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Study of the rust penetration and circumferential stresses in reinforced concrete at early stages of an accelerated corrosion test by means of combined SEM, EDS and strain gauges

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HIGHLIGHTS

- Rust penetration in RC at early stage of corrosion is studied.
- Circumferential stress generated by rust products of rebar in concrete is assessed.
- Penetration of the rust into the pore network was measured by means of SEM and EDS.
- Accelerated corrosion test with current density of 50 and 100 $\mu A/cm^2$ was performed.
- Rust penetration velocity in porous network correlates with cracking pressure.

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ABSTRACT

Corrosion of steel bars for reinforcement leads to expansive pressure on the surrounding concrete that causes internal cracking and, eventually, spalling and delamination. The numerical and analytical modelling of cover cracking due to the corrosion of concrete usually involves a delay in such corrosion as a consequence of accepting a propagation time, after the beginning of the process, in which rust products penetrate the porous network of the concrete and pressure is mitigated. However, the assessment of this delay is based on empirical data. Regarding such a time, there is limited published research that focuses on the initial stage of the propagation of rust products in the porous structure of the surrounding concrete.

This work offers a combination of scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS) and strain gauges to study the phenomena involved at the beginning of corrosion. It focuses on the analysis of penetration of rust products into pores and measurement of strain and stresses caused in the concrete, near to the rebars, at the beginning of corrosion. It also involves use of an analytical model to calculate the width of the crack that could be used to estimate the time of cracking. The method has been applied to two concretes with a different porous network and with two distinct corrosion current densities to examine how the technique could monitor the reinforcement corrosion process and detect cracking of the surrounding concrete. The experimental work was performed by using an accelerated corrosion test on a conventional concrete (CC) and a concrete with silica fume (SFC) by submitting them, respectively, to a current density of 50 $\mu A/cm^2$ and 100 $\mu A/cm^2$. Part of the concrete specimens had embedded strain gauges, placed as closely as possible to the rebar, used to monitor the strain. The penetration of the rust layer was observed and measured by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). A good relationship between the velocity of the penetration of the rust products in the porous network and the delay of the cracking pressure in concrete was observed by introducing a reduction factor.

1. Introduction

Corrosion of steel reinforcement is one of the most common deterioration mechanisms identified in reinforced concrete structures, in many cases causing significant structural problems and

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even collapse and the associated cost of repair and maintenance [1,2]. Passivity represents the principal mechanism of protection against corrosion of steel bars embedded in concrete. Under this status an oxide film, formed during hot rolling when there is sufficient oxygen, protects steel bars from this process. There are various factors that might cause such protection to fail. Among them, several modifications to the chemical composition of the concrete may be involved: in particular, depletion of alkalinity due to carbonation, penetration of chloride ions and depletion of oxygen. Once the breakdown of passivity has occurred, the steel is exposed to corrosion. Particularly, consequences such as a reduction of the net section, degradation in steel-concrete adherence and decrease of the load-bearing capacity and degradation of concrete integrity, should be taken into account [3,4]. In essence, corrosion is known to be a major cause of premature rehabilitation of reinforced concrete structures.

The present work is focused on chloride attack [5,6]. Depending on environmental conditions, various levels of corrosion products may be formed with a distinct expansion coefficient which can vary from two to six times the original iron volume. This increase of volume in the bar surface within the hardened concrete produces internal pressure on the surrounding concrete that may lead to cracking, spalling or delamination of the cover after exceeding the concrete tensile strength [7]. Since such effects severely influence long-term performance of the structure, models are capable of predicting the time interval to the cover cracking and the remaining service life of the structure [8–11].

When concrete is exposed to an aggressive environment with chlorides, ions penetrate the porous network and (after the time required to travel along the cover has passed) reach the reinforcement bar. Once the chloride concentration threshold value in the rebar surroundings has been reached, corrosion starts. It is accepted that when the corrosion process has started there are three propagation stages [12,13]: a first stage in which the corrosion products penetrate the porous network around the steel rebar, filling the steel/concrete interface; a second stage characterised by stress initiation since the corrosion accommodation region is completely filled with rust products that start to exert stress; and a third stage identified by the formation of cracks when stress reaches the tensile strength of the concrete and rust fills the cracks as they are created. Consequently, expansive stress appears in the concrete, causing cracking, spalling or delamination of the cover. Therefore, the determination of the corrosion accommodation region thickness is important in order to predict the time of cracking initiation in reinforced concrete structures exposed to chlorides. Recent works have focused on the formation and propagation of corrosion-induced cracks and the corrosion accommodation region size by using the X-ray attenuation technique [14,15]. Some authors, such as Zhao et al. [16], suggest that the penetration of corrosion products into the porous zone of concrete and the formation of a corrosion layer at the steel/concrete interface might proceed simultaneously after the initiation of steel corrosion. In addition, they state that rust might not penetrate the corrosion-induced cracks before the cracks reach the concrete surface. These last points invite debate [17,18].

In summary, at the last part of the propagation stage corrosion causes reinforcement cross-section reduction and loss of bond between concrete and steel. The oxide products occupy a significantly greater volume than the original steel consumed [19,20], causing tensile stresses in the surrounding concrete and generating cracking upon reaching tensile strength.

In assessing and interpreting experimentally the phenomena involved at the first stage of the corrosion process, while many researchers have carried out accelerated experimental tests on concrete with rebar specimens monitored with strain gauges [21–23] others have preferred the use of microscopic techniques to study the concrete/steel interface [12]. This work proposes integrating both ways of addressing the problem by combining the use of strain gauges placed as closely as possible to the rebar and electron microprobe analysis to examine the concrete/steel interface, contributing to a reduction in confusion and incompatibility concerning cracking models.

There are many models used, reported the literature, to simulate the cracking process of the concrete. Many are based on finite element (FE) approaches. Among them, it is necessary to highlight two types: smeared cracking and discrete cracking which have both been complemented by the use of the so-called strong discontinuity approach (SDA) [24,25]. The result entails complex numerical models used to analyse the fracture of quasibrittle materials. In particular, a numerical approach based on the SDA, complementing a classical model of discrete cohesive crack, has been used to reproduce fracture process of concrete around the rebar induced by the expansion of the steel due to corrosion, with a good fit [7]. As a simpler approach, an analytical implementation of the discrete crack model based on the thick walled-cylinder approach has also been proposed (for example [7,26,27]). Even though the thick-walled cylinder approach introduces some difficulties when extended to real and complex cases, it has provided good results with simple geometries. In this work, such a model is used for verifying the experimental results obtained for the first stages of the corrosion development obtained by strain gauges [21] placed at the concrete surface close to the rebar.

This paper studies the early stages of the corrosion process in which corrosion products penetrate the concrete porous network surrounding the reinforcement, given that this period has invited little research and that most of the calculation models try to avoid it by assuming a delay in the time of propagation of corrosion from its initiation. It examines how a combination of scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS) and strain gauges could monitor the evolution of corrosion products during reinforcement corrosion and detect cracking of the surrounding concrete. The setup of the first part involved an experiment that used accelerated corrosion tests performed on two high-strength concretes with distinct microstructure to test the ability of the method in examining the behaviour against corrosion in two concretes with a different porous network and with two distinct corrosion current densities generally used for accelerated corrosion studies [5,28,29]. Both concretes had a steel rebar embedded in the middle and imposed on a current density: one without admixtures and another with silica fume (SF). The intensity per unit area in the concrete with silica fume is 100 $\mu A/cm^2$, and 50 $\mu A/cm^2$ in the case of the plain concrete specimens [5,28,29]. The strain of the concrete due to corrosion of the rebar was monitored by means of strain gauges. In addition, penetration of the rust layer in the concrete was observed and measured by means of scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). Lastly, the work entailed use of the thick-walled cylinder approach to reproduce the experimental results. A combination of wavelength dispersive spectroscopy along an analytical line covering the interface and the radial displacement of the gauges can be used to predict the crack width in a second stage. In addition, time-to-cracking can be obtained from converting the retrieved strain data into stresses and by comparing the circumferential stress with the tensile strength.

This paper focuses on the application of the combination of experimental and analytical techniques proposed with different testing conditions. The study of the influence of the porous microstructure of concrete and the corrosion current density in the surface of the rebar is beyond the scope of the present research. The significance of this research entails the combined study of both techniques: the assessment of the hoop displacement of the