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State of the Art Report on Corrosion-Resistant Reinforcement

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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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.[1]

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[(1)] 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.[2] During the initiation stage, of duration ti, an external contaminant (most commonly 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.[3] 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^3 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-

[(1)] ASTM International (ASTM), 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

cently published.[4,5] The applicable value of C_T of each alternative rebar material and its comparison to that of carbon steel has been given consideration throughout this report. It is noted that some classes of materials such as stainless steels involve a wide range of alloy compositions and require consideration of C_T variability within each composition and within a given specific condition such as service temperature.

1.2.3 Corrosion Propagation Stage

The duration t_p is, all else being the same, shorter the faster the rate of generation of corrosion products. In general, however, t_p is a complicated function of various factors. These factors include exposure conditions; mechanical, physical, and electric properties of concrete; reinforcement layout; extent of corrosion localization; cathodic and anodic polarization characteristics of the rebar and other reinforcement contacting it; and the types of corrosion product generated.[6] Therefore, comparisons of the performance of different types of rebar in the propagation stage cannot be made based only on the relative value of the corrosion present in a given test arrangement, but all of the other factors are considered as well.

Efficient support of the cathodic reaction on the rebar surface can promote corrosion macrocell action with high local corrosion rates at anodic spots where corrosion has initiated, and significantly shorten t_p. As a result, it is of interest to know to what extent alternative rebar materials can act as a cathode compared to carbon steel bar. In general, the lesser cathodic action is the more beneficial to corrosion resistance. Likewise, where corrosion product accumulation is the prevalent factor, for a given rebar corrosion rate, the rebar materials that generate the less expansive corrosion products tend to have the longer t_p. Similar considerations would apply for other deterioration modes such as pitting corrosion in stainless steels. As a result, comparisons in the following of performance of alternative materials in the propagation stage consider whenever possible the combined influence of how much of an anode the material is at a given polarization level, but also the extent of cathodic reaction and the expansiveness of the corrosion products or other factors that are manifested in distress such as noted in the next paragraph.

1.2.4 Environmentally Assisted Cracking

The initiation-propagation approach has been historically oriented toward reinforcement corrosion that induces cracking of the concrete. Processes that result in early mechanical distress of the reinforcement itself, such as deep local pitting and especially stress corrosion cracking (SCC) and hydrogen embrittlement (HE) are considered separately. Those latter two processes are likely to be manifested only in high-strength reinforcement (> 200 ksi), and then only if the material has a high C_T value, since other damage from formation of corrosion products would have dominated and obscured these rebar cracking modes. At present there is only minor evidence of EAC in the materials considered in this report when produced in commonly used strength grades. There are concerns, however, that SCC may be an issue in stainless steel corrosion resistant pre- or post-tensioned strand where high-strength levels are required. By extension, it is meaningful to conduct investigations focused on the possible onset of SCC in the higher strength grades of stainless steel (SS) rebar if large scale use of those materials is contemplated.

1.3 Methods of Corrosion Resistance Assessment

1.3.1 Field Performance

Field performance is the ultimate assessment tool and is given preference in this report whenever appropriate data are available. However, some promising corrosion-resistant materials have been introduced or put in wide use only recently. In those cases, laboratory or test yard data are discussed in detail.

1.3.2 Laboratory/Test Yard Investigations

Because these studies tend to be of limited duration and involve some form of acceleration, the significance of the results must be critically assessed. A common problem is disparity in the relative acceleration of the initiation and propagation stages. In such cases a material may be declared to be superior to another simply because testing ceased shortly after the end of the initiation stage. Had testing continued over a longer period, strong differences in the propagation stage behavior of both materials could have become apparent, potentially resulting in a reversal of the performance ranking assigned based on the shorter exposure.

Keeping in mind the above caveat, studies of performance of alternative metallic rebar materials have typically involved relatively long-term exposure of freely corroding specimens embedded in concrete that was either ponded with a Cl^- solution or admixed with chlorides during fabrication (or both). The test assemblies typically consist of a concrete block with embedded rebar, some of it near the upper surface where the pond is placed, and others further down connected to the upper rebar by a resistor shunt that allows macrocell current to be measured. As chloride penetration causes C_T to be exceeded in the upper rebar, there is a sharp increase in corrosion macrocell current that signals the end of the initiation stage and beginning of the propagation stage. The magnitude of the current is a partial indicator of the corrosion rate of the upper rebar, providing some in-