Admixed Chlorides in Concrete: History, Impacts, and Standardization

David Trejo¹ and Richard Weyers²

Abstract: The presence of chlorides in cementitious materials results in corrosion of the embedded metallic materials. Early construction practices (pre 1960s) relied on admixed calcium chloride to accelerate the early strength gain of concrete. Until the 1950s, few publications focused on the effects of chlorides in concrete on corrosion and the use of chlorides was well established. However, in the 1960s significant publications reported on the effects of chlorides on the corrosion of prestressed wires and strands - these publications were the result of several failures of prestressed systems. Later, significant research was performed on the corrosion of steels in cementitious materials—a significant portion of this work attributable to the researchers being recognized in this symposium: Brian Hope and Morris Schupack. Their considerable efforts led to new knowledge regarding corrosion durability of reinforced and prestressed systems. Recently, ACI Committees 201 and 222 standardized limits on allowable admixed chlorides in the constituent materials. However, more standardization is needed-ACI Committees 318 and 349 report different admixed chloride limit requirements than Committees 201 and 222. This paper provides an overview of past research, analyzes the effects of chlorides on service life and economy and provides data from a research project. Using this information, the authors propose a standardized limit for chlorides in concrete.

Keywords: chlorides; corrosion; concrete; threshold; durability; service life; economic analysis

^{1.} Department of Civil an Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR 97331

^{2.} Department of Civil and Environmental Engineering, Virginia Tech, 200 Patton Hall, Blacksburg, VA 24061-0105

David Trejo is Professor and Hal D. Pritchett Endowed Chair in the School of Civil and Construction Engineering at Oregon State University. He is the Chair of ACI 222—Corrosion of Metals in Concrete and members of 201—Durability, 236—Materials Science, and 365—Service Life. His research interests include assessment and development of materials for improved constructability and durability.

Richard Weyers is the Via Emeritus Professor in the Charles E. Via, Jr. Department of Civil and Environmental Engineering at Virginia Polytechnic University. He is actively involved in research investigating corrosion and durability of concrete structures, with specific focus on bridges. He is a member of ACI Committees 222—Corrosion, 345—Concrete Bridge Construction, Maintenance, and Repair, 365—Service Life, and 548—Polymers and Adhesives.

INTRODUCTION

It is well known that chlorides cause premature corrosion of steel reinforcement in concrete. However, significant debate exists as to how chlorides initiate and propagate corrosion of the steel reinforcement in concrete, how much chlorides can safely be admixed³ in fresh concrete, and how much chlorides are needed to initiate the corrosion process. This paper will provide a simple overview of how chlorides initiate and propagate corrosion of steel reinforcement embedded in concrete. A review of the literature and specifying codes and how these documents evolved over time is then presented. This information is used to better understand the challenges associated with limiting admixed chlorides and how and why the existing limits were developed. Using the current limits for allowable admixed chlorides in concrete, a deterministic analysis of the effects of admixed chlorides on time to corrosion initiation and service life is provided. This is followed by an economic analysis that assesses the value of not using concrete constituent materials that contain chlorides. This analysis is followed by a section describing a small research test program that evaluated the corrosion activity of cementitious systems containing varying amounts of admixed chlorides. Using the information on the mechanisms of chloride induced corrosion, the history of admixed chloride limits in the literature and ACI documents, the effect of admixed chlorides on time to corrosion, service life and costs, and using the data obtained from the research, recommendations are made for standardizing limits on admixed chlorides.

MECHANSIMS OF CHLORIDE INDUCED CORROSION

Chloride-induced corrosion of steel reinforcement requires that sufficient chlorides be present at the steel-cementitious materials interface. Chlorides can be introduced to the steel-cementitious materials interface via inclusion of chlorides into the fresh mixture or via transport through the cementitious system. When chlorides are included in the fresh concrete mixture, either from residual or contaminated constituent materials or intentionally added, these chlorides are immediately present at the steel-cementitious material interface, available for the corrosion

^{3.} Admixed chlorides are defined in this paper as any chlorides that are present in the concrete during mixing. This can include chlorides naturally present in constituent materials (cement, aggregate, water, or supplementary cementing admixture) or from an admixture.

process. If present in sufficient quantities, these chlorides can initiate corrosion immediately; if present in less than sufficient quantities, these chlorides reduce the amount of transported chlorides needed to initiate corrosion. If sufficiently low or no chlorides are present in the cementitious system, all chlorides must be transported through the cementitious material to the interface. Because the transport (diffusion, permeation, convection, or migration) of chlorides through cementitious systems is a relatively slow process, the addition of chlorides to the fresh mixture can reduce the time to corrosion initiation of the steel reinforcement. Significant debate exists as to how much chlorides can be present in the fresh mixture and this topic will be addressed later. The point here is that chlorides are needed at the steel surface.

The corrosion resistance of steel is often related to the formation of a passive film. Passive films protect the base steel from reacting with constituents from the environment, thus improving its corrosion resistance. Very little research has been performed to assess the passive film on hotrolled steel reinforcement. Steel reinforcement is generally produced using scrap materials. The scrap materials are melted and molded into billets. These billets are often stored and when needed, rolled at high speeds. The rolling process consists of continuously reducing the steel cross-section until the desired shape and size is achieved. Most steel mills hot roll the steel product under atmospheric conditions, resulting in the formation of a mill-scale on the surface of the steel. Mill-scale typically consists of iron oxides, often hematite or magnetite and can be both beneficial and detrimental to corrosion initiation and propagation. If the mill-scale is continuous and in compression, the scale acts as a barrier and is considered beneficial. If the mill-scale is in tension and discontinuous, the discontinuous sites are susceptible to accelerated corrosion because the protection from the mill-scale does not exists and because the mill-scale is cathodic to the base steel. Large cathodes to anode areas, as would be the case for breaks in the mill-scale, result in accelerated corrosion. Pillai and Trejo (2005), Mohammed and Hamada (2006), Mahallati and Saremi (2006), and Ghods et al. (2011) all reported that reinforcing steels containing mill-scale exhibited lower resistance to corrosion than polished steels, indicating that the current process of producing steels results in the mill-scale being discontinuous. Figure 1 shows typical surfaces for two commercially available reinforcing steels. These conditions make for variable corrosion.



Figure 1—Micrographs of mill-scales for steel meeting ASTM specifications (a) A615 and (b) A1035

At locations where the mill-scale is discontinuous, a passive film likely exists. Passive films have been reported to be thin layers of oxides that occupy the reactive atom sites on the metal surface. By occupying these reactive sites, the film reduces the opportunity of metal atoms from reacting, thus preventing corrosion. Ghods et al. (2010, 2011a, 2011b) showed that the passive film on

steel in highly alkaline environments is approximately 5 nm ($2x10^{-4}$ mils) thick and is composed of a thin and dense protective inner layer on the steel surface and a thick and porous outer layer. The inner protective layer was reported to be mostly composed of Fe²⁺ oxides and contained relatively smaller amounts of Fe^{3+} oxides. The outer layer contained relatively larger amounts of Fe⁺³ oxides than the inner layer. Other theories are also reported. However, this film is also likely heterogeneous, discontinuous, and its integrity and thickness vary with time before the chloride reaches the steel surface. Jones (1982) reported that corrosion initiation is likely a result of the electrostatic attraction between the positively charged metal surface (without an oxide layer) and the negatively charged chlorides. Hime and Erlin (1987) reported that the chlorides react with the unprotected ferric and ferrous ions to first produce ferrous chloride. The ferrous chloride then reacts with hydroxyl ions to produce iron hydroxide (Fe(OH)₂), freeing the chlorides to further react with more ferric and ferrous ions. Janik-Czakor et al. (1975) reported that chlorides accumulate at the steel surface and form a hydrochloric acid below the accumulated chlorides. The porous iron hydroxide and the lower pH environment lead to localized corrosion. Figure 2 shows a schematic of the process. Note that water is converted to hydroxyl ions and the chlorides are released to further react with the base steel. This indicates that once chlorides react, they are always available for further reaction. This also shows that the availability of water is necessary for the reaction to continue.



Figure 2—Simplified schematic of chloride-induced corrosion.

HISTORY OF CHLORIDE LIMITS

Chloride salts have been used in or on concrete for some time and the potential negative impacts of salt on corrosion were reported as early as 1924. Abrams (1924) reported when using seawater as mixing water for concrete that "in spite of satisfactory strength results, it seems unwise to use sea water in reinforced-concrete construction, particularly in the tropics on account of danger of corrosion of reinforcement." In 1936, Gonnnerman et al. reported on the effects of calcium and sodium chloride deicers on concrete performance and in 1939, Jackson and Kellermann reported on the potential use of chlorides as curing compounds. However, with the exception of Abrams reference, little was published early on chlorides and corrosion. In 1959, Shalon and Raphael performed a comprehensive study investigating the effects of sea water on corrosion of reinforcement in concrete. The authors concluded that "sea water used for mixing mortar or

concrete for air-exposed reinforced structures tends to make the reinforcement highly vulnerable to corrosion." Further highlighting the potential challenges with chlorides in concrete, Monfore and Verbeck (1960) reported that calcium chloride should not be used in prestressed concrete. The work by Monfore and Verbeck was initiated mostly as a result of several corrosion failures of prestressed structures. However, the benefits of chloride as a deicer and accelerator had already been established (Rosenberg 1964). In 1965, ACI 604-Recommended Practice for Cold Weather Concreting, reported that "calcium chloride can be used safely as an accelerating admixture" but should not be used for prestressed concrete or when galvanized forms or decks are used. The document also noted that galvanic corrosion is intensified when calcium chloride is added to concrete. Hausman (1964) provided a good overview of corrosion of steel in concrete and later in 1969 Szilard reported that "reinforced and prestressed concrete bridges exposed to marine environment... frequently exhibit damage due to corrosion." Szilard also noted that this corrosion was in part due to the seawater's chloride content. Hausman's and Szilard's work further supported the concept that chlorides led to early and continued corrosion of reinforcement in concrete. However, in 1970, Tenaja reported that seawater could be used to make concrete if "proper mix design, quality, and workmanship" were employed. Later, Verbeck (1975) published a comprehensive article on the mechanisms of corrosion for steel in concrete and in the same year Erlin and Verbeck (1975) documented specific research needs to prevent corrosion for new and existing structures. The relationship between chlorides and corrosion was now clearly established.

Even with this knowledge, few limits were placed on using admixed chlorides in concrete. Even though there was some early (1904) work on corrosion of steel in concrete, the early ACI documents did not address the issue of chlorides and corrosion. ACI 318-47 (1949) made no reference to limiting chlorides in concrete and in fact, ACI 604-48-Recommended Practice for Winter Concreting Methods (1949) allowed the use "of small amounts of additional cement or accelerators such as calcium chloride to accelerate the hardening of the concrete at low temperatures (above 32 F) ..." The 318-47 requirement for water noted that water "shall be clean, and free from injurious amounts of oils, acids, alkalis, organic materials, or other deleterious substances." ACI 318-63 modified the requirement for water to the following: "water used for mixing concrete shall be clean and free from injurious amounts of oils, acids, alkalis, salts (emphasis added), organic materials, or other substances that may be deleterious to concrete or steel." The commentary for ACI 318-63 (1964) specifically noted that for prestressed structures, "calcium chloride or an admixture containing calcium chloride shall not be used" for concrete or grout. The document also specified that "seawater shall not be used" for prestressed concrete, however, no limits on the use of seawater in grout were specified. ACI 604-56 (1964) still allowed "calcium chloride to accelerate hardening of the concrete in cold weather" allowing 2% calcium chloride, except when sulfate-resisting concrete was required. Sulfate-resisting cements have low C₃A contents—Hope and Ip (1987) reported that cements and supplementary materials that contain higher C₃A contents have higher chloride binding capacities, thus reducing the potential for corrosion. More interesting, however, was a footnote added to the section on accelerators. The footnote noted that "another exception to use calcium chloride may be when there is reason to suspect that steel will be corroded by stray currents. In this event, an extra sack of cement should be used in preference to calcium chloride." The footnote went on to discuss results from the U.S. Bureau of Standards Technical Paper No. 18 (1913) reported in the Highway Research Board Bibliography No. 13, where "calcium chloride, even to the small extent of 0.03 percent, has been found to accentuate the effect of stray electric currents in

causing corrosion of iron." The footnote further went on to note that "calcium chloride should not be used in prestressed concrete because of possible stress corrosion of the highly stressed special wire steel, but ordinary reinforcement is not affected." Clearly, the cause and effect of chloride and corrosion had not yet made it into the code. ACI 604-56 noted that only 1 percent calcium chloride was the "minimum requirements for jobs taking maximum risk."

The potential issues with chlorides in concrete had been established, but the ACI Committees were struggling with how or whether limits were needed for conventionally reinforced structures. The issue with limits on chlorides in prestressed structures was clear as several failures had occurred with prestressed structures that had chlorides admixed into the concrete. As such, ACI 201 (1970) reported that "calcium chloride and other soluble chlorides should not be used as admixtures in prestressed concrete." The document also discussed the potential challenges of adding chlorides to concrete for structures exposed to marine conditions or conditions where "water-soluble salts" were present. Although caution was expressed, no limits on chlorides were presented for conventionally reinforced concrete structures. However, ACI 201 (1970) did place limits on the water-cement ratio and these limits were based on exposure condition and member type. For thin sections exposed to seawater, a maximum water-cement ratio of 0.4 (4.5 gallons per sack)—for moderate and thick sections the water-cement ratio could be increased to 0.45 (5.0 gallons per sack). Recommended water-cement ratios ranged from 0.4 to 0.53 (4.5 to 6 gallons per sack).

ACI 318-71 underwent significant changes from ACI 318-64. The former document prohibited the use of calcium chloride in both grout (for bonded tendons) and concrete and noted that "attention is called here to the possible adverse effects of excessive chloride ions in the presence of aluminum and, and in prestressed concrete." The commentary also noted that "a new provision has been added concerning chloride ion content of water (including the portion of the mixing water contributed from the free moisture of aggregates) to be used in prestressed concrete or in concrete with aluminum embedment." The commentary went on to note that "no numerical quantities are stipulated" but "it is suggested that chloride ion concentrations exceeding 400 or 500 ppm might be considered dangerous…" The commentary also noted that ACI 222 recommended levels well below these values and recommended that chlorides contained in the aggregate and admixtures should be considered in evaluating the acceptability of total chloride content in the mixing water.

ACI 318-77 included only minor revisions to the chloride limits established in ACI 318-71. Interestingly, the commentary noted that "*high* (emphasis added) concentrations of chloride ion may be harmful in prestressed concrete, because of possible corrosion, and in concrete containing aluminum..." The suggested levels of 400 to 500 ppm were replaced by "high." Clearly, the Committee was struggling with the issue of chloride limits and corrosion.

ACI 201.2R-77 was one of the first ACI documents to detail challenges associated with chlorides and specifically addressed the issue of limiting admixed chlorides in the concrete mixture. The document noted the potential hazards of chlorides but noted that "specifying a zero chloride content for the mix, however, is impossible to realize in practice." The 1977 document noted that "the threshold value for a chloride content in concrete necessary for the corrosion of embedded steel can be as low as 0.15 percent by weight of cement" but cautioned that this universal limit did not consider availability of chlorides, oxygen, and moisture. Interestingly, this chloride limit

seemed to be based on three references: two from studies on bridge decks and one on general corrosion of steel in concrete. A discussion was provided regarding "soluble" and "combined" chlorides, challenges with these different tests methods, and how these influence corrosion. More specifically, the 201.2R-77 document provided specific limits for chloride in concrete prior to service exposure based on total chlorides (i.e., free and combined chlorides). These limits were 0.06 for prestressed concrete, 0.10 for reinforced concrete in moist environment and exposed to chlorides in service, 0.15 for reinforced concrete in a moist environment but not exposed to chlorides, and no limits for above ground building construction that will stay dry—all chloride limits were based on weight percent of cement. The document noted that these limits were in agreement with ACI Committee 222, even though the 222 Committee would not publish its first document for another eight years. The 201 document also noted that calcium chloride should not be "intentionally added to the mix in prestressed concrete or conventionally reinforced concrete which will be exposed to moisture and chlorides in service."

ACI 318-83 revised the requirements for chlorides to state that "calcium chloride or admixtures containing chloride from other than impurities from admixture ingredients shall not be used in prestressed concrete, in concrete containing embedded aluminum, or in concrete cast against stay-in-place galvanized metal forms." This did not agree with the 1977 201 document that limited calcium chloride use to conventionally reinforced structures that were exposed to a dry environment with or without chlorides and to moist environments containing no chlorides. The 1983 318 code also published specific limits (based on weight of cement) on the chlorides based on structure type or exposure conditions-the beginning of a long dispute. The 318 code specifically noted that "for corrosion protection, maximum water soluble chloride ion concentrations in hardened concrete at an age of 28 days contributed from the ingredients" shall not exceed a specific weight percent of the cement. The published limits were 0.06 for prestressed concrete, 0.15 for reinforced concrete exposed to chlorides in service, 1.00 for reinforced concrete that will remain dry in service, and 0.30 for other reinforced concrete. The 1977 201 guide and the 1983 318 Code agreed on the 0.06 limit for prestressed concrete. However, the 1977 201 Guide recommended lower limits than the 1983 318 Code for reinforced concrete exposed to chlorides in service (0.10 versus 0.15) and for reinforced concrete exposed to moisture (0.15 versus 0.30). The 1983 318 Code was more conservative on chloride limits for dry conditions, requiring one percent maximum versus no limit for the 1977 201 Guide. The 1983 318 Code also placed a maximum water-cement ratio (0.40), a minimum strength (4750 psi [33 MPa]), and a minimum cover for corrosion protection of reinforced concrete exposed to deicing salts, brackish water, seawater or spray from these sources. Although progress was being made on limiting chlorides in concrete, variations in limits were leading to confusion.

In 1985 ACI Committee 222 published its first document on corrosion of metals in concrete and noted in the document that "placing limits on the allowable amounts of chloride ion in concrete is an issue still under active debate." The document suggested acid soluble limits based on weight of cement of 0.08 for prestressed concrete and 0.20 for reinforced concrete. The Committee opted to specify chloride limits based on acid soluble testing because it was believed that acid soluble testing provided more consistent results than water soluble testing and because carbonation could lead to release of the chlorides (Tutti 1982). In general, the 0.08 limit was considered to be similar to the 0.06 limits reported by Committees 201 and 318 as water-soluble chloride contents were widely reported to be about 75 to 85% of acid soluble chloride contents (Hope and Poland 1987, Enevoldsen et al. 1994). The 222 chloride limits reported for reinforced

concrete were similar to those reported by 201 (75% of 0.20 is 0.15, where 0.15 is the limit in the 201 document). The 1985 222 document noted that "there are some exposure conditions where the chloride levels may exceed the recommended values and corrosion will not occur." These conditions included submerged conditions where oxygen would not be available and cases where "concrete is continuously dry." However, no limits were suggested for these cases. The 1985 222 document noted that its chloride limits differed from the values reported in the documents by Committees 201 and 318 and noted that "committee 222 has taken a more conservative approach because of the serious consequences of corrosion, the conflicting data on corrosion threshold values, and the difficulty in defining the service environment throughout the life of a structure." In fact, the 222 limits could be considered to be less conservative than the limits published in the 201 document, but more conservative than the limits published in the 318 document.

ACI 318-86 attempted to further clarify limits on chlorides in concrete. First, the 1986 document specified testing for chlorides be performed on the hardened concrete of ages between 28 and 42 days (ACI 318-83 required testing at an age of 28 days). This document also defined that testing conform to test procedures described in Federal Highway Administration Report No. FHWA-RD-77-85, *Sampling and Testing for Chloride Ion in Concrete*. The commentary for ACI 318-86 also noted that the chloride limits were different than those published in ACI 222 and ACI 201. Table 1 shows a comparison of the limits published by the different ACI documents in 1987. The 318 code tended to take a less conservative approach to limiting chlorides than recommendations from Committees 201 and 222.

| Exposure/Structure Type | Max Chloride (% weight of cement) Allowed in New Concrete as Published in 1986 ACI Committee Documents | | | |
|---|---|---------------------------------|---|--|
| | 201 (water-soluble) | 222 (acid-soluble) | 318 (water-soluble) | |
| prestressed concrete | 0.06 | 0.08 | 0.06 | |
| reinforced concrete exposed to chlorides in service | 0.10 | 0.20 | 0.15 | |
| reinforced concrete exposed to damp exposure in service | 0.15 | 0.20 | 0.3 | |
| reinforced concrete that will remain dry in service | 1.0 | higher than other 222 limits | 1.0 | |
| reinforced concrete that is continuously submerged | Depends on whether exposure is to fresh or salt water – see above | higher than other 222 limits | Depends on whether exposure is to fresh or salt water – see above | |

Table 1 Published chloride limits in concrete as reported by different ACI Committees

The 1995 and 2002 318 Codes required the same limits published in Table 1. One significant difference between the ACI 318-86 and 318-95 codes were that allowable water-cement ratio (w/c) limits were changed to allowable water-cementitious materials ratio (w/cm) limits. The limiting values were in general the same values. The 1996 version of the 222 document included recommended limits for acid- and water-soluble chlorides. In addition, the 1996 222 document included a new test method for assessing water-soluble chlorides in the constituent materials. The limits published in the 1996 222 document are shown in Table 2 (these limits were also published in the 2001 and 2011 versions of the document). These limits varied significantly from the 201 and 318 limits published in 1986 and specifically noted that limits were "expressed as a percentage by weight of portland cement," potentially implying that limits for w/cm were not

appropriate. In addition, the 1992 and 2001 201.2R document removed chloride limits and simply referred to levels reported in the 222R document. The 201.2R-08 document reprinted the 222 table limiting admixed chlorides. Committees 201 and 222 seemed to reach agreement on limiting admixed chlorides in concrete.

| Eurosuus/Stanatuus Turo | Chloride Limit for New Construction (by wt. of portland cement) | | | |
|---------------------------------------|---|---------------|--------|--|
| Exposure/Structure Type | Acid-Soluble | Water-Soluble | | |
| Test Method | ASTM C1152 | ASTM C1218 | Soxlet | |
| prestressed concrete | 0.08 | 0.06 | 0.06 | |
| reinforced concrete in wet conditions | 0.10 | 0.08 | 0.08 | |
| reinforced concrete in dry conditions | 0.20 | 0.15 | 0.15 | |

Table 2 Chloride limits published in ACI 222R-96, ACI 222-01, and ACI 222-11

In 2008, ACI 318 published a significant revision to the chloride limits. The document defined exposure classes for different exposure conditions. The document listed three classes: class C0 consisted of concrete that is dry or protected from moisture; class C1 (moderate exposure) consisted of concrete exposed to moisture but not to external sources of chlorides, and; class C2 (severe exposure) included concrete exposed to moisture and an external source of chlorides. Class C0 was to be assigned when exposure conditions do not require additional protection against the initiation of corrosion; C1 and C2 are assigned when additional protection is required, making the degree of protection dependent on the severity of the exposure condition. The 318-08 document specified maximum w/cm, minimum design strength (f_c') , minimum cover, and maximum chloride content. The limits from 318-08 are shown in Table 3. These limits are essentially the same limits from the earliest 318 document, but with defined exposure conditions.

| Exposure Class | Max w/cm | Min specific strength, f'_c , psi [MPa] | Max water-soluble chloride content in concrete, percent by weight of cementReinforcedPrestressed | |
|-------------------|----------|--|--|----------|
| | | | Concrete | Concrete |
| CO | N/A | 2500 (17) | 1.00 | 0.06 |
| C1 | N/A | 2500 (17) | 0.30 | 0.06 |
| C2 | 0.40 | 5000 (34) | 0.15 | 0.06 |

Table 3 Chloride limits published in ACI 318-08

In addition to the 201, 222, and 318 documents, Committee 349—*Concrete Nuclear Structures* provides limits for admixed chlorides in concrete. ACI 349-06 recommends a maximum water-soluble chloride content for corrosion protection of 0.06 percent by weight of cement for prestressed structures and 0.15 percent by weight of cement for reinforced concrete structures. These limits are higher than the 222 limits for "wet conditions" and the 201 limits for exposure "to chlorides in service," and are the same as the 318 document for reinforced structures exposed to chlorides in service.

The 222R document is currently being revised. It is anticipated that limits could be recommended for different exposure classes. However, history shows that limits for reinforced concrete recommended by ACI Committee 222 have been consistently lower than those specified by ACI Committees 318 and 349. Limits for prestressed structures have been consistent over time, much of this justified based on research by Hope (1988 *[with Ip]* and1994 *[with Enevoldsen and Hansson]*) and Schupack (1978, 1982, 1991, and 1998 *[with Stark]*). Care must be taken to balance risks associated with corrosion and costs associated with requiring low chloride levels. Additional costs could include using different and more expensive chemical admixtures, using different aggregate sources which could have higher material and transportation costs, using cleaner water, or others. In addition to costs, risks must be considered when making these decisions.

ASSESSING INFLUENCE OF CHLORIDES ON CORROSION

As noted in this paper, chlorides can have a significant influence on the corrosion activity of steel reinforcement embedded in concrete. The initial chloride limits published by ACI 201.2R-77 referenced three studies. Since this time, limited research has been performed to assess the influence of admixed chlorides and how these chlorides influence the corrosion activity of steel in concrete. A simple investigation was carried out to assess the influence of chloride content on the corrosion of reinforcement embedded in mortar containing various admixed chloride concentrations and exposed to water and saltwater environments. The following sections provide a theoretical assessment of the influence of admixed chlorides on corrosion, service life, and costs. This is followed by a brief description of the research program and results. It is anticipated that these sections will provide the reader with a better understanding of the potential impacts of admixed chlorides.

Theoretical Analysis of the Effects of Admixed Chlorides

The transport of chlorides into concrete towards the steel reinforcement is a complex phenomenon. Many studies have been performed to assess the rate at which chlorides are transported through the cementitious materials to the steel reinforcement, initiating corrosion of this reinforcement (Schießl and Wiens 1997, Weyers 1998, Liu and Weyers 1998, Li 2000, Li 2002, Zhang and Gjørv 2005). Pack et al. (2010) reported that the time-dependent transport of chlorides could be effectively modeled for bridge columns using simple diffusion models, assuming that the chloride surface concentration, C_s , and the apparent diffusion coefficient, D_a , are also time dependent. The authors noted that D_a decreases exponentially with time and C_s increases logarithmically with time and the chloride concentration at any depth and at any time, C(x, t), can be determined as follows:

$$C(x,t) = C_s(t) \cdot \left(1 - erf\left(\frac{x}{2\sqrt{D(t)\cdot t}}\right)\right)$$
(Eq. 1)

where x is the depth of interest (length units), t is time (units dependent on units of diffusion coefficient), $C_s(t)$ is the time-variant chloride surface concentration, and D(t) is the time-variant diffusion coefficient. Pack et al. (2010) reported that $C_s(t)$ and D(t) could be estimated as follows:

$$C_s(t) = \alpha [ln(\beta t + 1)] + k$$
(Eq. 2)