category F can be selected as follows:

- If the concrete member will not be exposed to freezing-and-thawing cycles, select F0.
  Commentary Table R19.3.1 includes the following examples for assigning members to F0:
  - Members in climates where freezing temperatures will not be encountered;
  - Members that are inside structures and will not be exposed to freezing;
  - Foundations not exposed to freezing; and
  - Members that are buried in the soil below the frost line.
- If concrete members will be exposed to freezing-and-thawing cycles with limited exposure to water, select F1. Commentary Section R19.3 indicates that 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. Commentary Table R19.3.1 lists the following examples for assigning members to F1:
  - Members that will not be subject to snow and ice accumulation, such as exterior walls (vertical members), beams, girders, and slabs not in direct contact with soil; and
  - Foundation walls depending upon their likelihood of being saturated.
- If concrete members will be exposed to freezing-and-thawing cycles with frequent exposure to water, select F2. Commentary Section R19.3 indicates that 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 F1 or F2 to a member, the more conservative choice, F2, should be selected. F1 and F2 are conditions where exposure to deicing chemicals is not anticipated. Commentary Table R19.3.1 provides the following examples for assigning members to F2:
  - Members that will be subject to snow and ice accumulation, such as exterior elevated slabs;
  - Foundation or basement walls extending above grade that have snow and ice buildup against them; and
  - Horizontal and vertical members in contact with soil.
- If concrete members will be exposed to freezing-and-thawing cycles with frequent exposure to water and deicing chemicals, select F3.
  Commentary Table R19.3.1 provides the following examples for assigning members to F3:
  - Members exposed to deicing chemicals, such as horizontal members in parking structures; and
  - Foundation or basement walls extending above grade that can experience accumulation of snow and ice with deicing chemicals.

For members assigned to F1, F2, and F3, select the maximum *w/cm*, minimum specified compressive strength, and air content from Table 19.3.2.1, respectively (see Tables 1 and 2). Limits on the quantity of supplementary cementitious materials (SCMs) listed in Table 26.4.2.2(b) apply to F3, that is, concrete with frequent exposure to water and deicing chemicals (see Table 3). These limits should not be specified for other concrete mixtures as they can adversely impact the ability to achieve durable concrete.

Note that the *w/cm* and strength requirements for F3 are intended for reinforced and prestressed concrete members and are intended to be consistent with the requirements for C2 (that is, exposed to an external source of chlorides). Plain concrete is defined as structural concrete with no reinforcement or with less reinforcement than the minimum amount specified for reinforced concrete in the applicable building code.

Sulfate exposure

Sulfate resistance of concrete depends on the sulfate resistance of the cementitious materials used and the *w/cm* that minimizes the penetration of sulfates into concrete. Determine the sulfate concentration in soil, in percent by mass, in accordance with ASTM C1580[7] or the concentration of dissolved sulfates in water, in ppm, in accordance with ASTM D516[8] or ASTM D4130.[9] Select the appropriate sulfate exposure class based on these exposures (see Table 4). Members in contact with seawater must be assigned to S1. Because seawater represents exposure to an external source of chlorides, the requirements for *w/cm* and specified strength for C2 will govern.

Table 1:
Requirements for concrete exposed to freezing and thawing (based on Table 19.3.2.1)

Exposure class	Maximum w/cm*	Minimum f'_c, psi	Additional minimum requirements	
			Air content	Limits on SCM
F0	N/A	2500	N/A	N/A
F1	0.55	3500	Table 19.3.3.1	N/A
F2	0.45	4500	Table 19.3.3.1	N/A
F3	0.40†	5000†	Table 19.3.3.1	Table 26.4.2.2(b)

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

†For plain concrete, the maximum w/cm shall be 0.45 and the minimum f'_c shall be 4500 psi

Table 2:
Total air content for concrete exposed to cycles of freezing and thawing (based on Table 19.3.3.1)

Nominal maximum aggregate size, in.	Target air content, %	
	F1	F2 and F3
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

Note: Specified air content can be reduced by 1% when $f'_c \geq 5000$ psi

Table 3:
Limits on cementitious materials for concrete assigned to Exposure Class F3 (based on Table 26.4.2.2(b))

SCM	Maximum total by mass, %
Fly ash or other pozzolans conforming to ASTM C618[4]	25
Slag cement conforming to ASTM C989/C989M[5]	50
Silica fume conforming to ASTM C1240[6]	10
Total of fly ash or other pozzolans and silica fume	35
Total of fly ash or other pozzolans, slag cement, and silica fume	50

From Table 19.3.2.1, select maximum w/cm, minimum specified compressive strength, and type of cementitious materials for S1, S2, and S3 (see Table 5). Using SCMs such as Class F fly ash, slag cement, silica fume, and some natural pozzolans improves the sulfate resistance of the cementitious systems. Type V cement is not available in most of the United States. The Code does recognize successful service history for types of cementitious materials used. Do not restrict cementitious materials to the types listed in Table 5 (see footnote ||). Do not permit calcium chloride admixtures, typically used as accelerating admixtures, for S2 and S3.

For S3, Table 26.4.2.2(c) provides two options—a lower w/cm can be specified with a less sulfate-resistant cementitious system (see Table 6). This also reduces the test age from 18 to 12 months for qualifying a sulfate-resistant cementitious system in accordance with ASTM C1012/C1012M.[13]

Section 26.4.2.2(c) provides an alternative performance evaluation of the combination of cementitious materials by testing in accordance with ASTM C1012/C1012M to achieve the stated expansion criteria. Note that the same criteria are used to determine the (MS) and (HS) special property for blended cements (ASTM C595/C595M and ASTM C1157/C1157M).

Water exposure and alkali-aggregate reactivity

This exposure category relates to concrete in contact with water.

Table 4:
Exposure classes for sulfate exposure (based on Table 19.3.1.1)

Exposure category	Exposure class	Condition	
		Water-soluble sulfate (SO_4^{2-}) in soil, % by mass*	Dissolved sulfate (SO_4^{2-}) in water, ppm†
Sulfate (S)	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	$0.20 \leq SO_4^{2-} < 2.00$	$150 \leq SO_4^{2-} < 1500$
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10,000$

*Percent sulfate by mass in soil shall be determined by ASTM C1580

†Concentration of dissolved sulfates in water, in ppm, shall be determined by ASTM D516 or ASTM D4130

Members in contact with water either require a reduced permeability for their service condition or not. If members are in contact with water, the LDP has to address requirements for alkali-aggregate reaction (AAR). The Code does not provide any criteria for AAR, but Commentary Section R26.4.2.2(d) refers the LDP to ASTM C1778,[14] which is a comprehensive guide to AAR.

Exposure classes for concrete exposed to water are determined as follows:

- If the concrete member will be dry in service, select W0. This will be consistent with selecting C0.
- If the concrete member will be in contact with water where low permeability is not required, select W1. This will be consistent with selecting C1.
- Commentary Section 19.3.2.1 advises assigning W1 or W2 to members that may be exposed to continuous contact with water, to intermittent sources of water, or can absorb water from the surrounding soil. If these members do not require concrete with low permeability, assign W1.
- If the concrete member will be in contact with water where low permeability is required, select W2. Select the maximum *w/cm* and minimum specified compressive strength for members assigned to W2 (see Table 7).
- Commentary Section 19.3.2.1 suggests assigning W2 if the penetration of water through the concrete will reduce its durability or serviceability.

Table 5:
Requirements for concrete exposed to sulfates (based on Table 19.3.2.1)

Exposure class		Maximum *w/cm*[*,†]	Minimum f'_c, psi	Additional minimum requirements			
				Cementitious materials[‡] – Types			
				ASTM C150/C150M[10]	ASTM C595/C595M[11]	ASTM C1157/C1157M[12]	Calcium chloride admixture
S0		N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1		0.50	4000	II[§,#]	Types with (MS) designation	MS	No restriction
S2		0.45	4500	V[#]	Types with (HS) designation	HS	Not permitted
S3	Option 1	0.45	4500	V plus pozzolan or slag cement[‖]	Types with (HS) designation plus pozzolan or slag cement[‖]	HS plus pozzolan or slag cement[#]	Not permitted
	Option 2	0.40	5000	V[**]	Types with (HS) designation	HS	Not permitted

[*]The *w/cm* is on all cementitious and SCMs in the concrete mixture

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

[‡]Alternative combinations of cementitious materials to those are permitted when tested for sulfate resistance and meeting the criteria in Section 26.4.2.2(c)

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

[#]Other available types of cement such as Type I or Type III are permitted in S1 or S2 if the C_3A contents are less than 8% for S1 or less than 5% for S2

[‖]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 the service record to improve sulfate resistance when used in concrete containing Type V cement

[**]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 shall be specified

Table 6:
Requirements for establishing suitability of combinations of cementitious materials for Exposure Category S (based on Table 26.4.2.2(c))

Exposure class		Maximum expansion strain if tested using ASTM C1012/C1012M, %		
		At 6 months	At 12 months	At 18 months
S1		0.10	No requirement	No requirement
S2		0.05	0.10[*]	No requirement
S3	Option 1	No requirement	No requirement	0.10
	Option 2	0.05	0.10[*]	No requirement

[*]The 12-month expansion limit applies only if the measured expansion exceeds the 6-month maximum expansion limit

For members assigned to W1 and W2, Section 26.4.2.2(d) states a compliance requirement for submitted evidence that the aggregates are not alkali-silica reactive, or that measures to mitigate ASR have been established. The use of aggregates that are alkali-carbonate reactive is prohibited.

The LDP is referred to ASTM C1778, a comprehensive document that goes through the process of determining the reactivity level of aggregates, exposure conditions, and risk level of occurrence of ASR in a structure and recommends prescriptive and performance alternatives for mitigation.

ACI SPEC-301-20, Section 4.2.2.6(a), and MasterSpec[15] provide simplified specification requirements for mitigating ASR with the following options:

- For each aggregate used in concrete, the expansion result determined in accordance with ASTM C1293[16] shall not exceed 0.04% at 1 year;
- For each aggregate used in concrete, the expansion result of the aggregate and cementitious materials combination determined in accordance with ASTM C1567[17] shall not exceed 0.10% at an age of 16 days. Submit supporting data for each aggregate showing expansion in excess of 0.10% at 16 days when tested in accordance with ASTM C1260[18]; and
- Alkali content in concrete, excluding that from SCMs and pozzolan and slag cement in blended cements, shall not exceed 4 lb/yd^3 for aggregate with expansion greater than or equal to 0.04% and less than 0.12%, or not exceed 3 lb/yd^3 for aggregate with expansion greater than or equal to 0.12% and less than 0.24%. Reactivity shall be determined by testing in accordance with ASTM C1293. (Note: Alkali content in concrete is determined by the product of the equivalent alkali content of portland cement and the portland cement content in concrete in lb/yd^3.)

Table 7:
Requirements for concrete exposed to water (based on Table 19.3.2.1)

Exposure class	Maximum *w/cm**	Minimum f'_c, psi	Additional requirements
W0	N/A	2500	None
W1	N/A	2500	26.4.2.2(d)
W2	0.50	4000	26.4.2.2(d)

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

Corrosion protection of reinforcement

Corrosion of reinforcement is a significant durability concern for concrete members. Corrosion initiates when chlorides or carbonation negate the passivation provided by the high pH of concrete surrounding reinforcing steel. The provisions establish limits on water-soluble chlorides in concrete mixtures (from the materials used) and require the use of concrete mixtures with lower permeability if the member is exposed to an external source of chlorides. The LDP is also advised to increase clear cover to the reinforcement when there are external chlorides to delay the initiation of corrosion. Other means, such as the use of corrosion-inhibiting admixtures, coatings, and coated or noncorrosive reinforcement, can be additionally adopted.

The first two exposure classes are like those for Exposure Category W. The exposure class selection is as follows:

- If the concrete member will be dry or protected from moisture, select C0. This will be consistent with selecting W0;
- If the concrete member will be exposed to moisture but not to an external source of chlorides, select C1. This will be consistent with selecting W1; and
- If the concrete member will be exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources, select C2.

Once the exposure class is determined, specify the minimum compressive strength, limits for water-soluble chloride content for concrete mixtures, and maximum *w/cm*, as well as cover to reinforcement for members assigned to C2 (see Table 8).

Table 8:
Requirements for corrosion protection of concrete (based on Table 19.3.2.1)

Exposure class	Maximum *w/cm**	Minimum f'_c, psi	Additional requirements		
			Maximum water-soluble chloride ion (Cl^-) content in concrete, % by mass of cementitious materials†,‡		Additional provisions
			Nonprestressed concrete	Prestressed concrete	
C0	N/A	2500	1.00	0.06	None
C1	N/A	2500	0.30	0.06	None
C2	0.40	5000	0.15	0.06	Concrete cover§

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

†The mass of SCMs used in determining the chloride content shall not exceed the mass of the cement

‡Criteria for determination of chloride content are in Section 26.4.2.2

§Concrete cover shall be in accordance with Section 20.5

Section 26.4.2.2 indicates that compliance with the specified chloride ion content limits shall be demonstrated by:

- Calculating the total chloride ion content of the concrete mixture on the basis of the measured total chloride ion content from concrete materials and concrete mixture proportions; or
- Determining the water-soluble chloride ion content of hardened concrete in accordance with ASTM C1218/C1218M[19] at an age between 28 and 42 days.

Section 20.5 includes minimum requirements for cover, but has some specific requirements for members in severe exposure or members assigned to C2. Commentary Section R19.3.2 states: "Coated reinforcement, corrosion-resistant steel reinforcement, and cover greater than the minimum required in 20.5 can provide additional protection under such conditions." The relevant parts of Section 20.5 for members in severe exposure conditions include:

- "In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary." (Section 20.5.1.4.1)
- "Additionally, for corrosion protection, a specified concrete cover for reinforcement not less than 2 in. for walls and slabs and not less than 2-1/2 in. for other members is recommended. For precast concrete members manufactured under plant control conditions, a specified concrete cover not less than 1-1/2 in. for walls and slabs and not less than 2 in. for other members is recommended." (Commentary Section R20.5.1.4.1)
- "For prestressed concrete members classified as Class T or C in 24.5.2 and exposed to corrosive environments or other severe exposure categories such as those given in 19.3, the specified concrete cover for prestressed reinforcement shall be at least one and one-half times the cover in 20.5.1.3.2 for cast-in-place members and in 20.5.1.3.3 for precast members." (Section 20.5.1.4.2)
- "If the precompressed tension zone is not in tension under sustained loads, 20.5.1.4.2 need not be satisfied." (Section 20.5.1.4.3)

In summary

Specify strength that is higher than that required for structural design or durability based on assigned exposure classes. Specify strength at 28 days or other test age. If anticipated loading is later, a later test age, such as 56 or 90 days, may be specified. This permits the use of more sustainable concrete mixtures. If an early-age strength is required for construction, the strength at the later test age can be significantly greater than that required for loads.

Select *w/cm* only if in-service durability exposure conditions apply to the structural member. Select the lowest *w/cm* as required for the assigned durability exposure classes. Make sure that the *w/cm* is consistent with the specified compressive strength. If these are not consistent, acceptance based on strength will not assure that the *w/cm* is being achieved. A comprehensive list of items that should be considered in the specification is covered in Section 26.4.2.2.

Performance Alternative to *w/cm*

Durability of concrete is impacted by the resistance of the concrete to fluid penetration or its permeability. A high rate of water absorption in concrete will increase the degree of saturation making concrete less resistant to freezing-and-thawing cycles, thereby accelerating the deterioration. Similarly, penetration of sulfates or chlorides will result in sulfate attack and corrosion of steel reinforcement in concrete.

Currently, industry standards (ACI CODE-318-19(22) and ACI SPEC-301-20) provide limits on *w/cm* to achieve low permeability and the intended durability. With the same *w/cm*, concrete mixtures containing fly ash, slag cement, silica fume, other pozzolanic materials, or a combination of these materials will experience reduced permeability (increased resistance to fluid penetration) and improved durability. We believe that the use of SCMs to reduce permeability is not given appropriate credit in the Code.

Conductivity and resistivity

ASTM C1202[20] and ASTM C1876[21] are used to determine the conductivity or resistivity of concrete, respectively. These electrical properties have been correlated to the rate of chloride ingress. A lower charge passed, measured in coulombs per ASTM C1202, or a higher resistivity, measured in Ω·m per ASTM C1876, represents reduced penetrability. These tests could be used as an alternative to specifying *w/cm* when reduced permeability is required. This is typically done by performing the test on the proposed mixture and documenting the result with a submittal. The specimens should ideally be tested after 56 days of curing in laboratory conditions. A longer curing period allows for the SCMs to demonstrate effectiveness in reducing the permeability of concrete. ASTM C1202 includes an accelerated curing procedure for 28 days that should be used for mixtures containing SCMs if 56-day curing is not feasible.

Results from these test methods, especially ASTM C1202, can be variable and are very sensitive to specimen curing and care. If improper practices are followed in the field for curing test specimens (as is common for strength specimens), the results will not be reliable. It is suggested that these tests be used as a means to prequalify mixtures (approved based on a submittal), and strength is used as the jobsite acceptance process. If it is proposed to use these tests for acceptance purposes, a statistical approach should be used. Such a statistical approach is discussed in the article in the May 2007 issue of *Concrete International*.[22]

If performance tests in accordance with ASTM C1202 or C1876 are proposed to be used on a project, a maximum *w/cm* for concrete mixtures should not be specified. Instead, the following conductivity (ASTM C1202) or resistivity (ASTM C1876) limits associated with a specific *w/cm* should be considered in specifications:

- For ASTM C1202:
  - w/cm = 0.55 → Maximum 3000 coulombs
  - w/cm = 0.50 → Maximum 2500 coulombs
  - w/cm = 0.45 → Maximum 2000 coulombs
  - w/cm = 0.40 → Maximum 1500 coulombs
- For ASTM C1876:
  - w/cm = 0.55 → Minimum 60 Ω·m
  - w/cm = 0.50 → Minimum 72 Ω·m
  - w/cm = 0.45 → Minimum 90 Ω·m
  - w/cm = 0.40 → Minimum 120 Ω·m

Drying shrinkage

For some types of structural members where shrinkage is a concern because of the potential for cracking or curling that may impact functionality or reduces durability, shrinkage requirements may be considered. The test method typically specified is ASTM C157/C157M.[23] Specimen size is 3 x 3 x 10 in. but larger specimens of 4 x 4 x 10 in. may be used for concrete containing aggregates larger than 1 in. Specimens are immersed in saturated lime water for 7 days and then placed in an environment of 73 ± 3°F and 50% relative humidity (RH) for 28 days (for a test age of 35 days). Compliance with this requirement is done during prequalification and documented in a submittal. Three test specimens are used and the length change of each is averaged for the test result. This test should not be performed on samples obtained at the jobsite.

To minimize the potential for shrinkage cracking, specify a length change limit of 0.04 or 0.05% when tested in accordance with ASTM C157/C157M. Specimens should be prepared in the laboratory in accordance with provisions in ASTM C192/C192M.[24] The testing agency performing this test should be proficient and preferably have this test method included in the scope of accreditation.

Modulus of elasticity

The empirical relationship between f_c' and modulus of elasticity E_c in the Code is adequate for most design purposes. This equation is less accurate to estimate E_c for high-strength concrete ($f_c' > 8000$ psi). Design conditions that are sensitive to E_c may warrant testing. Examples include applications where deflections are critical, tall buildings or similar structures for which axial deformation or lateral stiffness impacts performance, and where estimation of E_c is important for acceptable vibration or seismic performance.

The Code requires the measured E_c to be documented to the designer in a submittal, if specified. E_c should be measured in accordance with ASTM C469/C469M[25] and the measured result, the average of three specimens, should be equal to or exceed the specified value.

The Code does not provide acceptance criteria for E_c tests performed on concrete samples obtained and prepared at the jobsite. Per Commentary Section R19.2.2.2, if designers require these tests, they should state the appropriate acceptance criteria. When tests will be made on jobsite samples, it should be ensured that the testing agency selected is proficient in performing these tests and the producer should target a higher than the specified E_c to allow for testing variability.

Density of lightweight concrete

The equilibrium density of structural lightweight concrete is typically specified:

- To meet certain fire rating values of building assemblies. Typically 4 to 7% air is also required for these mixtures designed to achieve the lower density to comply with established fire ratings;
- To establish dead load that is used to design flexural members and estimate deflections based on the span length; and
- In seismic design, to reduce lateral forces of a structure during an earthquake.

Equilibrium density is an estimate of the density of lightweight concrete assuming some degree of drying after initial construction. ASTM C567/C567M[26] defines it as the density reached by structural lightweight concrete after exposure to RH of 50 ± 5% and a temperature of 73.5 ± 3.5°F for a period of time sufficient to reach constant mass.

The Code requires equilibrium density to be determined in accordance with ASTM C567/C567M, which permits two alternatives: measured or calculated. The measured equilibrium density can take over 2 months, whereas the calculated approximate equilibrium density can be more rapidly estimated from the measured or calculated oven-dry density. ACI SPEC-301-20, Section 7.2.2.1, states that unless otherwise specified, the equilibrium density should be determined using the calculation method in ASTM C567/C567M.

The Code Section 26.12.5.1(d) states that the fresh density corresponding to the specified equilibrium density shall be used as the basis of acceptance with an acceptance tolerance of ±4.0 lb/ft^3. The fresh density of the proposed mixture that complies with the specified equilibrium density should be documented in a submittal.

Temperature considerations

Select temperature limits as follows:

- Concrete temperature as delivered shall not exceed 95°F (Section 4.2.2.5(b) in ACI SPEC-301-20). If concrete delivered in hot weather with a temperature higher than 95°F has been used successfully in a local region, the higher temperature may be permitted.
- In cold weather, per Section 4.2.2.5(a) in ACI SPEC-301-20, concrete temperature as delivered shall not be less than 55°F for section sizes less than 12 in., 50°F for section sizes from 12 to 36 in., 45°F for section sizes from 36 to 72 in., and 40°F for section sizes greater than 72 in. The temperature of concrete as placed shall not exceed these values by more than 20°F.
- For mass concrete members (typically with a minimum dimension of 3 ft), per Section 8.1.3 in ACI SPEC-301-20,

the maximum temperature of concrete after placement in the core of these members shall not exceed 160°F, and the maximum temperature difference between the center and surface of placement shall not exceed 35°F. ACI 308R-16, Section 3.10,[27] recommends the maximum internal temperature of up to 185°F for concrete mixtures containing some types of cement and SCMs. A thermal control plan that models a lower risk of thermal cracking can be used to permit a higher temperature differential.

Details of a thermal control plan for mass concrete are discussed in Section 8 of ACI SPEC-301-20.

In summary

All requirements for concrete for different members in the project can be summarized in a table (as shown in the Table 9 template). Additional performance requirements can be added as applicable.

The nominal maximum size of aggregate is selected as smaller than (Section 4.2.2.3 in ACI SPEC-301-20):

- 1/5 the narrowest dimension between sides of forms;
- 1/3 the depth of slabs; or
- 3/4 the minimum clear spacing between reinforcement.

For slabs that will receive a hard-troweled finish, specified air content should not exceed 3% (Section 4.2.2.4(b) in ACI SPEC-301-20),

Slump or slump flow (for self-consolidating concrete [SCC]) selection is permitted to be done by the contractor and documented in a submittal. Per Section 4.2.2.1 in ACI SPEC-301-20, maximum selected slump shall not exceed 9 in.; and per Section 4.2.2.2, maximum selected slump flow for SCC shall not exceed 30 in. This can be used for acceptance testing for consistency between loads of concrete. Determine the slump in accordance with ASTM C143/C143M[28] or slump flow in accordance with ASTM C1611/C1611M.[29] Applicable tolerances for slump and slump flow are addressed in ASTM C94/C94M.[30]

Examples of Prescriptive- and Performance-Based Requirements

Case 1: Nonprestressed concrete parking garage slab in Denver, CO, USA

Concrete strength requirements and exposure classes:

- 4000 psi compressive strength based on structural design;
- F3—Concrete will be exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals;
- S3—Concrete in contact with the soil will be exposed to dissolved sulfates. Soil tests indicate water-soluble sulfate content of 3% by mass. Concrete not in contact with soil can be assigned S0;
- W2—Concrete will be in contact with water where low permeability is required; and
- C2—Concrete will be exposed to moisture and an external source of chlorides from deicing chemicals.

Table 9:
Concrete requirements (based on ACI CODE-318-19(22))

Member	Mix ID	Exposure category				Specified strength, f_c', psi	Maximum *w/cm* or performance alternative	Nominal maximum aggregate size, in.	Air content, %	Slump or slump flow, in.	Chloride limit	Temp. limits
		F	S	W	C							
Footings												
Foundation walls												
Slabs-on-ground												
Exterior slabs												
Elevated slabs (interior)												
Elevated slabs (exterior)												
Frame members												
Beams (interior)												
Columns (exterior)												
Columns (interior)												
Columns (exterior)												
Walls (interior)												
Concrete toppings												

Prescriptive durability requirements per ACI CODE-318-19(22) include:

- Maximum *w/cm* = 0.40 (F3, C2);
- Specified compressive strength of 5000 psi (F3, C2);
- Air content of 5 ± 1.5% assuming 3/4 in. nominal maximum coarse aggregate (F3). Because strength is 5000 psi, air content is reduced by 1%;
- Maximum limit on SCMs of 25% fly ash and 50% slag cement (other limits for silica fume and combinations of SCMs) (F3);
- These limits could be problematic if ASR or sulfate resistance calls for a higher quantity of SCMs;
- Cementitious type—Blended cement with (HS) special property (S3, Option 2) or a combination of cement and SCM with ASTM C1012 maximum expansion of 0.05% at 6 months or 0.10% at 12 months. No restriction on cement types for concrete not in contact with soil;
- Maximum water-soluble chloride ion (Cl^-) content in concrete of 0.15% by mass of cementitious materials (C2);
- Minimum cover for reinforcement—Increase cover from the Code minimum (C2);
- Documentation that the potential for ASR has been evaluated for each aggregate source:
  - The expansion result determined in accordance with ASTM C1293 shall not exceed 0.04% at 1 year; or
  - The expansion result of the aggregate and cementitious materials combination determined in accordance with ASTM C1567 shall not exceed 0.10% at an age of 16 days.

Performance requirements include:

- As an alternative to the maximum *w/cm*:
  - Maximum charge passed of 1500 coulombs measured in accordance with ASTM C1202; or
  - Minimum resistivity of 120 Ω·m determined in accordance with ASTM C1876.

Specimens shall be cured for at least 56 days in saturated lime water.

- Maximum length change of 0.05% determined per ASTM C157/C157M on 3 x 3 x 10 in. specimens cured for 7 days in saturated lime water and dried for 28 days; and
- The SCM limits can be exceeded if the mixture submittal documents an ASTM C672/C672M[31] visual rating less than or equal to 2. Additionally, the contractor installing the slab should be certified or should have documented previous acceptable work.

Case 2: Interior floor slab in Austin, TX, USA

Concrete strength requirements and exposure classes:

- Compressive strength of 3500 psi based on structural design; and
- Exposure Classes F0, S0, W0, C0—Concrete will not be exposed to freezing and thawing, sulfates, water, or deicing chemicals. Soil tests reveal no water-soluble sulfates. The interior floor slab will be placed on a 10 mil vapor retarder and isolated from soil.

There are no prescriptive durability requirements per ACI CODE-318-19(22).

Performance requirements include:

- Specified compressive strength of 3500 psi;
- Maximum length change of 0.05% tested per ASTM C157/C157M on 3 x 3 x 10 in. specimens cured for 7 days in saturated lime water and dried for 28 days. This requirement is to minimize the potential for midpanel cracking and to reduce the potential for curling;
- Test slab placement or documentation of successful past field history to ensure the desired setting time, workability, finishability, and bleed characteristics; and
- ASR: Because the slab is considered to be dry in service (W0), ASR requirements are not necessary, but local practice may require something. Consider the ASR clauses used in ACI SPEC-301-20

Conclusions

ACI CODE-318-19(22) defines exposure classes and applicable requirements for concrete used to construct buildings and ACI SPEC-301-20 incorporates these Code requirements in the ACI reference specification. This article summarizes those requirements and also offers performance alternatives to the *w/cm* requirements in the Code.

The aim of prescriptive requirements for concrete mixtures is not for prescription sake but to attain the intended performance. However, prescriptive requirements may not result in the desired concrete performance but will restrict options. There are effective performance alternatives to specifying prescriptive requirements such as minimum cement content, limits on paste, combined aggregate grading, and limits on the quantities of SCMs. More information on performance-based specifications can be found in Reference 32.

References

1. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI CODE-318-19(22)) and Commentary (Reapproved 2022)," American Concrete Institute, Farmington Hills, MI, 2019, 624 pp.

2. ACI Committee 301, "Specifications for Concrete Construction (ACI SPEC-301-20)," American Concrete Institute, Farmington Hills, MI, 2020, 69 pp.

3. "Resources for Selecting Durability Exposure Classes and Concrete Requirements," National Ready Mixed Concrete Association, Alexandria, VA, www.nrmca.org/association-resources/research-and-engineering/p2p/durability-exposure-classes/ (last accessed, Mar. 28, 2023)

4. ASTM C618-22, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM International, West Conshohocken, PA, 2022, 5 pp.

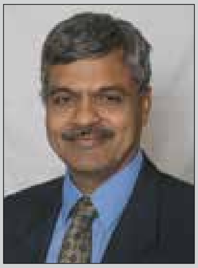
5. ASTM C989/C989M-22, "Standard Specification for Slag Cement for Use in Concrete and Mortars," ASTM International, West Conshohocken, PA, 2022, 7 pp.

6. ASTM C1240-20, "Standard Specification for Silica Fume Used in Cementitious Mixtures," ASTM International, West Conshohocken, PA, 2020, 7 pp.

7. ASTM C1580-20, "Standard Test Method for Water-Soluble

Sulfate in Soil," ASTM International, West Conshohocken, PA, 2020, 4 pp.
8. ASTM D516-16, "Standard Test Method for Sulfate Ion in Water," ASTM International, West Conshohocken, PA, 2016, 5 pp.
9. ASTM D4130-15, "Standard Test Method for Sulfate Ion in Brackish Water, Seawater, and Brines," ASTM International, West Conshohocken, PA, 2015, 5 pp.
10. ASTM C150/C150M-22, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 2022, 9 pp.
11. ASTM C595/C595M-21, "Standard Specification for Blended Hydraulic Cements," ASTM International, West Conshohocken, PA, 2021, 10 pp.
12. ASTM C1157/C1157M-20a, "Standard Performance Specification for Hydraulic Cement," ASTM International, West Conshohocken, PA, 2020, 5 pp.
13. ASTM C1012/C1012M-18b, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," ASTM International, West Conshohocken, PA, 2018, 9 pp.
14. ASTM C1778-22, "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete," ASTM International, West Conshohocken, PA, 2022, 13 pp.
15. "MasterSpec®," The American Institute of Architects, Washington, DC.
16. ASTM C1293-20a, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction," ASTM International, West Conshohocken, PA, 2020, 6 pp.
17. ASTM C1567-22, "Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)," ASTM International, West Conshohocken, PA, 2022, 6 pp.
18. ASTM C1260-22, "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)," ASTM International, West Conshohocken, PA, 2022, 5 pp.
19. ASTM C1218/C1218M-20, "Standard Test Method for Water-Soluble Chloride in Mortar and Concrete," ASTM International, West Conshohocken, PA, 2020, 3 pp.
20. ASTM C1202-22e1, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 2022, 8 pp.
21. ASTM C1876-19, "Standard Test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete," ASTM International, West Conshohocken, PA, 2019, 7 pp.
22. Obla, K.H., and Lobo, C.L., "Acceptance Criteria for Durability Tests," *Concrete International*, V. 29, No. 5, May 2007, pp. 43-48.
23. ASTM C157/C157M-17, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM International, West Conshohocken, PA, 2017, 8 pp.
24. ASTM C192/C192M-19, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 2019, 8 pp.
25. ASTM C469/C469M-22, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," ASTM International, West Conshohocken, PA, 2022, 6 pp.
26. ASTM C567/C567M-19, "Standard Test Method for Determining Density of Structural Lightweight Concrete," ASTM International, West Conshohocken, PA, 2019, 4 pp.
27. ACI Committee 308, "Guide to External Curing of Concrete (ACI 308R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 36 pp.
28. ASTM C143/C143M-20, "Standard Test Method for Slump of Hydraulic-Cement Concrete," ASTM International, West Conshohocken, PA, 2020, 4 pp.
29. ASTM C1611/C1611M-21, "Standard Test Method for Slump Flow of Self-Consolidating Concrete," ASTM International, West Conshohocken, PA, 2021, 6 pp.
30. ASTM C94/C94M-22a, "Standard Specification for Ready-Mixed Concrete," ASTM International, West Conshohocken, PA, 2022, 16 pp.
31. ASTM C672/C672M-12, "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals (Withdrawn 2021)," ASTM International, West Conshohocken, PA, 2012, 3 pp.
32. "Guide to Improving Specifications for Ready Mixed Concrete," NRMCA Publication 2PE004-21, National Ready Mixed Concrete Association, Alexandria, VA, 2021, 37 pp.

Selected for reader interest by the editors.



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