Durability

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Durability

- First off, I'd like to present some context before we open it up for discussion on the topic of Durability.
- Can anyone in this room predict how long a structure or elements of a structure will last?
- Do the various Code bodies and/or specifications provide the Industry with sufficient guidance on how to design, fabricate, or construct infrastructures with or without durability provisions?
  - If not, why not
  - As owners, don't we want long-lasting structures?
  - If yes, then what can be prescribed to obtain the longest lasting structures?
- There are numerous publications and research related to durability; so how do we know what to add to the cauldron?
- Do we know what we currently have in terms of durability?
  - Do we have bridge records that provide number of years and condition states for various bridge elements
  - Can we obtain additional forensic information on how existing bridge elements have performed over the last X number of years in terms of durability

<u>Factors to consider</u>

- Exposure conditions
- Design life
- Loads
- Type of materials
  - Water
  - Admixtures
  - Cement
  - Aggregates
  - Curing
  - Temperatures
- Material proportions
- Mix-designs
- Type of and quality of construction & fabrication
  - Cast-in-place
  - Precast
- Cost
- Functional classifications
- Detailing
- Allowable stresses
- Corrosion mitigation
- Industry tests for durability (ASTM, etc.) to validate durability performance
- Service-Life prediction models
- Life-Cycle costs
- Bridge Preservation strategies

AASHTO LRFD Bridge Design Specs

2.5.2—Serviceability

2.5.2.1—Durability

2.5.2.1.1—Materials

The contract documents shall call for quality materials and for the application of high standards of fabrication and erection.

Structural steel shall be self-protecting, or have long-life coating systems or cathodic protection.

Reinforcing bars and prestressing strands in concrete components, which may be expected to be exposed to airborne or waterborne salts, shall be protected by an appropriate combination of epoxy and/or galvanized coating, concrete cover, density, or chemical composition of concrete, including air-entrainment and a nonporous painting of the concrete surface or cathodic protection.

Prestress strands in cable ducts shall be grouted or otherwise protected against corrosion.

Attachments and fasteners used in wood construction shall be of stainless steel, malleable iron, aluminum, or steel that is galvanized, cadmium-plated, or otherwise coated. Wood components shall be treated with preservatives.

Aluminum products shall be electrically insulated from steel and concrete components.

Protection shall be provided to materials susceptible to damage from solar radiation and/or air pollution.

Consideration shall be given to the durability of materials in direct contact with soil and/or water.

C2.5.2.1.1

The intent of this Article is to recognize the significance of corrosion and deterioration of structural materials to the long-term performance of a bridge. Other provisions regarding durability can be found in Article 5.12.

5.12—DURABILITY

5.12.1—General

Concrete structures shall be designed to provide protection of the reinforcing and prestressing steel against corrosion throughout the life of the structure.

Special requirements that may be needed to provide durability shall be indicated in the contract documents. Portions of the structure shall be identified where:

- Air-entrainment of the concrete is required,
- Epoxy-coated or galvanized reinforcement is required,
- Special concrete additives are required,
- The concrete is expected to be exposed to salt water or to sulfate soils or water, and
- Special curing procedures are required.

Protective measures for durability shall satisfy the requirements specified in Article 2.5.2.1.

C5.12.1

Design considerations for durability include concrete quality, protective coatings, minimum cover, distribution and size of reinforcement, details, and crack widths. Further guidance can be found in ACI Committee Report 222 (ACI, 1987) and Posten et al. (1987).

The principal aim of these Specifications, with regard to durability is the prevention of corrosion of the reinforcing steel. There are provisions in *AASHTO LRFD Bridge Construction Specifications* for air-entrainment of concrete and some special construction procedures for concrete exposed to sulfates or salt water. For unusual conditions, the contract documents should augment the provisions for durability.

The critical factors contributing to the durability of concrete structures are:

- Adequate cover over reinforcement,
- Nonreactive aggregate-cement combinations,
- Thorough consolidation of concrete,
- Adequate cement content,
- Low *W/C* ratio, and
- Thorough curing, preferably with water.

The use of air-entrainment is generally recommended when 20 or more cycles of freezing and thawing per year are expected at the location and exposure. Decks and rails are most vulnerable, whereas buried footings are seldom damaged by freeze-thaw action.

Sulfate soils or water, sometimes called alkali, contain high levels of sulfates of sodium, potassium, calcium, or magnesia. Salt water, water soluble sulfate in soil above 0.1 percent or sulfates in water above 150 ppm justify use of the special construction procedures called for in *AASHTO LRFD Bridge Construction Specifications*. These include avoidance of

AASHTO LRFD 8th Edition

5.14—DURABILITY

5.14.1—Design Concepts

Protective measures for durability shall satisfy the requirements specified in Article 2.5.2.1.

Concrete structures shall be designed to provide protection of the reinforcing and prestressing steel against corrosion throughout the life of the structure.

Special requirements that may be needed to provide durability shall be indicated in the contract documents. Portions of the structure shall be identified where any of the following are required:

- air-entrainment of the concrete;
- epoxy-coated or galvanized reinforcement;
- stainless steel bars, cladded bars or the use of nonferrous bars;
- sealing or coating;
- special concrete additives;

C5.14.1

NCHRP (2013) points out that "durability" is not a single property of concrete but rather it is a series of properties required for the particular environment to which the concrete will be exposed during its service life. While material aspects of concrete design are a major factor in producing durable concrete structures, attention to design, detailing and construction QA/QC are also vital for a successful outcome.

The literature contains numerous reports and papers on concrete durability. This commentary contains information from several sources but should not be considered exhaustive, nor should it be interpreted as conflicting with documented good local experience with other durability enhancing policies or protocols.

Concrete cover & control of cracking

- AASHTO LRFD Table 5.12.3-1

5.12.3—Concrete Cover

Revise table 1 of this Article as follows:

Table 5.12.3-1—Cover for Unprotected Main Reinforcing Steel (in.)

Situation	Cover (in.)
Direct exposure to salt water	4.0
Cast against earth	3.0
Coastal	3.0
Exposure to deicing salts	2.5
Deck surfaces subject to tire stud or chain wear	2.5
Exterior other than above	2.0
Interior other than above	
• Up to No. 11 bar	1.5
• No. 14 and No. 18 bars	2.0
Bottom of cast-in-place slabs	
• Up to No. 11 bar	1.0
• No. 14 and No. 18 bars	2.0
Precast soffit form panels	0.8
Precast reinforced piles	
• Noncorrosive environments	2.0
• Corrosive environments	3.0
Precast prestressed piles	2.0
Cast-in-place piles	
• Noncorrosive environments	2.0
• Corrosive environments	
○ General	3.0
○ Protected	3.0
• Shells	2.0
• Auger-cast, tremie concrete, or slurry construction	3.0
Precast concrete box culverts	
• Top slabs used as a driving surface	2.5
• Top slabs with less than 2 ft of fill not used as a driving surface	2.0
• All other members	1.0

- Control of cracking by distribution of reinforcement (LRFD 5.7.3.4)

The spacing s of mild steel reinforcement in the layer closest to the tension face shall satisfy the following:

$$s \leq \frac{700\gamma_e}{\beta_s f_{ss}} - 2d_c \qquad (5.7.3.4\text{-}1)$$

in which:

$$\beta_s = 1 + \frac{d_c}{0.7(h - d_c)}$$

- Distribution of reinforcement (AASHTO STD Equation 8-61)

$$f_s = \frac{z}{(d_c A)^{1/3}} \leq 0.6\, f_y \qquad (8\text{-}61)$$

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- 19.3-Concrete Durability Requirements
  - Addresses concrete durability on the basis of exposure categories and exposure classes defined in Table 19.3.1.1

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

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	$0.10 \leq SO_4^{2-} < 0.20$	$150 \leq SO_4^{2-} < 1500$ 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 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 D516 or ASTM D4130.

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, with or without deicing chemicals.

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 nonprestressed and prestressed concrete exposed to conditions that require additional protection against corrosion of reinforcement.

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, the slabs of a parking garage in a cold climate might be assigned to Exposure Classes F3, S0, W2, and C2, and a potable water tank inside a heated building might be assigned to Exposure Classes F0, S0, W2, and C1.

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

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- 19.3.2-Requirements for concrete mixtures
  - 19.3.2.1 Based on the exposure classes assigned from Table 19.3.1.1, concrete mixtures shall conform to the most restrictive requirements in Table 19.3.2.1

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			Limits on cementitious materials
F0	N/A	2500	N/A			N/A
F1	0.55	3500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			N/A
F2	0.45	4500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			N/A
F3	0.40[3]	5000[3]	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			26.4.2.2(b)
			Cementitious materials[4] — Types			Calcium chloride admixture
			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[5][6]	Types with (MS) designation	MS	No restriction
S2	0.45	4500	V[6]	Types with (HS) designation	HS	Not permitted
S3 Option 1	0.45	4500	V plus pozzolan or slag cement[7]	Types with (HS) designation plus pozzolan or slag cement[7]	HS plus pozzolan or slag cement[7]	Not permitted
S3 Option 2	0.40	5000	V[8]	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[9,10]			
			Nonprestressed concrete	Prestressed concrete	Additional provisions	
C0	N/A	2500	1.00	0.06	None	
C1	N/A	2500	0.30	0.06		
C2	0.40	5000	0.15	0.06	Concrete cover[11]	

R19.3.2-Additional protection for Exposure Class C2-For nonprestressed and prestressed concrete

Exposure Class C2: For nonprestressed and prestressed 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, 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 increased levels of specified compressive strength provide increased protection. Use of silica fume meeting ASTM C1240 with an appropriate high-range water reducer, ASTM C494, Types F and G, or ASTM C1017 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 the performance of the mixtures.

ACI Publications on Durability

- ACI 350-Code Requirements for Environmental Engineering Concrete Structures
- ACI 224-Guide to Design Detailing to Mitigate Cracking
- ACI 201-Guide to Durable Concrete
- ACI 222-Guide to Design & Construction Practices to Mitigate Corrosion Reinforcing in Concrete Structures

ASTM requirements

- ASTM G109

Standard Test Methods for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments

- ASTM C1582

Standard Specification for Admixtures to Inhibit Chloride-Induced Corrosion of Reinforcing Steel in Concrete

PCI's Recommended Practice for Design, Manufacture and Installation of Prestressed Concrete Piling, July-August 2019

For the sake of durability, concrete piles should have a minimum cementitious material content of 564 lb/yd^3 (335 kg/m^3) of concrete. The water–cementitious material ratio (by weight) should correspond to the least amount of water

that will produce a plastic mixture and provide the desired workability for the most effective placement of the concrete. Maximum water–cementitious material ratios are typically based on exposure. In aggressive environments, such as for marine applications or for sites with high chloride or high sulfate exposure, a minimum cementitious material content of 658 lb/yd^3 (390 kg/m^3) is recommended. See ACI 201.2R-08[4] for durability recommendations where pozzolans and fly ash (ASTM C618) are used.

Durability Aspects of Precast Prestressed Concrete Part 1 & 2

Durability Aspects of Precast Prestressed Concrete Part 1: Historical Review

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A review of past research on the effect of heat curing on strength, frost resistance, and AASHTO T 277 (also ASTM C 1202) "coulomb" values is presented, and the research experience compared to present-day codes, specifications, and test methods. Historically, properly heat-cured concretes produced at low water-cement ratios have been found to have strength and frost resistance properties equal to or better than conventionally-cured concretes. The AASHTO T 277 test, and the similar ASTM C 1202 test, were also reviewed as they relate to precast concrete, revealing that significant questions remain regarding their appropriateness for use in concrete project materials qualifications and specifications.

Since 1950, the engineering profession has observed that weather-exposed precast, reinforced concrete structures and precast, prestressed concrete structures with adequate air-void systems have exhibited excellent durability. The resistance of precast concrete to freezing and thawing and to corrosion of reinforcement has also been researched extensively since 1960. Some studies were made on properly air-entrained and properly steam-cured or heat-cured concretes, while other studies were performed on improperly air-entrained or non-air-entrained concretes and improperly steam-cured or heat-cured concretes.

Part 1 of this two-part report will review the specific

Durability Aspects of Precast Prestressed Concrete Part 2: Chloride Permeability Study

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A laboratory study was undertaken to investigate the good past performance of low water-cement ratio, heat-cured precast, prestressed concrete in highway bridges, parking garages, and other applications. The study included salt water ponding testing, AASHTO T 277 or ASTM C 1202 "coulomb" tests, compressive strength tests, and absorption and volume of permeable voids tests. Heat-cured, water-cured, and moist-cured concretes with water-cementitious ratio values of 0.46, 0.37 and 0.32 with and without silica fume were tested. Using the measured chloride contents, chloride diffusion coefficients were calculated and estimates of the time-to-corrosion were developed. The water-cement ratio was found to be the most important influence on the performance of the concrete, with low w/c, heat-cured conventional concretes having comparable performance to realistic silica fume concretes having 0.37 to 0.46 water-cementitious ratios. It was also found that the use of heat curing could reduce the permeability of AASHTO-grade, 0.46 w/c concrete by 40 to 50 percent. The addition of silica fume to concrete caused an increase in the absorption and volume of permeable voids in concrete, while heat curing was seen to decrease the absorption and volume of permeable voids in concrete.

ASPIRE Fall 2023, Thoughts about Durability and Service-Life Design of Bridges by Dr. Elizabeth I. Wagner and Dr. Michael C. Brown, Wiss, Janney, Elstner Associates Inc.

- More and more, owners are requirement that bridges be designed with durability in mind, with specifications commonly calling for bridges to achieve service lives of 75 or 100 years-and sometimes beyond.
- The industry has come to recognize that design for durability is needed, such that the combination of materials, design details, construction practices, and planned maintenance activities will enable the bridge to achieve its target service life.
- The durability engineer will examine the components and their environmental exposures, identify the relevant deterioration mechanisms, and develop a protective strategy to provide confidence that each component and the overall structure will achieve their target service lives. There are several approaches for developing a protective strategy for durability.

ASPIRE Fall 2023, Thoughts about Durability and Service-Life Design of Bridges by Dr. Elizabeth I. Wagner and Dr. Michael C. Brown, Wiss, Janney, Elstner Associates Inc.

Definitions

- Design life-The period of time on which the statistical derivation of transient loads is based; this period is 75 years for the AASHTO LRFD specifications.
- Target service life-The assumed period of time the bridge is expected to remain in operation, without rehabilitation or significant repair, and with only routine maintenance (intended life). This maintenance would include replacement of renewable elements.

Details

Using durable materials is key to achieving long service lives; however, without proper design details, a structure may not achieve its target service life.

If the cover over reinforcement is too shallow, it may not provide enough concrete to protect the reinforcement from corrosion.

ASPIRE Fall 2023, FHWA’s Service Life Design Reference Guide, by Raj Ailaney, Office of Bridges and Structures, Federal Highway Administration

- Service life design principles have been gaining broader acceptance as a tool to improve the performance of existing highway bridges and to design new bridges for enhanced durability.
- The objective of service life design is to assess the potential deterioration mechanism affecting structural elements, and to design those elements to achieve a target service life duration.
- Implementing new specifications can be challenging.
- FHWA’s Service Life Design Reference Guide was published in November 2022 is a “road map” to service life design concepts and methods for bridge owners and designers. The guide focuses on North America design practices and provides references for applying service life design principles to concrete and steel highway bridges with examples provided.
- May 1, 2023, FHWA conducted a national webinar with 42 states participating.
- FHWA will conduct regional workshops starting in Fall/2024 and will be 1.5 days, specific to regional needs, and coordinated through the host state agency. The workshops will be open to regional and state DOT’s, consulting design engineers, and construction professionals.

Durability

- Q/A

References:

- David A. Tomley, P.E., “Concrete Repairs/Service Life of Bridges/Structures & Life-Cycle Costs”, PCI Gulf South Summer Convention, July 27, 2019
- David A. Tomley, P.E., “Bridge Preservation”, PCI Gulf South Transportation Committee meeting with MDOT, November 6, 2019, ALDOT, June 11, 2020, and Virtual meeting with LADOTD, June 19, 2020