

# State of the Art Report on Corrosion-Resistant Reinforcement

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## **ABSTRACT**

*This NACE International state-of-the-art report contains information about materials that provide a corrosion-resistant alternative to plain carbon steel reinforcing bar (rebar). The report is intended for use by engineers when considering the use of alternative concrete reinforcement and post- or prestressing strand materials with higher corrosion resistance than that of conventional carbon steel alloys.*

*Materials that have actual, or potentially, wide commercial availability are emphasized in the report. Each material is briefly described and includes descriptions of the field and laboratory performance with attention to quantitative consideration of the parameters that determine durability relative to that of plain carbon steel bar. The report includes four tables with information such as common stainless steel designations for reinforcing bar, chloride threshold results for concrete specimens reinforced with stainless steels, and laboratory evaluation of corrosion performance of steel bars versus carbon steel bar. Throughout this report reference is made to pertinent, available standards.*

## **KEYWORDS**

*black bar, carbon steel bar, carbon steel reinforcing bar, carbonation (of concrete), cathodic prevention, chloride threshold, coefficient of thermal expansion, concrete, concrete reinforcing steel institute, corrosion hydrogen embrittlement, corrosion macrocell test, corrosion propagation, dual polymer/zinc coated rebar, environmentally assisted cracking, epoxy-coated reinforcing steel bars, fiber reinforced polymers, galvanized steel, issues, potentiodynamic polarization scans, rebar, stainless steels, stainless steel clad rebar, stress corrosion cracking, TG 057, STG 01, water-to-cement ratio, water treatment systems.*

# Foreword

This NACE International state-of-the-art report is intended for use by engineers when considering the use of alternative concrete reinforcement and post- or prestressing strand materials with higher corrosion resistance than that of conventional carbon steel alloys. Throughout this report reference is made to pertinent, available standards. Alternative corrosion-resistant materials can have significant differences in the mechanical, thermal, and electrical properties relative to those of conventional steel, and therefore can impact the structural performance of the system. A review of such impact prepared by a qualified structural engineer can be helpful.

This state-of-the-art report was prepared in 2018 by Task Group (TG) 057\*, "Reinforced Concrete: Corrosion Resistant Reinforcement." This TG is composed of corrosion researchers, corrosion engineers, corrosion consultants, structure owners, and representatives of both industry and government. TG 057 is administered by Specific Technology Group (STG) 01, "Reinforced Concrete" and is sponsored by STG 11, "Water Treatment Systems." This report is issued by NACE under the auspices of STG 01.

NACE International technical committee reports are intended to convey technical information or state-of-the-art knowledge regarding corrosion. In many cases, they discuss specific applications of corrosion mitigation technology, whether considered successful or not. Statements used to convey this information are factual and are provided to the reader as input and guidance for consideration when applying this technology in the future. However, these statements are not intended to be requirements or recommendations for general application of this technology, and must not be construed as such.

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# State of the Art Report on Corrosion-Resistant Reinforcement

1.	Introduction .....	4
2.	Definitions .....	6
3.	Solid Metallic Products—Stainless Steels.....	7
4.	Solid Metallic Products—Moderate Cr Content Alloys .....	13
5.	Solid Metallic Products—Stainless Steel Strand and High Strength Wire .....	15
6.	Metal Coated Reinforcement—Stainless Steel Clad Rebar.....	17
7.	Metal Coated Reinforcement—Galvanized Steel.....	19
8.	Metal Coated Reinforcement—Specialty Coatings.....	22
9.	Organic-Coated Reinforcement—Epoxy Coated Rebar .....	23
10.	Multiple-Coated Reinforcement –Polymer-Zinc Dual Coated Rebar.....	26
11.	Organic-Coated Steel Strand - Epoxy-Coated Strand .....	27
12.	Nonmetallic Reinforcement—Fiber Reinforced Polymer.....	29
	References.....	30
	Appendix A List of ASTM Standards .....	38
	Appendix B Corresponding UNS Grade Designations and AISI Numbers.....	39
	Appendix C Abbreviations of Terms Used Throughout the Text.....	40

## Tables

Table 3.1	Some Common Stainless Steel Designations for Reinforcing Bar.....	8
Table 3.2	Chloride Threshold ( $C_T$ ) Results for Concrete Specimens Reinforced with Commercially Produced Stainless Steels .....	10
Table 3.3	Chloride threshold ( $C_T$ ) Results for Stainless Steels Exposed to Aqueous Solutions .....	11
Table 4.1	Laboratory Evaluation of Corrosion Performance of ASTM A1035 Type CS Steel Bars and Other Corrosion Resistant Reinforcements (Mentioned in Chapter 3) Relative to ASTM A615 Carbon Steel Bar.....	14

# Section 1: Introduction

## 1.1 Scope of the Report

This NACE report contains information about materials that provide a corrosion-resistant alternative to plain carbon steel reinforcing bar (rebar), known also as black bar. Throughout this report the term “carbon steel bar” is used to refer to the plain carbon steel reinforcing bar. Emphasis is given on materials that have actual, or potentially, wide commercial availability. Information on fabrication, detailing, and placement of commercially available corrosion-resistant steel reinforcement is given elsewhere.<sup>1</sup>

Each material is briefly described, indicating the principles for its corrosion resistance, applicable chemical composition and standards, manufacturing method, history of application and current availability, and extent of use. Field and laboratory performance is described with attention whenever possible to quantitative consideration of the parameters that determine durability relative to that of plain carbon steel bar. ASTM<sup>(1)</sup> standards referenced in this report are listed in alphabetical order in Appendix A; however, the international user can refer to relevant standards applicable in his/her country.

## 1.2 Corrosion Issues Common to All Metallic Materials Considered

### 1.2.1 The Corrosion Initiation-Propagation Approach

In very general terms, corrosion-related durability of reinforcement can be viewed as a two-stage process, including an initiation and a propagation stage.<sup>2</sup> During the initiation stage, of duration  $t_i$ , an external contaminant (most commonly  $\text{Cl}^-$  ions) causing breakdown of passivity on the steel surface builds up there until a critical chloride concentration ( $C_T$ ) (sometimes called the chloride threshold) is reached and corrosion starts. Comparable treatments apply to other sources of corrosion such as concrete carbonation. Due to the severity and widespread occurrence of chloride-induced deterioration, it is the main mode of degradation addressed in this report. It is recognized however that much of the treatment could be extended to carbonation induced damage if appropriate consideration is given to the mechanistic processes involved in each case.

The corrosion may take the form of pitting or general corrosion in materials with metal directly exposed to the concrete, or of crevice corrosion in coated or clad rebar. During the propagation stage, of duration  $t_p$ , corrosion effects increase until a limit state is reached where damage requires repair or other user action. In plain steel and other types of reinforcement the deterioration is commonly due to corrosion products that accumulate so that and tensile stresses develop in the surrounding concrete, resulting in cracking and delamination, or spalling of the concrete with consequent need for repair. In atmospherically exposed concrete, very small amounts of expansive corrosion products are often sufficient to cause concrete distress, so the need for repairs tends to be manifested while the reinforcing steel still retains much of its initial load-carrying capacity. In very wet or submerged concrete the corrosion products may not be solid or may not accumulate near the steel, so a given level of other forms of distress such as loss of bond or of steel cross section could constitute the limit state. A similar situation may apply also to stainless steel reinforcement, for which there is still little information as to how much expansive corrosion product generation exists compared to, for example, local loss of cross section due to pitting or loss of strength from environmental assisted cracking (EAC; see subsequent section). Regardless of the specific declaration used to define the end of the propagation stage, a nominal corrosion-related service life can be assigned as the sum of the durations  $t_i$  and  $t_p$ .

### 1.2.2 Corrosion Initiation Stage

The duration  $t_i$  can be estimated from the environmental severity, the characteristics of chloride transport in concrete (chloride permeability), and through or around cracks, and from the value of  $C_T$ , using calculations based on solutions of Fick's second law of diffusion or more sophisticated transport treatments.<sup>3</sup> All else being the same, the value of  $t_i$  increases significantly with the value of  $C_T$ . For a given exposure condition,  $C_T$  is a generally considered property of the rebar material and the electrochemical environment surrounding the structure, and therefore, it is a key parameter in measuring the corrosion resistance benefit obtained by the use of an alternative rebar type.

With carbon steel bar, it is generally agreed that for a given exposure condition there is not a fixed value of  $C_T$ , but rather a statistical distribution of values. The threshold value is usually understood to correspond to the chloride concentration at which that cumulative probability of corrosion initiation is appreciable, and open to some latitude in judgment when adopting a value for corrosion forecasting purposes. The lowest threshold in common use is 0.2% chloride by mass of cement, equivalent to 0.028% by mass of concrete or 0.66 kg/m<sup>3</sup> based on 14% cement content. The latter level (approximated to 1.2 pounds per cubic yard) is often used in North America, although a threshold of 0.4% is frequently used in the European and Latin American literature. Thorough overviews of factors influencing the corrosion threshold values for carbon steel bar have been re-

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