

Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures

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Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures

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Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures

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Corrosion of metals in concrete is a significant problem throughout the world. In many instances, corrosion can be avoided if proper attention is given to detailing, concrete materials and mixture proportions, and construction practices. This guide contains information on aspects of each of these. In addition, the guide contains recommendations for protecting in-service structures exposed to corrosive conditions. The guide is intended for designers, materials suppliers, contractors, and all others engaged in concrete construction.

Keywords: admixtures; aggregates; aluminum; cathodic protection; cement; chlorides; consolidation; corrosion; curing; epoxy coating; high-range water-reducing admixtures; mixing; mixture proportioning; permeability; reinforcing steel; water-cementitious material ratio.

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FOREWORD

This guide represents a compendium of technology to combat the problems of corrosion and is arranged into four major chapters. Chapter 2 discusses design considerations pertinent to corrosion, including environmental factors, performance of structural types, and the influence of structural details. Chapter 3 addresses the effects of concrete materials and mixture proportions on susceptibility to corrosion, including cements, aggregates, water, reinforcing steels, admixtures, and other embedded materials. Chapter 4 examines corrosion as it is influenced by the changes that concrete undergoes as it is mixed, transported, placed, consolidated, and cured. Chapter 5 describes several procedures available for protecting in-place structures.

This guide will aid in the design and construction of corrosion-resistant reinforced concrete structures and assist those involved in ensuring that reinforced concrete continues to function as a reliable and durable construction material.

CHAPTER 1—INTRODUCTION

Corrosion of metals in concrete is a serious type of deterioration that affects concrete in service. Corrosion is seen in parking structures, marine structures, industrial plants, buildings, bridges, and pavements. The Federal Highway Administration published a report in 2001 that the estimated cost of corrosion of highway bridges was between \$6.43 and \$10.15 billion (FWHA-RD-01-097 2001). This problem drains resources in both the public and private sectors. Implementation of solutions is needed, both in the design of structures resistant to corrosion and the rehabilitation of structures suffering the effects of corrosion.

Concrete provides a highly alkaline environment, which results in the formation of a passivating film that protects the steel from corrosion. Corrosion of embedded metals in concrete can occur, however, if concrete quality and details such as concrete cover and crack control are not adequate; if the functional requirement of the structure is not as anticipated or is not adequately addressed in the design; if the environment

is not as anticipated or changes during the service life of the structure; or a combination of thereof. For more details on the mechanism of corrosion of metals in concrete, refer to ACI 222R.

Once corrosion begins, it is aggravated by factors such as moisture and elevated ambient temperatures. Cracking, stray currents, and galvanic effects can also exacerbate corrosion. Other causes of corrosion include steel directly exposed to the corrosive elements due to incomplete placement or consolidation of concrete, and industrial or wastewater chemicals that attack the concrete and the reinforcing steel. Reinforced concrete structures should be designed either to avoid these factors when they are present or be protected from these factors when they cannot be avoided.

CHAPTER 2—DESIGN CONSIDERATIONS**2.1—Structural types and corrosion**

Corrosion of steel in concrete was first observed in marine structures and chemical manufacturing plants (Biczok 1964; Evans 1960; Tremper et al. 1958). The design considerations relevant to corrosion protection depend on the type of structure and its environment and intended use. Certain minimum measures—for example, adequate concrete cover and concrete quality—should always be specified, even for structures such as concrete office buildings completely enclosed in a curtain wall with no exposed structural elements. Depending on the type of structure and its expected exposure, additional design considerations can be required to ensure satisfactory performance over the intended service life of the structure.

2.1.1 Bridges—The primary issues in designing the deck, substructure, and superstructure of a concrete bridge for increased corrosion resistance are knowing the potential for chloride ion exposure while in service and the degree of protection required. In theory, the design considerations for a bridge located in a semi-arid region of the U.S., such as parts of Arizona, should be different from a bridge located in either Illinois or on the coast of Florida. ACI 318, ACI 345R, and AASHTO HB-17 recognize this and contain additional requirements for concrete structures exposed to different levels of chloride ions in service.

There are differences in interpretation when applying these provisions for corrosion protection of bridge structures. For exposure to deicing chemicals, the top mat of reinforcement is more susceptible to chloride-induced corrosion than the bottom mat and, therefore, acts as the anode with the bottom mat acting as the cathode in macrocell corrosion. AASHTO HB-17 recognizes this and requires greater concrete cover for the top mat of reinforcement. This basic premise of chloride-ion exposure is reversed for a bridge located in a warm climatic area over saltwater where the underside of the bridge deck can be more vulnerable to chloride-ion ingress. Consequently, the concrete cover should be increased for the bottom mat of deck reinforcement in this type of application.

So much has been written about the bridge deck problem since the early 1970s that corrosion protection of a bridge superstructure and substructure has sometimes been overlooked. Leakage of chloride-contaminated water through expansion and construction joints and cracks in the superstructure

substructure pier caps, abutments, and piers, can lead to corrosion of steel in these components. Additionally, snow-removal operations can pile chloride-containing snow around piers, and piers located in marine tidal splash zones are continuously subjected to wetting-and-drying cycles with chloride-laden seawater. To design a bridge deck, superstructure, and substructure with adequate corrosion protection over its intended service life of 75 years, as required by AASHTO HB-17, it is important to recognize the potential for chloride-ion ingress due to improper placement or functioning of joints, drains, and other openings in the structure.

2.1.2 Parking structures—In many respects, the potential for corrosion-related deterioration in a parking structure is greater than that for a bridge. Because of the intended function of a parking structure, chloride-laden slush on the underside of parked vehicles has ample time to drip onto parking decks, increasing the potential for chloride-ion penetration. Also, unlike bridge decks, parking structures, except for exposed roofs, are not rinsed by precipitation. Moreover, poor drainage permits chloride-laden water to pond on the concrete deck.

Design considerations pertinent to corrosion protection of a parking structure are similar to those of bridge design in that they depend on location and expected exposure. Corrosion-protection measures for a parking garage constructed in warm climates, where there is minor or no use of deicing salts, will be different from one constructed in cold climates, where deicing salts are heavily used.

All structural components for a parking structure located in a northern or mountainous climate where deicer chemicals are used should be provided with additional corrosion-protection measures. Additional corrosion-protection considerations are also needed for parking structures located in close proximity to marine areas where exposure to salt spray, salty sand, and high moisture conditions is probable. ACI 362.1R contains further recommendations.

2.1.3 Industrial floors—The type of expected exposure will impact design considerations necessary for corrosion protection of industrial floors. The primary concern in industrial and manufacturing facilities is exposure to acids or other aggressive chemicals that can lead to disintegration of the concrete. Membranes and coatings can protect these floors from their environment.

2.1.4 Concrete façades—Knowledge of the expected environmental exposure is the primary issue regarding satisfactory corrosion protection of concrete façades, such as architectural precast panels. The proximity of façades to heavily industrialized areas and geographical location is of particular importance. Some cities have higher levels of carbon monoxide, carbon dioxide, and pollutants from industrial smoke discharge, which can lead to a greater rate of concrete carbonation.

Concrete façades are occasionally exposed to chloride-induced corrosion. This can occur when chloride-laden snow piled against a parking structure façade subsequently melts and drips down the side of the structure. Steel reinforcement in the concrete façade and metal connections used to secure the façade to the structure are both vulnerable to this type of attack.

2.1.5 Marine structures—Concrete structures, such as docks, piers, and storage tanks, located in a marine environment are vulnerable to chloride-induced corrosion. Chloride ions and other ions in seawater can penetrate concrete. The portion of a marine concrete structure located in the tidal and splash zones is generally the most susceptible to corrosion because of the availability of water, oxygen, and chlorides. All segments of a marine structure are at risk for chloride-induced corrosion, but low oxygen concentrations significantly reduce corrosion rates in submerged portions.

2.1.6 Concrete slab-on-ground—Casting reinforced concrete in contact with chloride-contaminated soil can cause corrosion of the embedded reinforcement if chloride ions migrate into the concrete. Concrete with a high water-cementitious material ratio (w/cm) and high permeability is more vulnerable to attack.

2.1.7 Other structures—Other types of concrete structures can experience corrosion-related problems. Concrete in sewage and waste facilities can disintegrate after prolonged exposure to acids and sulfates in wastes and expose the steel. Prestressing steel in wire-wound concrete prestressed tanks has also corroded as a result of inadequate shotcrete protection and cracking (Schupack 1964; Schupack and Poston 1989). In these cases, the prestressing wires used to wrap the tanks had inadequate shotcrete cover to provide protection. Carbonation, water from rain, or leakage from inside the tank, along with oxygen, are sufficient to cause electrochemical corrosion of the prestressing wires. Improved design and construction have mitigated these problems.

2.2—Environment and corrosion

An important consideration in the design for corrosion protection is the type of environmental exposure to which a concrete structure will be subjected over its service life.

2.2.1 Concrete not exposed to weather—Concrete structures with the lowest corrosion risk are those not exposed to weather, such as a structural concrete frame of an office building. Reinforcement in concrete structures not directly exposed to moisture and benefiting from the drying effect of heating has a low risk of corrosion. Barring any unusual conditions, and using code-recommended concrete cover and concrete quality, concrete structures not exposed to weather and other outside environmental factors should have a low risk of corrosion during the building service life. Exceptions would be interior sections of buildings exposed to periodic wetting such as kitchens, bathrooms, or water fountain areas, and concrete members and floor slabs made with chloride additions. Care should be taken in areas such as boiler rooms where floor slabs can be subjected to continuous heating and exposure to higher-than-normal carbon dioxide concentrations. Severe carbonation of the concrete can occur in these cases.

2.2.2 Concrete exposed to weather—Concrete structures exposed to weather have a higher risk of corrosion than those not exposed to weather. An exception can occur in enclosed concrete parking structures, where carbonation-induced corrosion is possible. Moisture, along with oxygen, causes corrosion if the steel loses its passivity due to chloride ingress or carbonation.

Temperature also influences the corrosion risk. Given two identical concrete structures exposed to weather, corrosion would occur at a faster rate for the one exposed to the higher average ambient temperature. In addition, temperature variations can cause cracking in concrete that leads to the ingress of deleterious substances and potential corrosion. Concrete structures exposed to weather are also more vulnerable to carbonation, acid rain, and freezing and thawing.

2.2.3 Concrete exposed to chemical deicers—Sodium chloride (NaCl) is a commonly used chemical deicer. NaCl is applied in rock-salt form and is at least 95% pure. Calcium chloride (CaCl_2) is more effective as a deicer and is normally used when ambient temperatures are less than -25°F (-3.9°C). Although the relationship between the rate of steel corrosion, concrete alkalinity, and chloride-ion concentration is not completely understood, it is known that chloride ions from deicing salts promote corrosion of reinforcing steel. Chloride ions can initiate active corrosion because they break down the passive oxide film that initially forms on concrete-embedded reinforcement.

Bridges, parking garages, and other concrete structures exposed to chemical deicers are at a high risk for corrosion. Code-required minimum concrete quality and concrete cover for structures exposed to chlorides in service are needed to prolong service life. Depending on the expected maintenance, such as periodic freshwater washes of exposed surfaces and the aggressiveness of the exposure, additional measures, such as increased cover, low-permeability concrete, corrosion-inhibiting admixtures, corrosion-resistant steel reinforcement, or protective coatings on reinforcing steel or concrete, can be required to meet the proposed design service life of the structure.

2.2.4 Concrete exposed to marine environment—Because of the potential for ingress of chloride ions from seawater, concrete structures exposed to a marine environment have a corrosion risk similar to structures exposed to chemical deicers. The most vulnerable region of the structure is the tidal or splash zones, which goes through alternating cycles of wetting and drying.

Because of this greater risk of corrosion, AASHTO HB-17 recommends 4 in. (100 mm) of clear cover for reinforced concrete substructures that will be exposed to seawater. Other protective measures may be required to extend the service life.

2.2.5 Concrete exposed to chemicals—Industrial concrete structures exposed to chemicals that can lead to the disintegration of concrete are at high risk for corrosion. This type of exposure may require protective measures beyond those required for structures exposed to moisture only. For particularly aggressive chemicals, an impermeable coating on exposed concrete surfaces, polymer concrete, or polymer/sulfur-impregnated concrete may be required to ensure long-term corrosion protection (ACI 548.1R and ACI 548.2R).

2.2.6 Concrete exposed to acid rain—Prolonged release of industrial pollutants, such as sulfur dioxide and nitrogen oxides, has changed the chemical balance of the atmosphere. In North America, this problem is more pronounced in the industrialized regions of the northern U.S. and Canada. When precipitation occurs, rainwater combines with these

oxides to form sulfuric acid, nitric acid, or both, known as acid rain. Acid attack of the concrete cover weakens the physical and electrochemical protection it offers to embedded steel, and the mechanisms of attack have been the subject of numerous studies (De Belie et al. 1997; Bakharev et al. 2003; Zivica and Bajza 2001) and is described in detail in ACI 201.2R.

2.3—Cracking and corrosion

In previous documents presented by ACI Committee 222, it was stated that the role of cracks in the corrosion of reinforcing steel was controversial. Following significant field and laboratory studies, it has been concluded by the committee that cracks, especially cracks parallel to reinforcing steel, reduce the service life of structures by permitting rapid and deeper localized penetration of carbonation and by providing a direct path for chloride ions, moisture, and oxygen to the reinforcing steel (Lindquist et al. 2006; Darwin et al. 2007). Thus, cracks can accelerate the onset and rate of active corrosion. It is not recommended that judicious placement of reinforcing steel to control crack width be used as a primary means of protecting against corrosion. It is essential to have concrete with a low permeability, low potential for plastic and drying shrinkage, low thermal expansion susceptibility, and sufficient cover to protect embedded steel reinforcement.

2.4—Structural details and corrosion

The two most important parameters for corrosion protection are concrete cover and concrete quality (Darwin et al. 1985). Concrete quality is discussed in Chapter 3.

2.4.1 Cover requirements—One of the easiest methods of improving steel reinforcement corrosion protection is to increase the amount of concrete cover. The required minimum cover for reinforcement in most concrete structures not exposed to weather is 3/4 in. (20 mm) (ACI 318). As the risk of corrosion increases, so does the required thickness of concrete cover.

2.4.1.1 ACI 318 requirements—The current ACI 318 minimum concrete cover requirements are summarized in Table 2.1. Where concrete will be exposed to external sources of chlorides in service or to other aggressive environments, a minimum concrete cover of 2 in. (50 mm) for walls and slabs and 2-1/2 in. (65 mm) for other members is required for corrosion protection. For precast concrete manufactured under plant control conditions, a minimum cover of 1-1/2 and 2 in. (40 and 50 mm), respectively, is recommended for walls and slabs.

2.4.1.2 AASHTO bridge specification requirements—Table 2.2 summarizes the minimum concrete cover requirements as specified in AASHTO HB-17. AASHTO HB-17 requires that the values reported in the table be modified depending on the w/cm being used. For w/cm values less than or equal to 0.4, a factor of 0.8 should be applied to the values in the table. For a w/cm greater than or equal to 0.5, a factor of 1.2 should be applied to the values in the table. These factors account for the changes in the rate of transport of deleterious agents in concretes with different w/cm . The

Table 2.1—ACI 318-required minimum concrete cover for protection of reinforcement

	Cast-in-place		Precast concrete, [†] in. (mm) (manufactured under plant-controlled conditions)
	Nonprestressed, [*] in. (mm)	Prestressed, [‡] in. (mm)	
Concrete cast against and permanently exposed to earth	3 (75)	3 (75)	—
Concrete exposed to earth or weather	No. 6 to No. 18 bars: 2 (No. 19 to No. 57 bars: 50) No. 5 bar or smaller: 1-1/2 (No. 16 bar, MW200 or MD200 wire, and smaller: 40)	Walls, panels, slabs, joists: 1 (25) Other members: 1-1/2 (40)	Wall panels: No. 14 and No. 18 bars: 1-1/2 (No. 43 and No. 57 bars: 40) No. 11 bar and smaller: 3/4 (No. 36 bar and smaller: 20)
			Other members: No. 14 and No. 18 bars: 2 (No. 43 and No. 57 bars: 50) No. 6 to No. 11 bars: 1-1/2 (No. 19 to No. 36 bars: 40) No. 5 bar and smaller: 1-1/4 (No. 16 bar, MW200 and MD200 wire, and smaller: 30)
Concrete not exposed to weather or in contact with ground	Slabs, walls, joists: No. 14 and No. 18 bars: 1-1/2 (No. 43 and No. 57 bars: 40) No. 11 bar or smaller: 3/4 (No. 36 bar or smaller: 20)	Slabs, walls, joists: 3/4 (20)	Slabs, walls, joists: No. 14 and No. 18 bars: 1-1/4 (No. 43 and No. 57 bars: 30) No. 11 bar and smaller: 5/8 (No. 36 bar and smaller: 15)
	Beams, columns: Primary reinforcement, ties, stirrups, spirals: 1-1/2 (40)	Beams, columns: Primary reinforcement: 1-1/2 (40) Ties, stirrups, spirals: 1 (25)	Beams, columns: Primary reinforcement: $d_b^{\frac{2}{3}}$ but not less than 5/8 (15) and need not exceed 1-1/2 (40)
			Ties, stirrups, spirals: 3/8 (10)
	Shells, folded plate members: No. 6 bar and larger: 3/4 (No. 19 bar and larger: 20) No. 5 bar and smaller: 1/2 (No. 16 bar, MW200 or MD200 wire, and smaller: 13)	Shells, folded plate members: No. 5 bar and smaller: 3/8 (No. 16 bar, MW200 or MD200 wire, and smaller: 10) Other reinforcement: $d_b^{\frac{2}{3}}$ but not less than 3/4 (20)	Shells, folded plate members: No. 6 bar and larger: 5/8 (No. 19 bar and larger: 15) No. 5 bar and smaller: 3/8 (No. 16 bar, MW200 or MD200 wire, and smaller: 10)

^{*}Shall not be less than that required for corrosive environments or for fire protection.

[†]For prestressed and nonprestressed reinforcement, ducts, and end fittings, but not less than that required for corrosive environments or for fire protection.

[‡] d_b = nominal diameter of bar, wire, or prestressing strand, in. (mm).

minimum cover should be in accordance with the provided table, but in no case should it be less than 1.0 in. (25 mm). Also, AASHTO allows that cover over stirrups or ties to be 0.5 in. (12 mm) less than the values reported in Table 2.2, but never less than 1.0 in. (25 mm). Unlike ACI 318, AASHTO HB-17 allows for reduced cover for epoxy-coated reinforcement. The standard allows for interior exposure cover requirements when the reinforcement is coated with epoxy.

2.4.2 Drainage—The long-term performance of concrete structures, particularly parking structures and bridges, is enhanced by adequate drainage. Unfortunately, this is one of the most overlooked design details. Adequate drainage reduces the risk of corrosion by reducing ponding and the quantity of water and deicing salts that can otherwise penetrate the concrete.

For both bridges and parking structures, the slope required for drainage is a function of both short-term and long-term deflections, camber, surface roughness, and the number and location of drains. Depending on the layout of the structural framing system, drainage can be provided by transverse or longitudinal slopes or both. No simple formula incorporates all the factors that influence slope and drainage. As a rule of thumb, the minimum slope should be 1.5%, with 2% being preferred (ACI 362.1R). Consideration of time-dependent deflections is a critical component of a good drainage system

Table 2.2—AASHTO-required minimum concrete cover for protection of reinforcement

Situation	Cover (in./mm)
Direct exposure to salt water	4.0/100
Cast against earth	3.0/75
Coastal	3.0/75
Exposure to deicing salts	2.5/65
Deck surfaces subject to tire stud or chain wear	2.5/65
Exterior other than above	2.0/50
Interior other than above	
—Up to No. 11 (No. 36) bar	1.5/40
—No. 14 (No. 43) and No. 18 (No. 57)	2.0/50
Precast soffit form panels	0.8/20
Precast reinforced piles	
—Noncorrosive environments	2.0/50
—Corrosive environments	3.0/75
Precast prestressed piles	2.0/50
Cast-in-place piles	
—Noncorrosive environments	2.0/50
—Corrosive environments	3.0/75
—General	3.0/75
—Protected	3.0/75
—Shells	2.0/50
—Auger-cast, tremie concrete, or slurry construction	3.0/75

design. Time-dependent deflections are particularly important for prestressed concrete structures.

Drains should be placed to prevent the discharge of drainage water against any portion of the structure or onto

moving traffic below and to prevent erosion at the outlet of downspouts. For safety reasons, drains in snow-belt areas should also be located to prevent melted snow from running onto a slab and refreezing. Drains, downspouts, and other drainage components should be made of a rigid, corrosion-resistant material and be easy to unclog. Additional information on drainage in parking structures can be found in ACI 362.1R.

2.4.3 Reinforcement—Differences between various types of steel reinforcement—for example, prestressing, nonprestressing, different grades, manufacturers, and sizes—may be significant factors in the electrochemical corrosion of steel. The level of stress in the steel is not a significant factor in electrochemical corrosion, but can be a factor in certain circumstances related to stress-corrosion cracking of prestressing steel.

For any concrete structure, independent of the risk of corrosion, steel reinforcement should be free of loose rust before casting the concrete. Measures should be made to protect steel from exposure to chlorides and other contaminants. Additionally, prestressing steel should be protected from the weather. It is not uncommon for the steel reinforcement in an entire project to be delivered to the site and exposed to weather for months before use. This should be avoided.

Lubricants used to draw prestressing steel appear to raise the chloride-corrosion threshold (Pfeifer et al. 1987). These oils, however, can also adversely affect bond.

Engineering specifications for a project should clearly state quality-control procedures to ensure that the reinforcement is adequately tied and secured to maintain the minimum specified concrete cover.

ASTM A767/A767M requires galvanized reinforcing steel to be treated with a hexavalent chromate to prevent the evolution of hydrogen in fresh concrete. This can occur when an unpassivated zinc surface reacts with hydroxides in fresh concrete (Boyd and Tripler 1968). Hydrogen evolution can also be prevented by adding a small amount of chromate salt to the fresh concrete (Rosenberg and Gaidis 1978). Calcium nitrite has been used to prevent hydrogen evolution of galvanized precast concrete forms (ACI 222R). Additionally, procedures should be provided to minimize electrical connection with nongalvanized metals. The use of chromate may be regulated due to health concerns. Research by Tan and Hansson (2008) has found that the chromate treatment may not be necessary.

When epoxy-coated reinforcement is used, ACI 222R recommends that there should be no reduction in cover. Because macrocells can develop where defects occur in the coating, project specifications should clearly state quality control of the coating and provide procedures to minimize or avoid electrical contact with uncoated metals.

Structures that use unbonded post-tensioned construction require protective measures, especially in aggressive chloride environments.

Because the prestressing elements may not be directly protected by an alkaline environment, but instead by a combination of either duct and grout or sheathing and grease, project specifications should clearly indicate that protection be maintained for the full length of the tendon and that the

duct or sheathing material should be impermeable to water. For unbonded tendons in aggressive environments, the project specifications should require that sleeves used to connect the sheathing to the anchorage of encapsulated systems should have a positive mechanical connection to the anchorage at all stressing, intermediate, and fixed ends.

ACI 423.7 and ACI 301 provide guidance for additional measures such as corrosion-resistant grease and anchorage protection. Corrosion-related failure of unbonded prestressing tendons in building and parking structures has occurred in the absence of chlorides (Schupack 1982; Schupack and Suarez 1982). Unbonded monostrand installed before 1985 often had inadequate sheaths and grease protection. When the provisions of Post-Tensioning Institute (PTI) “Specifications for Unbonded Single Strand Tendons” (1985) are rigorously followed, corrosion rarely occurs.

Grouted tendons have had corrosion incidents caused by poor grouting materials, techniques, and anchorage protection (Schupack 2004). The PTI grouting specification (1985) and ACI 423.9M provide more stringent requirements relating to grouting materials, techniques, and anchorage protection.

2.4.4 Joints—Joints should be constructed and sealed to prevent leakage. ACI 224.3R provides guidance on design and detailing of joints in concrete structures. Additional information on the design of joints for parking structures can be found in ACI 362.1R. A discussion on various coatings for waterproofing concrete can be found in ACI 515.1R.

2.4.5 Overlays—For concrete structures with a high risk of corrosion, particularly due to external chloride, low-permeability overlays have been used as an alternative protection method. The overlay provides additional concrete cover to protect embedded reinforcement. In some cases, however, such as bridge decks, the use of overlays has been shown to increase cracking (Darwin et al. 2004), with a commensurate increase in chloride content at the level of the reinforcing steel (Darwin et al. 2006).

Overlays intended to reduce chloride ingress have been made with concrete with a low w/cm , latex-modified concrete, polymer concrete, and concrete with pozzolan (ACI 224R). Designs should include the compatibility of the overlay and the substrate concrete in terms of mechanical properties and should consider potential shrinkage cracking caused by restrained volume changes.

2.4.6 Embedded items—In general, any embedded metal in concrete should have the same minimum concrete cover as that recommended for steel reinforcement for the anticipated exposure conditions. If this cannot be achieved, then additional protective measures are needed. Embedded items require additional protection when exposed to an aggressive environment.

Precast parking structures often contain weld plates used to connect components. In aggressive environments, consideration should be given to the use of galvanized or stainless steel for these plates or painting the plates with epoxy after field welding. If the connection plates are galvanized, consideration should be given to the possibility of developing galvanic cells if connections are made to nongalvanized steel. Similar galvanic cells can be formed between architectural features, such as handrails, and the

reinforcement. Such architectural features should be galvanized or otherwise protected such that galvanic cells are not formed.

In submerged concrete structures with unbedded, freely exposed steel components in contact with reinforcing steel, galvanic cells can develop with the freely exposed steel forming the anode and the embedded steel forming the cathode. This can cause corrosion of the embedded, freely exposed steel. If exposed connections are necessary, then corrosion protection, such as the use of an epoxy coating, is necessary.

CHAPTER 3—IMPACT OF MIXTURE PROPORTIONING, CONCRETING MATERIALS, AND TYPE OF EMBEDDED METAL

3.1—Influence of mixture proportioning on corrosion of reinforcing steel

3.1.1 Introduction—The proportioning of concrete mixtures that enhance the corrosion resistance of reinforcing steel is not substantially different from the proportioning of mixtures for any high-quality concrete. The goal is to use available materials to develop a concrete mixture that will permit mixing, transporting, placing, consolidating, and finishing in the fresh state and, when cured properly, will have a low permeability in the hardened state. Mixture proportions should permit pumping of the concrete, if required, and control bleeding and minimize shrinkage.

ACI 201.2R describes in detail the general durability of concrete, determined largely by the selection of cement, aggregates, water, and admixtures. When considering the effects of reduced permeability, freezing-and-thawing resistance, alkali-aggregate reaction, and sulfate attack on the corrosion of reinforcing steel, the most important concrete property is reduced permeability. Permeability describes the rate of movement of liquids or gases through concrete and is related to the connectivity of pores and voids in the hardened concrete. Assuming there is adequate curing, permeability can be reduced primarily through the use of chemical admixtures to achieve the lowest practical w/cm , and secondly through the use of pozzolanic admixtures, supplementary cementitious materials, and polymers (ACI 212.3R, ACI 212.4R, ACI 232.1R, ACI 232.2R, ACI 233R, ACI 234R, and ACI 548.1R).

3.1.2 Benefits of low w/cm —The benefits of reducing the w/cm to delay the corrosion of reinforcing steel are demonstrated in ACI 222R, which shows that the reduction in the flow of oxygen through concrete is a function of the reduction in w/cm . The report also shows the effects of w/cm on reducing salt penetration and increasing time-to-corrosion. In each of these cases, the benefit of reducing the w/cm can be interpreted as a result of the reduction in the permeability of the concrete.

For these reasons, w/cm is limited to certain maximum values for concrete that will be exposed to a corrosive environment. ACI 201.2R and ACI 211.1 contain recommended values for w/cm , and Chapter 4 of ACI 318 gives maximum values for the w/cm . All three documents recommend that w/cm should not exceed 0.40 for concrete exposed to chlorides from seawater, deicing salts, and other sources. AASHTO HB-17 limits the w/c to 0.49 for Class P > 4000 psi (> 28 MPa) concrete.

In cases where the shrinkage of concrete is restrained, such as bridge decks, the use of a lower w/cm can have negative

effects in the form of increased cracking (Krauss and Rogalla 1996; Darwin et al. 2004). The increased cracking is caused by a decrease in tensile creep that results from the increase in concrete strength obtained with the lower w/cm . High-strength concrete exhibits less creep, even at the same stress-strength ratio, than normal-strength concrete (Smadi et al. 1987).

3.1.3 Proportioning mixtures for low w/cm —Reducing the quantity of mixing water relative to the mass of cementitious materials decreases the w/cm . Simply removing water from a given mixture, however, will generally result in a less workable mixture. To preserve workability, which is typically characterized by slump, and reduce w/cm , it is necessary to maintain the water content while increasing the cementitious materials content. By doing this, the contractor's placement needs can be met, while at the same time providing the dense, low-permeability concrete required. This means that a low- w/cm mixture will have increased cement content and an accompanying increase in cost. For concrete with a low slump or low water demand, this approach is satisfactory for moderate reductions in the w/cm .

For mixtures requiring a greater slump for placement or finishing purposes, or for the establishment of a w/cm of 0.40 or less, an increase in cement content alone will lead to excessive cement factors, which can lead to concrete mixtures with high mortar contents and an increased tendency toward plastic and drying-shrinkage cracking. In addition, the heat of hydration developed with higher cement contents results in higher early-age temperatures, which can lead to thermal cracking if proper actions are not taken to minimize high thermal gradients in the concrete element. To reduce the water content at a given cement content, water-reducing admixtures, which effectively reduce the water content required to obtain a desired slump, are used. The reduced water content may then lead to reduced cement content for the same w/cm . For greater reductions in water, high-range water-reducing admixtures (HRWRAs) (ASTM C494/C494M Types F and G) are used.

The effects of aggregate size and gradation on the water content required for a particular level of workability should not be overlooked. Smaller aggregate sizes demand more water as do intentionally or unintentionally gap-graded aggregates. By using the largest aggregate size commensurate with the structural details of the members being placed and controlling gradations, it is possible to reduce the water and cement contents required for a particular w/cm . It can be more economical to design a low- w/cm , low-permeability mixture based on 1-1/2 in. (37.5 mm) coarse aggregates than with 3/8 in. (9.5 mm) coarse aggregates. Further, appropriate selection and gradation of aggregates permit pumping, placement, and finishing of concrete at a lower slump than required when less-than-optimum aggregate sizes and gradations are used.

3.2—Influence of selection of cement, aggregates, water, and admixtures on corrosion of reinforcing steel

3.2.1 Selection of cement—The influence of portland cement's chemistry on the corrosion of reinforcing steel is discussed in detail in ACI 201.2R, 222R, 225R, and Whiting

(1978). The characteristic alkaline nature of hardened cement paste normally maintains the corrosion resistance of steel in concrete; this protection is lost when chloride ions contaminate concrete or when carbonation occurs.

One of the mineral constituents of portland cement, C_3A , (tricalcium aluminate) has the ability to react with chloride ions to form chloroaluminates, thereby reducing the impact of chloride contamination on corrosion. C_3A can represent 4 to 12% of the mass of cement. ASTM C150/C150M cement types (Types I through V) contain varying amounts of C_3A , but the effect of this constituent is not sufficiently clear to warrant selecting a chloride-reducing cement on the basis of C_3A content. Further, other durability problems, such as sulfate attack, become more likely as the C_3A content is increased. There is work, however, that shows corrosion initiates early in Type V cements in the presence of chloride and in chloride environments (Masledhuddin et al. 2007; Page et al. 1981). Also, in the presence of chloride, there is no increase in the susceptibility to sulfate attack with higher C_3A content (Rasheeduzzafar et al. 1990; Sakr 2005).

Higher-alkali cements are effective in providing a higher pH environment around the steel and reducing the corrosion potential of steel in the presence of chloride ions. Similarly, the use of a cement with a higher alkali content increases the risk of alkali-aggregate reaction. Unless the producer is certain that the aggregate selected for the concrete mixture is non-alkali reactive, the use of high-alkali cement to enhance corrosion resistance is not recommended.

Any portland cement meeting the requirements of ASTM C150/C150M can be used to produce a high-quality concrete that will reduce or prevent the corrosion of embedded reinforcing steel. Factors such as the selection and maintenance of a low w/cm and proper placement, consolidation, finishing, and curing practices are more important than the selection of cement in regard to corrosion.

Blended cements, in which the portland-cement clinker is interground with a supplementary cementitious material, will result in reduced permeability in suitably designed concrete. Uniform dispersion of the blended cement is needed but is harder to maintain as the difference in particle-size distribution between the cement and the blended supplementary cementitious material increases. When properly dispersed, silica fume or other supplementary cementitious materials can significantly reduce chloride ingress.

3.2.2 Selection of aggregates—ACI 201.2R and 222R discuss aggregate selection for durable concrete. Issues such as soundness, freezing-and-thawing resistance, wear resistance, and alkali reactivity should be addressed in addition to other aggregate characteristics that relate to the corrosion protection for the steel.

Two primary issues govern the selection of aggregates for use in concrete exposed to a corrosive environment:

1. The use of aggregates that introduce chloride ions into the mixture, which is discussed in detail in ACI 201.2R and 222R; and
2. The development of corrosion-resistant concrete is the proper selection of aggregate size and gradation to enhance the workability of the mixture and reduce the required water content (Section 3.1).

The chloride-ion concentration limits discussed in this guide can be exceeded through the use of aggregates that contain absorbed chloride ions. Judicious materials selection requires that the chloride-ion content of the proposed aggregates be evaluated before use. Free chlorides on the surface or readily available from pore spaces in the aggregate can be determined by relatively simple analytical means (Gaynor 1986). Tightly bound chlorides, however, will not likely contribute significantly to corrosion. It has been shown, however, that the bound chlorides can be released and contribute to the corrosion (Glass and Buenfeld 2000). Determination of the amount of bound chlorides that can enter into the pore solution requires specialized testing procedures (Hope et al. 1985; ACI 222R).

Once an aggregate source has been selected, attention should be given to monitoring the moisture content of both the coarse and fine aggregates at the time of inclusion in the mixture. Errors in assessing the moisture content can lead to substantial increases in the w/cm of the mixture, resulting in dramatic increases in permeability.

3.2.3 Selection of mixture water—Seawater should never be used to make concrete for reinforced structures. Water with chloride contents exceeding values given in ASTM C1602/C1602M should not be used to make concrete for reinforced structures because it may contribute enough chloride ions to cause serious corrosion problems.

3.2.4 Selection of chemical and supplementary cementitious admixtures—A wide variety of chemical and supplementary cementitious admixtures is available that either directly improves the corrosion protection provided by the hardened concrete or modifies the properties of the fresh concrete, permitting the use of lower w/cm mixtures with their accompanying benefits in enhancing corrosion protection. Certain admixtures, however, can increase the chloride-ion content, lowering corrosion protection. It may be necessary to determine the chloride-ion contribution of the admixture before use. Additionally, it is wise to check the compatibility between cement, admixtures, and other concrete ingredients by making field trial batches before starting construction. Incompatibility of materials can lead to rapid slump loss, rapid set, and increased water demand, which can adversely affect the corrosion resistance of the concrete.

3.2.4.1 Chemical admixtures—These materials are generally added in liquid form either during batching or upon arrival at the job site. The quantities used are quite small relative to the mass or volume of other materials in the concrete mixture, and careful control of the dosage is required. For example, it would not be unusual to add less than 18 fl oz. (530 mL) of admixture to 4000 lb (1820 kg) of fresh concrete. ACI 212.3R contains specific guidance relating to the use of admixtures. Admixtures can be grouped into the following classifications:

- **Air-entraining admixtures**—The use of air-entraining admixtures to develop a proper air-void system in concrete is necessary in a freezing-and-thawing environment. In many concrete mixtures, air entrainment also permits a reduction in water content because the air bubbles increase the workability of the mixture. The cement content of the mixture is held constant while the