

ACI 222R-19

Guide to Protection of Reinforcing Steel in Concrete against Corrosion

Reported by ACI Committee 222



American Concrete Institute
Always advancing



Guide to Protection of Reinforcing Steel in Concrete against Corrosion

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Guide to Protection of Reinforcing Steel in Concrete against Corrosion

Reported by ACI Committee 222

David Trejo, Chair

O. Burkan Isgor, Secretary

Neal S. Berke
Michael C. Brown
David Darwin
Marwan A. Daye
Stephen D. Disch
Hamid Farzam

Ceki Halmen
Carolyn M. Hansson
Mohammad S. Khan
Tracy D. Marcotte
Robert Moser
Mohamad Nagi

Theodore L. Neff
Charles K. Nmai
Ruben M. Salas
Arpad Savoly
David G. Tepke
Richard E. Weyers

David W. Whitmore
John B. Wojakowski
Consulting Members
Richard O. Lewis
Andrea J. Schokker

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.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 3

CHAPTER 2—NOTATION AND DEFINITIONS, p. 3

- 2.1—Notation, p. 3
- 2.2—Definitions, p. 3

CHAPTER 3—MECHANISM OF CORROSION OF STEEL IN CONCRETE, p. 3

- 3.1—Introduction, p. 3
- 3.2—Principles of corrosion, p. 3

3.3—Reinforcing bar, p. 9

3.4—Concrete environment, p. 11

CHAPTER 4—PROTECTION AGAINST CORROSION IN NEW CONSTRUCTION, p. 13

4.1—Introduction, p. 13

4.2—Design approaches and choices, p. 13

4.3—Methods of excluding external sources of chloride from concrete, p. 19

4.4—Corrosion control methods, p. 22

4.5—Summary, p. 24

CHAPTER 5—PROCEDURES FOR IDENTIFYING CORROSIVE ENVIRONMENTS AND ACTIVE CORROSION IN REINFORCED CONCRETE STRUCTURES, p. 24

5.1—Introduction, p. 24

5.2—Condition evaluation of reinforced concrete structures, p. 26

5.3—Corrosion evaluation methods, p. 26

5.4—Concrete evaluation test methods, p. 35

CHAPTER 6—REMEDIAL MEASURES, p. 36

6.1—Introduction, p. 36

6.2—Applicability, p. 36

6.3—Remedies and their limitations, p. 37

6.4—Summary, p. 40

CHAPTER 7—REFERENCES, p. 40

Authored references, p. 42

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

ACI 222R-19 supersedes ACI 222R-01 and was adopted and published April 2019. Copyright © 2019, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

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 (Kerkhoff 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-

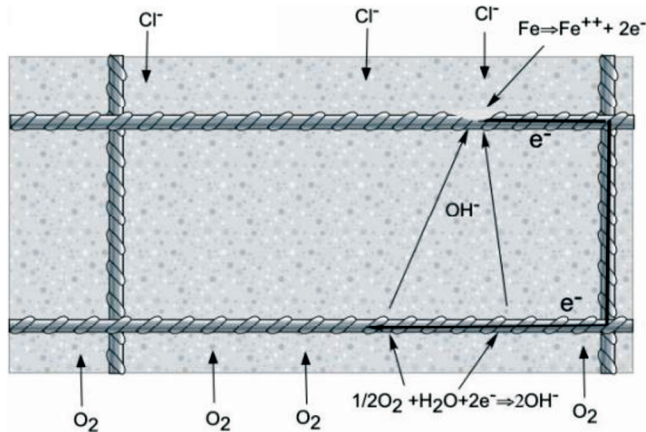


Fig. 3.2.1a—Macrocell corrosion (Hansson et al. 2006).

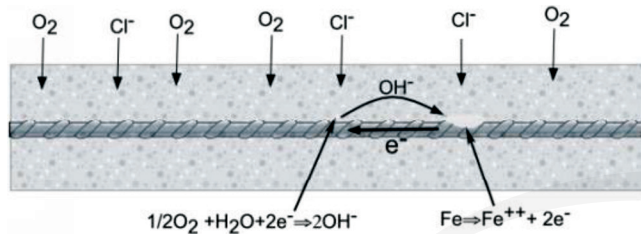


Fig. 3.2.1b—Microcell corrosion (Hansson et al. 2006).

forcement-concrete interface and not of the steel reinforcement itself. It is not possible to determine the absolute value of the potential and, therefore, it is necessary to measure the potential difference between the steel reinforcement surface and a reference electrode. This might be a standard hydrogen electrode (SHE), a saturated calomel electrode (SCE), a Cu/CuSO₄ electrode (CSE), or an Ag/AgCl electrode (SSCE). The value of the potential in a freely corroding system is commonly known as the corrosion potential, the open circuit potential, the free potential, or the half-cell potential. For the reaction shown in Eq. (3.2.1b) to occur, the potential should be more negative than that indicated by the upper dashed line, whereas the reaction shown in Eq. (3.2.1c) can only proceed at potentials more negative than the lower dashed line. In general, if all other factors are kept constant, when more oxygen is available, the electrochemical potential will be more positive (anodic).

For sound concrete, the pH of the pore solution is equal or greater than 13.0 and the half-cell potential more positive than -200 mV (CSE). Within this range, in the absence of any other factors, the iron oxides—Fe₃O₄ and Fe₂O₃ or hydroxides of these compounds—will form as solid phases and may develop as a protective (passive) layer on the steel reinforcement. If the pH of the pore solution is reduced, for example, by carbonation or by pozzolanic reactions, the system may be shifted to an area on the Pourbaix diagram in which these oxides do not form a protective layer and active dissolution is possible. Corrosion could theoretically be induced in very high pH environments at high temperature if the potential of the steel is held near -1.0 V (SHE), as per the following reaction



where iron dissolves as HFeO₂⁻ (refer to Pourbaix diagram in Fig. 3.2.1d) (Townsend 1970). This condition is highly unlikely to exist in a reinforced concrete structure.

Corrosion of reinforcing steel in concrete can be caused by stray current corrosion or other environmental factors in addition to chemicals (Gummow and Meyers 1986; Bertolini et al. 2007). Stray current is received by the reinforcing steel in concrete or any metal electrically connected to the embedded steel and discharged elsewhere on its way to the source. Reinforcing steel corrodes at the point of current discharge. The most common sources of stray currents for reinforced concrete structures include DC-powered electric railways and electroplating plants. This type of corrosion most commonly occurs in structural elements in contact with the earth.

3.2.2 Nature of the passive film—A passive film can be relatively thick and inhibit active corrosion by providing a diffusion barrier to the reaction product of the reacting elements (Fe and O₂). Alternatively, and more commonly, it may be thin, often a few monolayers thick. In this case, the oxides simply occupy the reactive atom sites on the metal surface and prevent the metal atoms at these locations from dissolving. A passive film does not stop corrosion, but it does reduce the corrosion rate to an insignificant level. For steel reinforcement in concrete, the passive corrosion rate is typically $\sim 4 \times 10^{-5}$ in./year (~ 1 $\mu\text{m}/\text{year}$) or less; without the passive film, the steel reinforcement can corrode at rates at least three orders of magnitude higher than this (Hansson

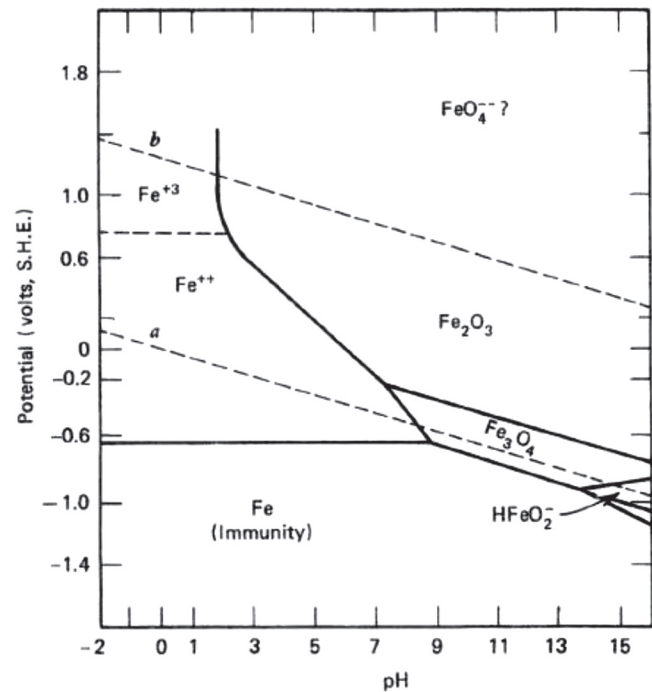


Fig. 3.2.1c—E-pH Pourbaix diagram 77°F (25°C) showing the potential pH ranges of stability of the different phases of iron in aqueous solutions (Revie and Uhlig 2008). The lines a and b represent the equilibrium potentials for the hydrogen evolution and oxygen reduction reactions, respectively.