ENGINEERING:
Specifying for Performance

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This article is an advisory to the engineer to minimize prescriptive requirements and to consider performance alternatives for concrete mixtures in project specifications (1, 2, 3). An important step is to assign exposure classes to structural members consistent with ACI 318 (and ACI 301). It is noted that the current version of AIA MasterSpec does not address the ACI 318 durability exposure requirements. Consider performance alternatives as needed for performance and serviceability of specific structural member types. Overly conservative specification requirements that are invoked when not applicable to different member types and exposures can increase cost and detract from sustainability initiatives.

CONCRETE MATERIAL REQUIREMENTS

The Building Code Requirements for Structural Concrete, ACI 318-14, covers requirements for concrete mixtures in Chapter 19, primarily for durability. Some details are covered in Chapter 26. The engineer of record is required to assign durability exposure classes based on an assessment of the severity of exposure to concrete members for each ACI 318 Exposure Category: F for freezing and thawing; S for exposure to water soluble sulfates in soil; W for concrete members in contact with water requiring low permeability; C for concrete members requiring protection from corrosion of reinforcement. Review the definitions of Exposure Categories in Appendix A. The ACI 318-14 Code has very few prescriptive concrete material requirements. Section 1.10 of the ACI 318-14 states that performance alternatives to prescriptive code requirements such as w/cm need approval from the building official.

Freeze Thaw Exposure

In accordance with ACI 318-14 select w/cm, air content and compressive strength for members assigned Exposure Classes F1, F2 and F3, respectively. Limits on the quantity of supplementary cementitious materials (SCM) are applicable to exposure class F3, i.e. concrete with frequent exposure to water and deicing chemicals.

Note that the w/cm and strength requirements for exposure class F3 are intended for structurally reinforced and prestressed concrete members and are intended to be consistent with the requirements for exposure class C2. Refer to the definition of "plain concrete" in ACI 318.

Specified air content can be reduced by 1% when f'_c >5000 psi.

(ACI 318-14) Table 19.3.2.1 – Requirements for Concrete by Exposure Class

Exposure Class	*Max w/cm*[1]	*Min f'_c, psi*	*Additional Requirements Air Content*	*Limits on SCM*
F0	N/A	2500	N/A	N/A
F1	0.55	3500	Table 19.3.1.1	N/A
F2	0.45	4500	Table 19.3.1.1	N/A
F3	0.40[2]	5000[2]	Table 19.3.1.1	26.4.2.2(b)

[1] The maximum w/cm limits in Table 19.3.2.1 do not apply to lightweight concrete.
[2] For plain concrete, the maximum *w/cm* shall be 0.45 and the minimum *fc'* shall be 4500 psi.

(ACI 318-14) 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, Percent*	
	F1	*F2 and F3*
3/8	6	7.5
½	5.5	7
¾	5	6
1	4.5	6
1½	4.5	5.5
2	4	5
3	3.5	4.5

(ACI 318-14) Table 26.4.2.2(b) – Limits on Cementitious Materials for Concrete Assigned to Exposure Class F3

Cementitious Materials	*Maximum Percent of Total Cementitious Materials by Mass*
Fly ash or other pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	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

Performance Requirement

Scaling is generally related to timing and procedures used for finishing. A performance alternative may be used if higher quantities of SCMs are needed. The performance alternative might be to evaluate the deicer salt scaling resistance measured in accordance with ASTM C672 with a "Visual rating less than or equal to 2." Experience

(ACI 318-14) Table 19.3.2.1 – Requirements for Concrete by Exposure Class

Exposure Class	*Max w/cm*[1]	*Min f′c, psi*	*Additional Minimum Requirements*			*Calcium Chloride Admixture*
			Cementitious Materials[3] *- Types*			
			ASTM C150	*ASTM C595*	*ASTM C1157*	
S0	N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1	0.50	4000	II[4][5]	Types IP, IS, or IT with (MS) designation	MS	No restriction
S2	0.45	4500	V[5]	Types IP, IS, or IT with (HS) designation	HS	Not permitted
S3	0.45	4500	V plus pozzolan or slag cement[6]	Types IP, IS, or IT with (MS) designation plus pozzolan or slag cement[6]	HS plus pozzolan or slag cement[6]	Not permitted

[1] The maximum *w/cm* limits in Table 19.3.2.1 do not apply to lightweight concrete.
[3] Alternative combinations of cementitious materials to those listed in Table 19.3.2.1 are permitted when tested for sulfate resistance and meeting the criteria in 26.4.2.2(c).
[4] For seawater exposure, other types of portland cements with tricalcium aluminate (C3A) 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 C3A 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.

indicates that the scaling test is quite severe and not reflective of field performance. When this requirement is specified, do not include a limit on SCM if the mixture has been evaluated for a quantity in excess of the limit. No performance alternative is suggested for w/cm.

Sulfate Exposure

In accordance with ACI 318-14, select w/cm, compressive strength, cementitious materials for the sulfate Exposure Classes S1, S2 and S3. Note that concrete members subject to marine exposure are assigned to exposure class S1. However, because of exposure to chlorides in seawater, the requirements of exposure class C2 for w/cm and f'_c would govern. Do not permit calcium chloride admixtures for S2 and S3 classes.

Performance Requirement

In accordance with ACI 318-14, as an alternative to cementitious materials specify that the combinations of cementitious materials proposed meet the ASTM C1012 expansion criteria. No performance alternative is suggested for w/cm.

Water Exposure

In accordance with ACI 318-14, select w/cm, and compressive strength for the water Exposure Class W1 where a low permeability is required.

(ACI 318-14) Table 26.4.2.2(c) – Requirements for Establishing Suitability of Combinations of Cementitious Materials Exposed to Water-Soluble Sulfate

Exposure Class	*Maximum Expansion Strain if Tested Using ASTM C1012*		
	At 6 Months	*At 12 Months*	*At 18 Months*
S1	0.10 percent	No requirement	No requirement
S2	0.05 percent	0.10 percent[1]	No requirement
S3	No requirement	No requirement	0.10 percent

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

(ACI 318-14) Table 19.3.2.1 – Requirements for Concrete by Exposure Class

Exposure Class	*Max w/cm*[1]	*Min f′c, psi*
W0	N/A	2500
W1	0.50	4000

[1] The maximum *w/cm* limits in Table 19.3.2.1 do not apply to lightweight concrete.

Performance Requirement

An alternate to the w/cm is to specify a requirement for rapid chloride permeability (RCP) measured in accordance with ASTM C1202. A suggested alternative to the max w/cm of 0.50 is a maximum RCP of 2500 coulombs. Do not include both w/cm and RCP requirements. RCP is performed when pre-qualifying the mixture and documented in a submittal.

For some types of structural members where cracking impacts functionality (e.g. water retaining structures), shrinkage requirements may be considered. Specify a length change limit of 0.05% tested in accordance with ASTM C157. General specimen conditioning for this limit is curing for seven days in water followed by drying for 28 days – test age is 35 days. Compliance with this requirement is done during pre-qualification and documented in a submittal.

Corrosion Protection of Reinforcement

In accordance with ACI 318-14, select w/cm compressive strength. Specify chloride limits for concrete mixtures. Specify cover to reinforcing steel for members assigned to exposure class C2.

Performance Requirement

An alternate to the w/cm is to specify a requirement for RCP measured in accordance with ASTM C1202. A suggested alternative to the max w/cm of 0.40 is a maximum RCP of 1000 coulombs. Do not include both w/cm and RCP requirements. RCP tests are performed during mixture prequalification and documented in a submittal. The RCP requirement features as an effective performance alternative to specifying types and quantities of SCM. The RCP and strength requirements ensure that concrete mixtures that are resistant

(ACI 318-14) Table 19.3.2.1 – Requirements for Concrete by Exposure Class

Exposure Class	*Max w/cm*[1]	*Min f′c, psi*	*Additional Requirements*		*Additional Provisions*
			Maximum Water-Soluble Chloride Ion (Cl^-) Content in Concrete, Percent by Weight of Cement[7]		
			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[8]

[7] Water-soluble chloride ion content that is contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall be determined on the concrete mixture by ASTM C1218 at age between 28 and 42 days.
[8] Concrete cover shall be in accordance with 20.6.

Table 1: Concrete Material Requirements (Based on ACI 318-14)

Member	*Mix ID*	*Durability Exposure*				*Specified Strength, f′c, psi*	*Max w/cm or Performance Alternative*	*Nom. max Aggregate, in.*	*Air Content*	*Slump/ Slump Flow*	*Chloride Limit*	*Temp. Limits*
		F	*S*	*W*	*C*							
Footings												
Foundation Walls												
Slabs-on-grade												
Exterior slabs												
Suspended slabs (interior)												
Suspended slabs (exterior)												
Frame members												
Columns (interior)												
Columns (exterior)												
Walls (interior)												
Concrete toppings												

to chloride penetration are selected (8). There is no technical merit in specifying a minimum cementitious content for corrosion protection of reinforcement (9, 10). To minimize the potential for cracking, shrinkage requirements can be considered. See section on Water Exposure for shrinkage test criteria.

State the concrete material requirements as shown in Table 1.

COMMENTS PERTAINING TO TABLE 1

Specify strength that is the higher of that required for structural design or durability based on assigned exposure class. Specify strength at 28 days or other selected age.

Select water-cementitious materials ratio (w/cm) only if in-service durability exposure conditions are applicable to the structural member. Select the lowest w/cm as required for the durability Exposure Class assigned. Coordinate water-cementitious materials ratio with compressive strength. Consider performance alternatives to w/cm as suggested.

Select nominal maximum size of aggregate as the smallest based on (1) 1/5 narrowest dimension between sides of forms, (2) 1/3 depth of slabs or (3) ¾ minimum clear spacing between reinforcement. Select air content based on the durability exposure classification. For hard-trowel finished slabs, specify that air content should not exceed 3.0%. The air content limit should be avoided for structural lightweight members when equilibrium density is important for fire rating or design loads. Hard-troweled finishes can be obtained with proper timing and procedures.

The required slump or slump flow (for SCC) of concrete will be selected by the contractor and notified to the architect/engineer. Slump or slump flow during delivery shall be at the level documented with applicable tolerances in ASTM C94. Select water soluble chloride limits if concrete is exposed to exposure class C1, C2 or C3 as stated in Appendix A.

Select temperature limits as follows:

(a) Concrete temperature as delivered shall not exceed [95°F]. If concrete delivered in hot weather with a temperature higher than 95°F has been used successfully in given climates or situations, the higher temperature may be specified in place of the 95°F limit.

(b) In cold weather, concrete temperature as delivered shall not be less than [55°F for section size <12 in] [50°F for 12-36 in] [45°F for 36-72] [40°F for >72 in].

(c) For mass concrete elements, maximum temperature of concrete after placement shall not exceed 160°F; maximum temperature difference between center and surface of placement shall not exceed 35°F. A thermal control plan that models lower risk of thermal cracking can be used to permit higher temperature differential. ACI 308R suggests higher temperature limits are possible for concrete mixtures containing SCMs. Thermal control plan is covered in Section 8 of ACI 301-16.

Other Material Requirements

Alkali Silica Reaction

In accordance with ACI 301-16, for members not assigned to Exposure Class C0 use one of the three options below:

(a) For each aggregate used in concrete, the expansion result determined in accordance with ASTM C1293 shall not exceed 0.04 percent at 1 year.

(b) For each aggregate used in concrete, the expansion result of the aggregate and cementitious materials combination determined in accordance with ASTM C1567 shall not exceed 0.10 percent at an age of 16 days.

(c) Alkali content in concrete shall not exceed 4 lb/yd^3 for moderately reactive aggregate or 3 lb/yd^3 for highly reactive aggregate. Reactivity shall be determined by testing in accordance with ASTM C1293 and categorized in accordance with ASTM C1778.

Modulus of Elasticity

When required, specify "Modulus of elasticity in accordance with ASTM C469 for specimens cured for 28 days (or other test age) shall be greater than ___ Million psi." This is only specified when higher stiffness is required by design typically for deflection control.

Density of Light Weight Concrete

When required, specify that the mixture be pre-qualified to achieve equilibrium density in accordance with ASTM C567. Specify the equilibrium density required by design. Correlate equilibrium density with the density of fresh concrete. Acceptance is based on equivalent density of fresh concrete with a tolerance of ±4 lb/ft^3. See Section 7.2 of ACI 301-16.

Table 4.1.2.9 – Minimum cementitious material content requirements for floors (from ACI 301-16)

Nominal Maximum Size of Aggregate, in.	*Minimum Cementitious Material Content, lb/yd^3*
1-1/2	470
1	520
¾	540
3/8	610

Requirements for Floors

In addition to strength and durability requirements, the minimum cementitious content in accordance with ACI 301-16 may be specified, primarily to ensure proper finishability. An alternate test slab placement can be specified in lieu of the limit on cementitious content.

Performance Requirement

To minimize potential for mid-panel cracking and reduce potential for curling, specify shrinkage requirements for concrete. See section on Water Exposure for shrinkage test criteria. Control of setting characteristics can be addressed between the concrete contractor and producer. A test slab placement or documentation of successful past field history can ensure adequate workability and finishability. These are effective performance alternatives to specifying prescriptive requirements such as paste content, combined aggregate grading and limits on the quantities of SCM to address these properties. The only way to confirm the effectiveness of a prescriptive requirement is to evaluate the concrete performance! Often, prescriptive requirements do not work the way they are intended. Further there are many approaches to attain a given performance.

Summary of Performance Alternatives

Durability Exposure Class/Property/MeNNumber	*Prescriptive Requirement*	*Performance Alternative*
F3	SCM limits (ACI 318)	ASTM C672 Visual rating less than or equal to 2. Note that this test is not very repeatable or necessarily representative of field performance.
S1, S2, S3	Cementitious types	ASTM C1012 expansion criteria (ACI 318-14 Table 26.4.2.2(c)
W1, C2	w/cm (ACI 318)	ASTM C1202 less than: 2500 coulombs (for W1) 1000 coulombs (for C2)
Alkali Silica Reaction	Low alkali cement, SCM types and dosages, alkali content of concrete	ASTM C1567 using combination of cementitious materials used in the project – length change less than 0.10% at 16 days
Shrinkage (W1, C2, Concrete Floors)	w/cm	ASTM C157 (7 days lime water curing and dried for 28 days – length change less than 0.05%
Concrete Floors	w/cm, SCM limits, cement content, paste volume, aggregate grading/shape	Shrinkage – see above ASTM C403 initial setting time (contractor requirement) Test slab placement to ensure desired workability, finishability

Appendix A

(ACI 318-14) 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	
	F3	Concrete exposed to freezing and thawing cycles with frequent exposure to water and exposure to deicing chemicals	
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	$0.10 \le SO_4^{2-} < 0.20$	$150 \le SO_4^{2-} < 1500$ or seawater
	S2	$0.20 \le SO_4^{2-} < 2.00$	$150 \le SO_4^{2-} < 1500$
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10{,}000$
In contact with water (W)	W0	Concrete dry in service Concrete in contact with water and low permeability is not required	
	W1	Concrete in contact with water and 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 chemicals, salt, brackish water, seawater, or spray 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 D512 or ASTM D4130

(ACI 318-14) 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 that are inside structures and will not be exposed to freezing • Foundations not exposed to freezing • Members that are buried in soil below the frost line
F1	• Members that will not be subject to snow and ice accumulation, such as exterior walls, beams, girders and slabs not in direct contact with soil • Foundation walls may be in this class depending upon their likelihood of being saturated
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 • Horizontal and vertical members in contact with soil
F3	• Members exposed to deicing chemicals, such as horizontal members in parking structures • Foundation or basement walls extending above grade that can experience accumulation of snow and ice with deicing chemicals

References

1. ACI Committee 329, "Report on Performance-Based Requirements for Concrete (ACI 329R-14)," American Concrete Institute, Farmington Hills, MI, 2014, 46 pp.
2. Bickley, J., Hooton, R.D., Hover, K.C., "Preparation of a Performance-based Specification for Cast-in-Place Concrete," RMC Research Foundation, January 2006, http://www.rmc-foundation.org/images/Phase%20I%20Report%20Final%20January%202006.pdf, 155 pp.
3. NRMCA Research Engineering and Standards Committee, SIP 1-5, Specification in practices series, https://www.nrmca.org/aboutconcrete/sips/default.asp.
4. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," 2014, 519 pp.
5. ACI Committee 301, Specification for Structural Concrete (ACI 301-16), 2016, 64 pp.
6. ASTM C94, C157, C403, C469, C567, C618, C672, C989, C1012, C1202, C1218, C1240, C1293, C1556, C1778, Annual Book of ASTM Standards, Volume 4.02, ASTM International, West Conshohocken, PA, 2016.
7. ASTM C150, C595, C1157, Annual Book of ASTM Standards, Volume 4.01, ASTM International, 2016.
8. Obla, K.H., Lobo C.L., and Kim, H., "Tests and Criteria for Concrete Resistant to Chloride Ion Penetration," ACI Materials Journal, Vol. 113, No. 5, pp. 621-631.
9. ACI 329.XT-XX (Approved 2017), "Minimum Cementitious Materials Content in Specifications," 4 pp.
10. Obla, K.H., Hong, R., Lobo C.L., and Kim, H., "Should Minimum Cementitious Contents for Concrete be Specified," Transportation Research Record: Journal of the Transportation Research Board, No. 2629, 2017, pp. 1–8.