

Chloride-induced corrosion of steel reinforcement – Mechanical performance and pit depth analysis

Charis A. Apostolopoulos^a, Sotiris Demis^b, Vagelis G. Papadakis^{c,*}

^a Department of Mechanical and Aeronautical Engineering, Laboratory of Technology and Strength of Materials, University of Patras, Patras 26500, Greece

^b Department of Civil Engineering, University of Patras, Patras 26500, Greece

^c Department of Environmental and Natural Resources Management, University of Western Greece, Seferi 2, Agrinio 30100, Greece

HIGHLIGHTS

- ▶ Effect of corrosion on bare B500c bars and embedded in concrete, under salt spray.
- ▶ Moderate loss of strength but significant reduction in ductility, on bare samples.
- ▶ Higher losses (strength/ductility) on embedded bars for same mass loss with bare.
- ▶ Development of pit depth measurement procedure, using advance imaging analysis.
- ▶ Pits significance analysis indicated more severe pitting corrosion on embedded bars.

ARTICLE INFO

Article history:

Received 6 April 2012

Received in revised form 13 July 2012

Accepted 23 July 2012

Available online 21 September 2012

Keywords:

Chloride-induced corrosion

Mechanical properties

Ductility

Pit depth

ABSTRACT

In the current study the effects of chloride-induced corrosion, in terms of mechanical properties and pit depths, are evaluated on B500c steel bars embedded in concrete (embedded samples) and directly exposed (bare samples), immersed in a salt spray chamber. The results indicate that for the same level of mass loss, degradation of the “embedded” samples was found to be much more severe than that of the “bare samples”, in terms of losses in yield strength and uniform elongation. Analysis of the statistical significance of the pit depth and area values measured, based on a methodology developed using advanced imaging analysis, indicate that degradation of the steel bars embedded in concrete produced a more severe pitting corrosion in terms of depth of pitting, compared to the steel samples directly exposed to the same corrosive medium, for the same (on average) mass loss.

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1. Introduction

It is well known, that corrosion of steel reinforcement is one of the most important durability issues in reinforced concrete design [1,2]. It can be initiated due to chloride ingress in concrete or due to depassivation of the protective thin oxide film of the steel reinforcement (afforded by the high alkaline concrete environment) through the action of carbon dioxide from the atmosphere. Corrosion impairs not only the appearance of the structure, but also its strength and safety, with the subsequent reduction in the cross sectional area of the reinforcement and with the decrease of bond with the surrounding concrete [3,4]. In coastal regions (or marine environments) where high chloride concentrations are encountered, chloride-induced corrosion is the major source of environmental deterioration of reinforced concrete structures.

Trying to model corrosion level as a function of time, the representation of a bi-linear model (Fig. 1a) is usually used [5,6]. It is assumed that there is a period of time before chloride ions reach the reinforcement (initiation period), during which substances as water, chloride ions (and/or carbon dioxide) diffuses into concrete and reach the certain concentration necessary to trigger corrosion of the steel reinforcement. This threshold of chloride ions depends on a number of factors (type of binder, C₃A content and aggregate, moisture level, air content of concrete, ratio of chloride to the hydroxyl ion) [5,7]. In general when the chloride concentration exceeds 0.4% by weight of cement (for chlorides cast into concrete) or 0.2% (for chlorides diffusing in) corrosion is observed [5,7,8].

Chlorides that reach the concrete surface, enter the pore system either by diffusion (in stationary pore water), or by capillary suction of the surface water in which they are dissolved (or by combination of both transport mechanisms) [1,6]. In the majority of papers, chloride transport in concrete is modeled using the Fick's second law of diffusion neglecting the chloride interaction with the solid phase [9]. However, it is widely proved that chlorides

* Corresponding author. Tel.: +30 2610 911571; fax: +30 2610 911570.

E-mail addresses: charrisa@mech.upatras.gr (C.A. Apostolopoulos), sdemis@upatras.gr (S. Demis), vgp@psp.org.gr (V.G. Papadakis).

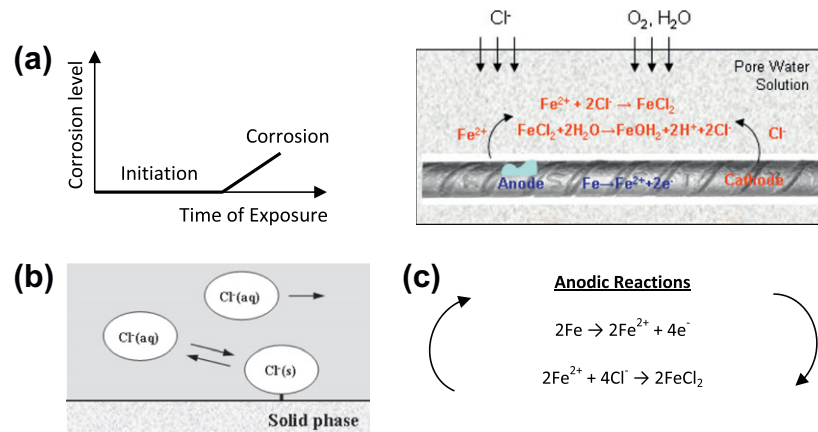


Fig. 1. Schematic representation of modeling aspects of chloride induced corrosion.

are bound from concrete components in a percentage of 30–60% depending on the cementitious materials' composition and content [5,6]. The interaction process (Fig. 1b) in general, includes binding of chlorides by cement hydration products, ionic interaction, lagging motion of cations and formation of an electrical double layer on the solid surface. Pereira and Hegedus [10] modeled chloride diffusion and reaction in fully saturated concrete as a Langmuirian equilibrium process coupled with Fickian diffusion. Papadakis et al. [11,12] extended this approach to more general conditions, offering a proven experimentally simpler solution. The physicochemical processes of Cl^- diffusion in the aqueous phase, their adsorption and binding in the solid phase of concrete and their desorption, are described by a non-linear partial differential equation [11,12], solution of which allows the calculation of the Cl^- bound in the solid phase and the estimation of the critical time for chloride-induced corrosion required for the total chloride concentration surrounding the reinforcement (located at a distance c from surface) to increase over the threshold for depassivation.

Chloride attack is distinct in that its primary action is the corrosion of steel reinforcement and only as a consequence of the corrosion process the surrounding concrete is damaged. The process leading to corrosion, and the factors affecting the corrosion of steel bars embedded in concrete (W/C ratio, type of binder, pore and capillary structure) have been widely investigated [1,7,8,13].

Corrosion propagation is taking place at a rate that depends on the availability of both oxygen and water at the cathode (Fig. 1c) [1,7,8,13]. However, even at low rates of O_2 , severe pitting corrosion has been noticed [1,6]. It can be attributed to the fact that the anodic sites may be localized but the corresponding cathodic sites may be spread out over a wide area. In this way, as the corrosion product is discouraged from precipitation, and due to the existence of highly active and localized anodic sites, a severe pitting corrosion may occur without an earlier warning through visible signs at the surrounding concrete. This can lead to rapid loss of cross-section and critically reduce the load bearing capacity of the reinforced concrete member [14,15]. When cracks develop, the corrosion product will be deposited along the crack. By the time rust staining becomes apparent at the surface, the extent of reinforcement deterioration may be structurally significant.

Most of the available studies on the effects of corrosion refer on steel bars directly exposed to the corrosive environment (bare bars), usually under salt-spray exposure [16,17]. Aspects, as the subsequent mass loss, the depth and the density of the pits formed on its surface are usually evaluated [18,19]. What is however neglected to a great extent, even by the appropriate standards, is the evaluation of how the accumulated corrosion alters the mechanical properties of the steel bar. In the relevant Greek

standard [20], for instance, (as well as in the other appropriate European National Standards), the ability of a steel bar for mechanical performance is considered as being unchanged during the entire lifetime of a reinforced concrete structure. It has been early recognized [19] that chloride induced corrosion, characterized by the continuous occurrence of pitted regions on the steel reinforcement, leads to substantial reductions in the bar cross-section. Such type of damage can have significant effects on strength [3,4,14,16,17,21–26] and ductility of reinforced concrete elements [19,23–25,27].

Given the above, apart a few valid efforts [4,14,16,17,19,21–27], investigations on the effects of corrosion on the mechanical performance of reinforcing steel bars remains rare. To this extend, the influence of accumulated corrosion damage of steel bars embedded in concrete on the reduction of bond strength between bar and concrete [3,4,19,21] has been investigated and assessed. ESEM observations on corroded steel bars (exposed to open atmosphere and sprayed daily with a 3.5 wt.% sodium chloride solution) [4] revealed that bond strength between steel rebar and concrete was reduced by 53%, for 122 days of exposure, due to the morphology and thickness of the rust layer on the steel surface. Furthermore, research results [25] on the effect of the degree of corrosion (expressed as the percent mass loss) on the mechanical properties of steel bars embedded in concrete slabs, indicated that a sudden failure of RC slabs in flexure was observed, for a mass loss of more than 13%. A decrease in the load bearing capacity of the steel reinforcement, due to the reduction of its cross sectional area (at the points where corrosion was concentrated) produced sudden failures without yielding, without the most desirable warning prior to failure of a structure.

Recently [22–24,26–28], it was demonstrated that steel bars subjected to corrosion (salt-spray) may suffer a relatively modest loss of strength but a significant loss of ductility. In general, in spite of research results available [29] were a correlation factor between natural corrosion and accelerated salt spray corrosion was estimated (in terms of corrosion attack rate and mass loss), there is not yet a widely accepted correlation of these results with those derived from bars embedded in concrete and exposed in a normal corrosive environment. Hence, additional experimental investigation is required in order to clarify the nature of the correlation of corrosion on bare and on embedded steel bars. Such is the aim of this study, where the effects of chloride induced corrosion on the tensile behavior of B500c reinforcing steel bars are investigated for samples exposed directly (noted as “bare”) and embedded in concrete (noted as “embedded”) under accelerated salt-spray exposure. Furthermore, the tensile properties of the corroded material were compared against the requirements set in the

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