

ACI 222R-19

Guide to Protection of Reinforcing Steel in Concrete against Corrosion

Reported by ACI Committee 222



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Guide to Protection of Reinforcing Steel in Concrete against Corrosion

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This guide reviews the most recent developments of metal corrosion, specifically reinforcing steel, in concrete. Individual chapters are devoted to corrosion of metals in concrete, protective measures for new concrete construction, procedures for identifying corrosive environments, active corrosion in concrete, and remedial measures.

Keywords: allowable chloride; carbonation; chloride; chloride threshold; corrosion; corrosion-resistant reinforcement; durability; prestressed concrete; reinforced concrete; reinforcing steels.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The corrosion of metals in concrete can be a serious problem because of its widespread occurrence in certain types of structures and the high cost of repairing such structures. This holds true especially for reinforcing steel. Some of the first widely documented cases of steel reinforcement corrosion were associated with marine structures and chemical manufacturing plants (Tremper et al. 1958; Evans 1960; Biczók 1964). Later, numerous reports of its occurrence in bridge decks, parking structures, and other structures exposed to chlorides emphasized the problem (Crumpton and Pattengill 1969; Fruggiero 1972; Stratfull 1973; Litvan and Bickley 1987). Extensive research on factors contributing to steel corrosion has increased understanding of the mechanisms and causes of corrosion, especially concerning the role of chlorides. It is anticipated that application of the research findings will result in fewer instances of corrosion in new reinforced concrete structures and improved methods of repairing corrosion-induced damage in existing structures. For these improvements to occur, the research information should be disseminated to those responsible for the design, construction, and maintenance of concrete structures.

The high-alkaline environment of concrete results in the formation of a tightly adhering film over the reinforcing steel that generally protects it from extensive corrosion. Therefore, the corrosion of reinforcing steel is not a significant concern in most concrete elements or structures. Corrosion of steel, however, can become a problem if:

- a) The concrete does not resist the ingress of corrosion-inducing substances
- b) The structure is not properly designed for the service environment
- c) The environment is not as anticipated
- d) The structure exhibits changes during the service life of the structure

Corrosion of steel reinforcement is the primary subject of this guide. Although several types of metals can corrode under certain conditions when embedded in concrete, the corrosion of steel reinforcement is the most common and of greatest concern.

Exposure of reinforced concrete to chlorides is the major cause of premature corrosion of steel reinforcement, although corrosion can also occur in some circumstances in the absence of chlorides. For example, sufficient amounts of other substances such as other halides, chlorate, and hypochlorite can result in corrosion (Kerckhoff 2007; ACI 515.2R). Carbonation of concrete or other exposure conditions that reduce the concrete's alkalinity can lead to corrosion of the embedded steel reinforcement. Carbonation damage can be extensive in structures with low cover and is at times repaired without consideration of the mechanism of deterioration. As the concrete infrastructure ages, systematic carbonation is likely to become a more apparent and wider problem, particularly in locations away from salt ingress (Sagüés et al. 1997a). Widespread deterioration and consideration for holistic repair for carbonation-induced corrosion

is not as common in North America as that for corrosion induced by chlorides. Chlorides are common in nature and very small amounts are generally present in the constituents of concrete. Chlorides can also be intentionally added into the concrete, most often as a constituent of accelerating admixtures. In addition, dissolved chlorides can penetrate hardened concrete in structures exposed to marine environments, salt-laden soils, or deicing or anti-icing salts.

The rate of corrosion of steel reinforcement embedded in concrete is influenced by environmental factors. Corrosion of reinforcement in concrete is an electrochemical process that generally depends on the presence of oxygen and moisture. Reinforced concrete with significant gradients of corrosive ions, such as chloride, is vulnerable to corrosion, especially when subjected to cycles of wetting and drying that is often prevalent in highway bridges and parking structures exposed to deicing or anti-icing salts, and in structures located in marine environments. Other factors that affect the rate and level of corrosion are:

- (a) Heterogeneity in the concrete and reinforcing steel
- (b) pH of concrete pore water
- (c) Carbonation of concrete cover
- (d) Cracks in the concrete
- (e) Stray currents
- (f) Time of wetness
- (g) Galvanic effects due to contact between dissimilar metals
- (h) The presence of other corrosive ions

Design features and construction practices also play an important role in the corrosion of embedded steel. Concrete mixture proportions, thickness of concrete cover over the reinforcing steel, crack-control measures, and implementation of measures designed specifically for corrosion protection are some of the factors that help control the onset and rate of corrosion.

Deterioration of concrete due to corrosion of the reinforcing steel results because the solid products of corrosion (rust) occupy a greater volume than the original steel and exert expansive stresses on the surrounding concrete. The outward manifestations of the rusting include staining, cracking, and spalling of the concrete (Torres-Acosta and Sagüés 2004). Concurrently, the cross-sectional area of the reinforcing steel is reduced. With time, structural distress may occur either because of loss of bond between the reinforcing steel and concrete due to cracking, delamination, and spalling, or because of the reduced steel cross-sectional area. This latter effect can be of special concern in structures containing high-strength prestressing steel because a small amount of metal loss could trigger a failure (Pillai et al. 2010a,b).

The National Research Council (2011) reported that one challenge facing the United States is the development of a cost-effective, environmentally friendly, corrosion-resistant material. Structures are now being constructed with alternative forms of reinforcement such as stainless steels (McDonald et al. 1995; Bower et al. 2000; Wenzlick 2007) and fiber-reinforced polymer reinforcing bars (Thippeswamy et al. 1998; Trejo et al. 2006; Benmokrane et al. 2007; ACI 440R). In addition, practice and research indicate the need

for quality concrete, careful design, good construction practices, and reasonable limits on the amount of chlorides in the concrete mixture constituents. Measures that are being taken and further investigated include the use of corrosion inhibitors, protective coatings on reinforcing steel, concrete coatings, cathodic protection, chloride extraction, and real-alkalization. Although these measures have been successful in general, problems resulting from corrosion of embedded reinforcing steel and other metals have not been eliminated. Thus, research into new measures to mitigate corrosion of reinforcing steel in concrete are vital.

1.2—Scope

This guide discusses the factors that influence corrosion of reinforcing steel in concrete, measures for protecting embedded reinforcing steel in new construction, techniques for detecting corrosion in in-service structures, and remedial procedures. Consideration of these factors and application of the discussed measures, techniques, and procedures should assist in reducing the occurrence of corrosion and result, in most instances, in the satisfactory performance of reinforced and prestressed concrete structural members.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A	= area of reinforcing steel polarized, in. ² (cm ²)
A_w	= atomic mass, lb/mol (kg/mol)
a	= constant
B	= proportionality constant, mV/mA
b	= Tafel slope, V/decade
c	= mass of cement, lb (kg)
cm	= mass of cementitious materials, lb (kg)
d_c	= depth of carbonation, in. (mm)
$D_{a,28}$	= apparent chloride diffusion coefficient at 28 days, ft ² /s (m ² /s)
D_{OPC}	= apparent chloride diffusion coefficient of ordinary portland cement concrete, ft ² /s (m ² /s)
D_{SF}	= apparent chloride diffusion coefficient of concrete containing silica fume, ft ² /s (m ² /s)
E	= applied potential, V
E_{corr}	= corrosion potential, V
F	= Faraday's constant, 96,500 coulombs/mol
i	= current density, mA/ft ² (μA/cm ²)
i_{corr}	= corrosion current density, mA/ft ² (μA/cm ²)
k	= carbonation rate constant, in./yr ^{0.5} (mm/yr ^{0.5})
M	= mass of dissolved metal, lb (kg)
n	= number of equivalents
R_p	= polarization resistance, ohm-ft ² (ohm-cm ²)
R_s	= concrete resistance, ohm
t	= time, seconds
t_y	= time, years
w	= mass of water, lb (kg)
β_a	= anodic Tafel constant, V/decade
β_c	= cathodic Tafel constant, V/decade
η	= polarization or overpotential, mV
ΔE	= voltage change resulting from the applied current, mV

ΔI = applied current required to obtain ΔE , mA

2.2—Definitions

Please refer to the latest version of “ACI Concrete Terminology” for a comprehensive list of definitions.

CHAPTER 3—MECHANISM OF CORROSION OF STEEL IN CONCRETE

3.1—Introduction

This chapter describes the thermodynamics and kinetics of the corrosion of steel reinforcement embedded in concrete. Subsequent sections explain the initiation of active corrosion by chlorides, carbonation of the concrete cover, and the rate-controlling factors for corrosion after it has been initiated. Finally, the influence of reinforcement types and of the concrete environments on corrosion of steel in concrete are discussed.

3.2—Principles of corrosion

3.2.1 The corrosion process—The corrosion of steel reinforcement in concrete is an electrochemical process that involves electron transfer between different species at the steel-concrete interface. In the absence of an external electrical source, the electron transfer takes place between two half-cell reactions—one capable of producing electrons and one capable of consuming electrons. The anodic half-cell reaction involves the oxidation or dissolution of iron, namely



Under normal atmospheric exposure conditions, the Fe^{++} ions then react further with oxygen and water to form oxides or hydroxides, and the most likely cathodic half-cell reaction is oxygen reduction



When oxygen is not available, the cathodic half-cell reaction can take place in the form of hydrogen evolution via



When the two reactions occur at widely separated locations, they are termed a macrocell (Fig. 3.2.1a). When they occur close together or essentially at the same location, they are termed a microcell (Fig. 3.2.1b).

The cathodic reaction that occurs in any specific case depends on the availability of oxygen and on the pH of the cement paste pore solution near the steel reinforcement. This is shown by the Pourbaix (E-pH) diagram (Pourbaix 1974), illustrated in Fig. 3.2.1c, which delineates the thermodynamic areas of stability for each of the iron oxide types as a function of electrochemical potential and pH of the environment. The electrochemical potential is a measure of the ease of electron charge transfer between a metal and its environment; in this case, between the steel reinforcement and the cement paste pore solution. It is a property of the steel rein-