New Perspective on Concrete Durability

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Introduction

Durability of concrete has always been important because many concrete failures, or signs of such, result from exposure to severe environmental or service conditions. It is generally true that concrete structures need to be repaired or replaced because it is not durable in the environment it was built and not because it is not strong enough to withstand the applied loads. The cost of repair and replacement of deteriorated structures is astronomical.

The ACI 318 Building Code for Structural Concrete includes minimum provisions for concrete materials and design, with a primary goal of protecting the safety of the occupants of the building during and after construction. In the sequence of the code, the chapter on durability precedes that on strength requirements. It clearly states that the more restrictive requirements for durability and strength shall apply. However, the requirements for durability in the current version of ACI 318 are cumbersome and sometimes misinterpreted or overlooked.

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For the 2008 version, ACI Committee 318 has approved a significant restructuring of the durability chapter of the Building Code in an effort to clarify the requirements. To ensure that this code change proposal was successful, major technical changes to the durability provisions were avoided in this code cycle. The restructuring involves the definition of various exposure categories that are subdivided into exposure classes depending on the severity of the anticipated exposure. The requirements for concrete are then clearly laid out once the exposure classes are assigned to different structural members. This is essentially the method used by most other international codes to address concrete durability. It offers a few advantages:

- It improves the clarity and flow of the durability provisions, thereby simplifying how a specification can be written. The requirements for concrete apply if the exposure class defined applies to the structural member and should not be otherwise specified.
- For each category a "not applicable" class is provided for the design professional to indicate that the exposure category does not apply to a structural member.
  - It facilitates future revisions for performance-based alternatives specific to defined exposure classes. The current provisions are essentially prescriptive to the concrete mixture.
  - ACI 318 addresses only the following durability-related exposure categories:
- **Category F** for exposure to freezing and thawing cycles
- **Category S** for exposure to sulfate solutions in soil or water in contact with concrete
- **Category C** for conditions that require protection of reinforcement from corrosion, and
- **Category P** for concrete in contact with water that requires a low permeability.

Each category is then subdivided into exposure classes with higher numerals for more severe exposure.

Category F - Freezing and Thawing Exposure

For concrete members subject to freezing and thawing cycles, the exposure classes are defined as follows:

- **F0 (Not applicable)** – for members not exposed to cycles of freezing and thawing
- **F1 (Moderate)** – Concrete exposed to freezing and thawing cycles and occasional exposure to moisture and no deicing salts are used. This would apply to

Figure 1: Damage due to exposure to freezing and thawing cycles. Courtesy Portland Cement Association.

Table F: Requirements for Concrete Subject to Freezing and Thawing Exposures

Exposure Class	Max w/cm	Min f'_c, psi	Entrained Air	Limits on cementitious materials
F0	-	-	-	-
F1	0.45	4500	Lower	-
F2	0.45	4500	Higher	-
F3	0.45	4500	Higher	Yes

exterior walls, beams and slabs not in direct contact with soil.

- **F2 (Severe)** – Concrete exposed to freezing and thawing cycles and in continuous contact with moisture. This would apply to structural concrete elements in contact with soil or water.
- **F3 (Very Severe)** – Concrete exposed to freezing and thawing cycles that will be in continuous contact with moisture and exposure to deicing chemicals. For the most part this exposure condition in buildings would apply to slabs in parking garages.

The requirements for concrete subject to different levels of freezing and thawing are summarized in Table F: (see page 24)

These requirements are the same as in the current version of ACI 318. The limit on w/cm is the same for all levels of exposure with the intent to minimize the movement of water into the concrete that makes it critically saturated. Strength requirements in the durability chapter of the code are included in an attempt to match the w/cm and for the acceptance of concrete. The entrained air requirements are referred to a table of required air content based on nominal maximum aggregate size with a lower air content (by about 1.5%) for exposure class F1 than for F2 and F3. The code does permit a reduction of air content for higher strength concrete with a specified strength greater than 5000 psi. Exposure class F3 also has limits on the quantity of fly ash, slag, silica fume or combinations of these because of concern of increased potential for scaling.

Category S – Exposure to sulfates

The exposure classes for concrete members in contact with sulfates in soil or water are defined based on the concentration of the sulfates, unchanged as in the current Code:

Table S1: Definition of Exposure Classes for Sulfate Exposure

Exposure Class	Water-soluble sulfate (SO_4) in soil, %	Sulfate (SO_4) in water, ppm
S0 (Not applicable)	$SO_4 < 0.10$	$SO_4 < 150$
S1 (Moderate)	$0.10 \le SO_4 < 0.20$	$150 \le SO_4 < 1500$ Seawater
S2 (Severe)	$0.20 \le SO_4 \le 2.00$	$1500 \le SO_4 \le 10,000$
S3 (Very severe)	$SO_4 > 2.00$	$SO_4 > 10,000$

A current problem in the Code is that there is no standard test method referenced for measuring the sulfate concentration in soil and different methods can provide different results. A new method has been recently standardized and could be referenced in project specifications - ASTM C 1580, *Test Method for Water-Soluble Sulfate in Soil*. Note that seawater, while typically at a higher sulfate concentration, is classified as a moderate sulfate exposure because the more complex chemistry makes it less severe relative to sulfate attack, while corrosion of reinforcing steel is a bigger concern.

Figure 2: Example of deterioration of concrete due to exposure to sulfates.

Requirements for concrete mixtures exposed to sulfates are summarized in Table S2.

To resist sulfate attack, concrete needs to have a lower w/cm to minimize the diffusion of sulfates into the concrete. Further, the type of cementitious material used is important since it is the aluminate phase in portland cement and in some supplementary cementitious materials that causes sulfate attack in concrete. Prior research by the US Bureau of Reclamation is cited as the reason for prohibiting the use of calcium chloride admixtures in concrete exposed to higher concentration of sulfates – Exposure Classes S2 and S3.

A revision to the 2008 code will permit the use of alternative combinations of cementitious materials to those in Table S2 that have been qualified by test. ASTM C 1012, *Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*, is the referenced method with the expansion criteria, shown in Table S3, as recommended by ACI Committee 201 on Durability. This code provision permitting the use of supplementary cementitious materials such as fly ash or slag for sulfate resistance has been common practice in areas that have higher concentrations of sulfates in soil or water. In the case of Exposure Class S2, the 12-month expansion criterion can be used if the 6-month criterion is not met. The use of cementitious materials with documented good service history is also permitted.

Table S2: Requirements for Concrete in contact with water-soluble sulfates in soil or water

Exposure Class	Max w/cm	Min f'_c, psi	Required Cementitious Materials - Types			Additional Minimum Requirement
			ASTM C 150	ASTM C 595	ASTM C 1157	
S0	-	-	-	-	-	-
S1	0.50	4000	II	IP(MS), IS(<70)(MS)	MS	-
S2	0.45	4500	V	-	HS	No calcium chloride admixtures
S3	0.45	4500	V + pozzolan or slag	-	HS + pozzolan or slag	

Table S3: Suitability of Cementitious Materials for Concrete Exposed to Water-Soluble Sulfate

Exposure Class	Maximum Expansion when tested using ASTM C 1012
S1	0.10% at 6 months
S2	0.05% at 6 months, or 0.10% at 12 months*
S3	0.10% at 18 months

Category C – Conditions needing Corrosion Protection of Reinforcement

Corrosion is probably the most common visible sign of deterioration in exterior concrete. It has significant safety implications when the effective area of reinforcing steel is reduced by conversion to rust that causes spalling of the concrete cover. Structural safety is more critical for prestressed concrete because of the greater susceptibility of prestressing strands to corrosion and potential for catastrophic failures if these strands are compromised by corrosion.

The exposure classes for conditions that need corrosion protection of reinforcement are:

- **C0 (Not applicable)** - Concrete that will be dry or protected from moisture in service
- **C1 (Moderate)** - Concrete exposed to moisture but not to an external source of chlorides in service
- **C2 (Severe)** - Concrete exposed to moisture and an external source of chlorides in service – from deicing chemicals, salt,

Examples of corrosion of reinforcing steel in concrete structures.

Table C: Requirements for Concrete in exposures needing corrosion protection of reinforcement

Exposure Class	Max w/cm	Min f'_c, psi	Chloride ion limit	Additional Minimum Requirement
Reinforced Concrete				
C0	-	-	1.00	-
C1	-	-	0.30	-
C2	0.40	5000	0.15	Cover
Prestressed Concrete				
C0	-	-	0.06	-
C1	-	-	0.06	-
C2	0.40	5000	0.06	Cover

brackish water, seawater or spray from these sources

Prestressed concrete has lower limits on chloride ions in the concrete mixture. The requirements are as summarized in Table C.

Only the severe condition – Class C2 - has limits on w/cm to minimize the penetration of chlorides through the concrete and to force a slower rate of carbonation, both of which impact the onset of corrosion. The chloride ion limit in Table C refers to water soluble chloride ion expressed in terms of percent by weight of cement. It is measured on crushed concrete samples by ASTM C 1218 at an age between 28 and 42 days. This requirement protects against using concrete ingredients, such as admixtures or marine aggregate that will incorporate chlorides in the concrete mixture. Some of the other ACI documents recommend more conservative chloride ion limits that are under consideration for adoption in the ACI 318 Code in its next cycle. For Class C2 the design professional is notified to pay attention to the clear cover of concrete to the reinforcing steel. For prestressed concrete, the Code specifically requires that the cover be increased by 50%. In reinforced concrete increasing the cover needs to be balanced with the potential for increased and wider cracks.

Category P – Concrete members in contact with water requiring a low permeability

Presumably, this exposure condition for structural members in buildings is one where the other exposure conditions are not pertinent. One example might be a water tank in a warm climate.

The exposure conditions are defined as:

- **P0 (Not applicable)** - Concrete where low permeability to water is not required
- **P1 (Required)** - Concrete required to have low permeability to water

The requirements for concrete are summarized in Table P.

The Code indicates that the primary means of reducing the permeability of concrete is to maintain a low w/cm. The w/cm for exposure class P1 is the least restrictive compared to the other exposure classes where it is controlled. Clearly, with today's technology and the use of supplementary cementitious materials, there are many ways by which one can achieve a low permeability for concrete.

Table P: Requirements for Concrete in contact with water requiring low permeability

Exposure Class	Max w/cm	Min f'_c, psi	Additional Minimum Requirements
P0	-	-	-
P1	0.50	4000	-

Concluding Remarks

The ACI 318 Building Code addresses only a limited number of durability concerns that impact the performance of concrete structures, since it focuses on minimum requirements to protect public safety. There are other aspects of durability design professionals must consider to satisfy owner needs. These include but are not limited to alkali aggregate reactivity, abrasion, cracking and spalling related to temperature, shrinkage and creep. Activity underway in ASTM is in the process of developing more rational requirements for alkali aggregate reactivity that will address the reactivity of the aggregates and the service function of a particular structure (i.e., such as a dam is considered more critical than a sidewalk). Other durability provisions specific to environmental structures are covered in the ACI 350 Code. Other durability concerns specific to a project need to be addressed by the design professional and there is adequate guidance in ACI 201.1R *Guide to Durable Concrete* and similar industry documents.

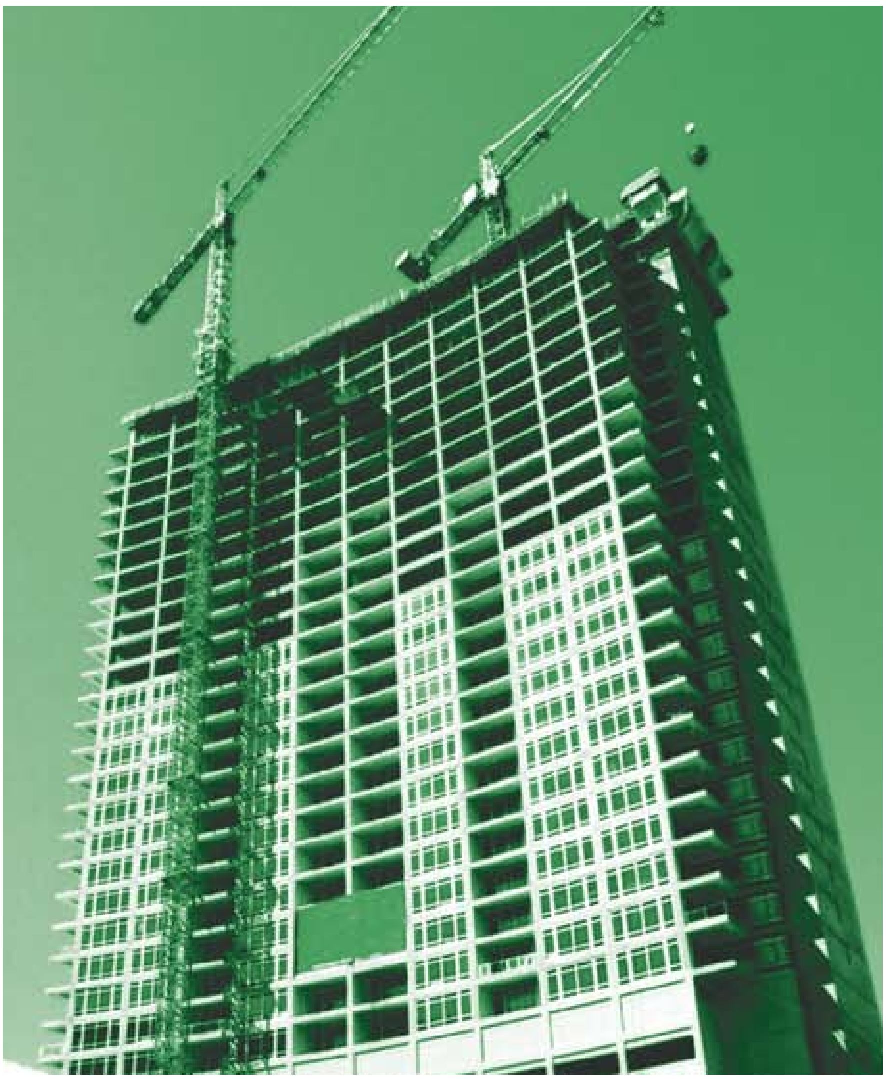

Figure 4: Building under construction.

Table X: Sample schedule of requirements for structural members on a project.

Building members	Loads	Durability Categories			
	f'_c, psi	F	S	C	P
Foundations and slabs on grade	3000	F2	S0	C1	P0
Interior columns, beams, and slabs	4000	F0	S0	C0	P0
Exterior columns, beams and walls	4000	F1	S0	C1	P0
Exterior slabs	4000	F2	S0	C1	P0

The next phase is to incorporate these exposure classes in a reference specification, like ACI 301, and for them to be used in project specifications.

This revision to the ACI 318 Code lends more clarity to the durability provisions for concrete. The clear definition of the exposure classes and the parallel requirements for concrete eliminates reasons for the design professional to impose restrictions on concrete if they are not needed. For instance, there is no reason to impose a maximum w/cm ratio on an interior building column where the primary performance function is strength. Improvements to this revision are surely possible and those will be developed in the next Code cycle, including proposing performance-based alternatives. The next phase is to incorporate these exposure classes in a reference specification, like ACI 301, and for them to be used in project specifications. When so defined, this simplifies the design professional's job of writing a specification.

A conceptual schedule for classes of concrete in a building might look like Table X.

In this case, the pertinent w/cm that is needed for a specified durability class will need to comply with the specified requirements and documented in a submittal. When the specified strength, f'_c, that pertains to a durability exposure class exceeds that required for loads, that higher strength level will govern and serve as the basis for the acceptance criteria for concrete strength. In the example above, f'_c, for the foundations and slabs on grade will be at 4500 psi and the maximum w/cm of that class of concrete will be 0.45 as required for Exposure Class F2. ■

Colin Lobo is a member of ACI 318 and ACI 301 and was involved in developing this code change proposal for the durability provisions in Chapter 4 of ACI 318.