



Corrosion behavior of steel reinforcement bars embedded in concrete exposed to chlorides: Effect of surface finish



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HIGHLIGHTS

- The corrosion behavior of thermo-treated and galvanized steel bars embedded in concrete exposed to chlorides was studied.
- The studies were conducted on concrete specimens with two water/cement ratios (0.45 and 0.65), not in solutions of simulation.
- Both, time to corrosion initiation (depassivation) and extent of the damage are influenced by the type of steel bar.
- Monitoring both during initiation and propagation phases allows a better understanding of corrosion development.

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ABSTRACT

The corrosion behavior of steel bars with different surface finish (ordinary (CS), dual phase (TTS) and galvanized (GS)) was studied in the laboratory using prismatic concrete specimens with two water/cement (w/c) ratios: 0.45 and 0.65. The specimens were exposed to penetration of chlorides using wetting and drying cycles for 2.6 years. The evolution with time of corrosion potential (E_{corr}) and polarization resistance (R_p) was studied. Microhardness, microstructural, chloride content and visual inspections of steel bars were also assessed. It was found that the different steels bars exposed followed a same sequence in depassivation for both w/c ratios; i.e. in this order: CS, TTS and GS. During initiation stage, the corrosion current density for TTS was lower than CS, similar behavior was observed in propagation stage for steel bars in specimens with w/c ratio of 0.45. The zinc-based coating obtained by hot-dip galvanization increases the time to corrosion initiation for CS bar and the amount of chlorides needed for this to occur. For GS and TTS bars, localized damage was observed, which was more severe for the GS bar.

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1. Introduction

Corrosion of steel reinforcement bars depends in large part on the physical and chemical stability of the phases that form in the cement paste and on the role of the oxide layer that is formed on the surface of the steel bars (passive layer) [1]. This process will initiate precisely when the passivating layer is destroyed [2,3]. For this type of protection, corrosion induced by chlorides is considered the primary cause of local breakdown of passive film on the steel bar surface [4]. These ions can be added to the concrete upon mixing, accidentally in the form of contaminants in the water, or in the aggregates.

Nevertheless, the primary source of chloride contamination is the exposure to the marine environment and the extensive use of

de-icing salts in many countries. The exposure of reinforced concrete structures (RCS) of this environments, causing chloride ions to penetrate through the concrete cover. As soon as a sufficient quantity of chlorides exceeds a critical level on the location of steel rebar, commonly called critical chloride content (C_{crit}) or chloride threshold value (Cl_{th}), the passive film will be destroyed (depassivation) and the corrosion is to be initiated [5–8]. The (Cl_{th}) value is influenced by various factors such as: concrete mix proportions, C_3A content of cement, chloride source, chemical compositions and surface properties of rebars [5,9–12].

For these reasons, attempts have been made on several fronts to mitigate deterioration as a result of corrosion. While several researchers have worked to improve the properties of concrete [13,14], others have proposed alternative methods of external protection, such as cathodic protection; and as a research in progress, electrochemical chloride extraction, electrochemical re-alkalization or cathodic prevention [15–17]. With respect to steel

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reinforcement bars, different protection options have been proposed that involve modifying the surface properties. One of the most used methods of protection has been hot-dip galvanization, in which an ordinary steel bar is coated with a zinc layer. This forms an adherent film that provides a physical barrier against corrosion and a cathodic protection of the reinforcement. During the initiation phase, this protection is evident; however, during the propagation phase, there is still uncertainty regarding their effectiveness in the presence of chlorides because the corrosion products occupy 1.5–3.6 times the volume compared to the original zinc [18–20]. It has been reported [18] that the products generated result in cracks in the element, even without the presence of red rust stains on the concrete surface.

Moreover, steel reinforcement bars that have different surface microstructures as a result of special heat treatments are commercially available. This steel bar is known as dual-phase, which consists primarily of a soft ferrite matrix and a hard outer layer composed of martensite. However, it is possible to find small amounts of bainite, pearlite, and tempered austenite phases present in the microstructure (see Fig. 1) [21]. With this treatment, the steel bar has the ability to simultaneously obtain good ductility and high resistance [22] and could also reduce production costs [23].

The reasons for making reinforcement bars that meet the aforementioned demands are clear. However, research has focused on evaluating the mechanical behavior and has ignored the response to the corrosion phenomenon. This is reflected in the scarcity of information related to the corrosion behavior of TTS bars used as steel reinforcing of concrete. In addition, the existing information yields contradictory results. For example, Trejo [22] and Ismail [24] assert that TTS bars exhibit improved corrosion resistance. This behavior was attributed to the absence of pearlite “colonies” (ferrite and carbide layers) on the surface of the bar, whose presence is normal in ordinary steel bars. Thus, the formation of galvanic couples between carbide (cathode) and ferrite (anode) would be eliminated. By contrast, Sarkar [25], Keleştemur [26], and Nadlene [27] stated that the TTS bars have a higher corrosion rate than that of ordinary steel bars, which is because an increase in the percentage of martensite in the dual-phase steel bar increases the corrosion rate.

The mechanism of corrosion damage in steel bars embedded in concrete invariably goes through three stages: initiation, depassivation and propagation. Most of the investigations have been performed in the stages of initiation until depassivation (or slightly beyond), whereas very few have focused on the propagation stage.

After being manufactured, it could be assumed that both galvanized bars and dual-phase bars exhibit a surface modification in the form of a metallic coating of a given thickness. Here, corrosion of the reinforcement bars caused by chlorides is seen as surface dissolution causing a loss in the initial diameter (pits growth in the surface of the steel bar). In addition, when zinc coating is consumed, the surface of the bars are in a medium that contains high content of chlorides, which could lead to an immediate increase in the degradation of the bars. Thus, tracking the electrochemical behavior of these bars under these conditions will provide information that contributes to a better understanding about corrosion behavior.

In this work, the electrochemical evolution (tracking of E_{corr} and i_{corr} via linear polarization resistance – LPR) exhibited by dual-phase steel reinforcement bars (TTS) and galvanized steel (GS) subjected to a process of chloride-induced corrosion is analyzed. The results are compared with those of ordinary steel reinforcement bars in concrete, referred to herein as CS. In addition, the chloride content near to steel bar – concrete interface (like a representation of chloride threshold value, Cl_{th}) and the extent of damage caused by corrosion in the various steel bars studied were contrasted.

2. Experimental procedure

2.1. Materials

Three types of G42 industrial-grade steel reinforcement bars (in accordance with the ASTM A615/615M [28]) were evaluated in this research: CS, TTS, and GS. The chemical compositions obtained by atomic emission spectroscopy for the CS and TTS steel bars are shown in Table 1. The GS bars were created from hot-dip galvanization (in accordance to ASTM A767/A767M [29]) of a group of CS bars. The average thickness of the zinc layer was 102 μm .

2.2. Microstructural characterization and microhardness

To perform the metallographic characterization and determine the microhardness, samples were taken from the bars by crosscuts. The samples were polished to a mirror finish. To this end, samples were mounted in a polymer and then roughened with silicon carbide paper with different grain sizes: 80, 240, 320, 600, 800, 1200, and 2400. Subsequently, the polishing was done with a cloth using $\frac{1}{4}$ μm abrasive diamond paste on a rotating disk. Prior to testing, samples were washed, degreased and ultrasonically cleaned in

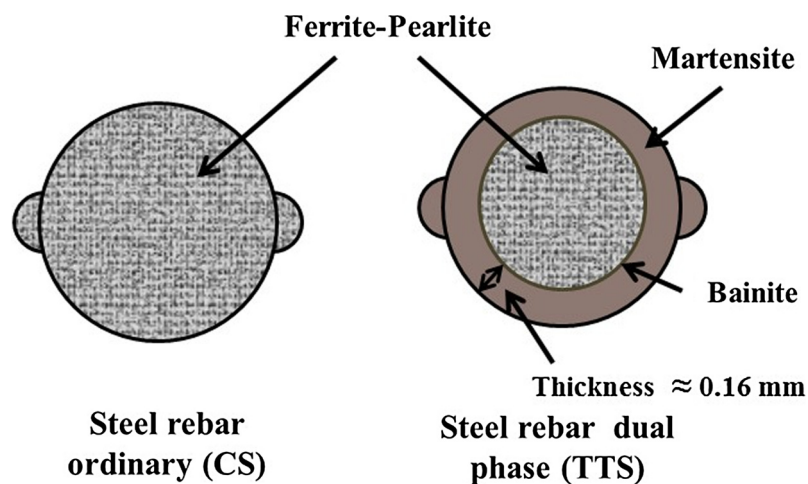


Fig. 1. Schematic representation of the different phases in ordinary steel (CS) and dual phase rebar (TTS).

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