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A method to determine the constitutive parameters of oxide in accelerated corrosion tests of reinforced concrete specimens

Beatriz Sanz[a,*], Jaime Planas[a], José M. Sancho[b]

[a] Universidad Politécnica de Madrid, Dep. de Ciencia de Materiales, ETS de Ingenieros de Caminos, Profesor Aranguren 3, Madrid 28040, Spain
[b] Universidad Politécnica de Madrid, Dep. de Estructuras de Edificación, ETS de Arquitectura, Avda. Juan de Herrera 4, Madrid 28040, Spain

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ABSTRACT

A novel methodology was developed for indirect determination of the mechanical parameters of the oxide in reinforced concrete corrosion, with satisfactory results. It combines accelerated corrosion tests performed over concrete prisms cast around a steel tube equipped with special instruments, and numerical simulations using a model that reproduces the oxide expansion and its mechanical behavior, and fracture of concrete by means of the cohesive crack model. In this work, systematization for determining the values of the oxide parameters is proposed, and strong verification of the method is provided by presenting the results of an extensive experimental campaign.

1. Introduction

Reinforced concrete is one of the most widely used materials for construction of infrastructures and buildings, due to its high mechanical resistance and to its economical manufacturing. However, corrosion of the steel rebars might occur when depassivating agents go through the cover and an oxide layer forms, resulting in a decrease in the cross-sectional area of the reinforcement, loss of bond and cracking of the cover [1]. Since those effects severely affect the service life of the structure, it is essential to have models that permit to calculate its degree of safety and its residual service life, which requires understanding the fracture behavior of the concrete and the mechanical action of the oxide.

With regard to fracture of concrete, there is a wide experience, both experimental and numerical, and there are models that reproduce accurately concrete cracking, such as smeared cracking and discrete cracking (see [2–4] for a description and discussion of the use of the main models). From those, in this work the cohesive model has been used, introduced by Hillerborg et al. [5], in which the crack is described as a discrete crack that transmits stress at its faces, following a softening curve, and the parameters defining that curve have been determined according to the method described in [6]. Regarding the oxide layer, accelerated corrosion tests have highly contributed to a better understanding of the effects of corrosion. For example, in the pioneering work from Andrade et al. [1], the amount of electrical charge necessary to induce initiation of cracking was measured. It was then possible to find the time to first cracking one can expect in a real structure given the real average corrosion rate. Further research of Andrade et al. [7] and Alonso et al. [8] sought the influence of other factors affecting corrosion-induced cracking, such as the cover-to-diameter ratio, the quality of concrete and the rate of corrosion. Regarding development of cracks, information has been reported in the literature, covering the evolution of the strain in concrete [1,9], the crack width [8,10], or the patterns of cracks observed by visual inspection at the concrete surface for advanced states of cracking [9,11] or at selected cross-sections of the specimens [12,13]. In recent works, new sophisticated techniques have been applied in combination with accelerated corrosion, such as X-ray attenuation measurements and digital image correlation, to monitor the development of corrosion products and to measure the deformations between steel and mortar [14–17]. However, there are still many uncertainties about the type of oxide generated and its characteristics, which are crucial in the models, due to the difficulty to perform on-site measurements. Moreover, there are some unknowns about the process of cracking itself, especially about initiation of cracking, due to limitations in the instrumentation of the cracks. For example, strain gages provide continuous measurements when glued prior to accelerated corrosion, but they may fail to capture any crack unless a large amount of gages is used, since the exact position of a crack varies from test to test due to the heterogeneity of concrete; nevertheless, if displacement transducers are glued once a crack is visible, the widening is measured exactly perpendicular to the crack, but no information is obtained about the cracking process before the crack gets visible. With regard to the simulation of the oxide effects, many works have been devoted to obtain reliable models that reproduce corrosion-induced cracking, from

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[*] Corresponding author.
E-mail addresses: beatriz.sanz@upm.es (B. Sanz), jaime.planas@upm.es (J. Planas), jose.sancho@upm.es (J.M. Sancho).

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Bazant's physical model [18,19] and the finite element model from Molina et al. [20] to the most recent models published in the last years, such as analytical models based on the thick-walled tube theory and smeared cracking [21], finite element models that use discrete cracking [12,22-24], coupled models that take into account chemical factors affecting the density of current and the transport of oxide within the cracks [25], and models that simulate non-uniform corrosion based on experimental observations [26] or based on calculations of the chloride penetration [27]. However, despite the great development and advance in the models, there is a lack of information about the constitutive parameters of the oxide, as mentioned before, due to the difficulty to test them directly. A crucial parameter is the expansion ratio of the oxide, which depends on the specific species of oxide formed, and can range from 2.0 to 6.5 [28,29]. For example, an expansion of 2.0 was reported for accelerated corrosion tests with 10 and 100 $\mu A/cm^2$ in [1,20]; in [15] presence of Fe_2O_3 and Fe_3O_4 was assessed by X-ray attenuation in accelerated corrosion tests with an impressed current of 250 $\mu A/cm^2$, which corresponds approximately to expansion ratios of 2.0. However, higher values are reported in other works, as 2.94 for experiments with 100 $\mu A/cm^2$ in [10], 3.39 in [21] which was obtained based on the experimental results in [30], or 6.5 for experiments with 100 $\mu A/cm^2$ in [14]. In most of the experimental inferences, an effective expansion ratio is determined, assuming that all the corrosion product formed is allocated between the steel and the concrete, although, as pointed out by Molina et al. [20], some of the oxidization products can diffuse or flow through the porous network of concrete, which was introduced as a *porous zone* by Liu and Weyers [30], and through the newly formed cracks, as considered by Pantazopoulou and Papoulia [31] and quantified by Val et al. [32]. The stiffnesses of the oxide are also crucial parameters, but no experimental information about them is available in the literature, although they have been assessed from numerical simulations to influence the resulting cracking [12], and elastic moduli are found ranging from 0.14 GPa [14], up to 20 GPa [16]. Those differences might be explained by the different conditions in the experiments, the simplifications in the models, and by the parameters being inferred from measurements that are almost insensitive to variations in those parameters, such as the crack width, as will be discussed in this paper.

To narrow the uncertainties about the mechanical parameters of the oxide, the authors presented a methodology that combines the results of accelerated corrosion tests and of numerical simulations [33]. A novel set-up for accelerated corrosion was designed, to get information close to the oxide layer, using as specimens concrete prisms cast around a steel tube that were equipped with special instruments to measure the deformation of the tube and the width of the main crack [33,34]. To simulate the tests, a model was programmed that combines elements with an *embedded adaptable crack* [35,36], which reproduce concrete cracking according to the cohesive crack model, and *expansive joint elements*, which reproduce the expansion of the oxide and its mechanical behavior, simulating a debonding and a separation between the oxide and the concrete [12,37], and it was proved to reproduce the experimental results. From the joint analysis of the experimental and numerical results, approximate values were obtained for the mechanical parameters of the oxide developed in those experiments.

In this work, a systematic procedure for the determination of the oxide parameters is presented, together with a stronger validation of the method, based on an extensive experimental campaign. A thorough study of the influence of the parameters of the model has been carried out, and details of the determination of the oxide parameters are reported, using as a reference the experimental results presented in [33]. Then the experimental results of new specimens manufactured from three different batches and corroded in the same manner than those in [33] are presented, as well as their simulation, using the fracture parameters determined in experiments for each batch of concrete and the oxide parameters determined previously for specimens corroded in similar conditions. It should be noticed that this study presents the results of laboratory specimens with accelerated corrosion, and the oxide developed might differ from that developed under natural conditions, but the aim of this paper is to provide a method to determine the mechanical properties of oxide, which could be applied in different scenarios.

The paper is organized as follows: For completeness of the text, Section 2 reviews the main aspects of the experiments and the numerical model presented in [12,33]. Section 3 describes the base results of accelerated corrosion tests, analyzes the influence of the parameters of the model, details the method to determine the values of the oxide parameters and discusses the definitive results obtained in the simulations. Section 4 presents the experimental results of the new experimental campaign and from simulations of those, using the values of the oxide parameters determined in Section 3. Finally, Section 5 summarizes the work and presents the conclusions of this paper.

2. Experimental and numerical method

2.1. Outline of the experimental and numerical method

The method proposed to characterize the mechanical oxide behavior combines the results from experiments and from numerical simulations, and is based on previous works [12,33]. To gain more insight in the way the corrosion product interacts with the steel and the surrounding concrete, the behavior in accelerated corrosion of prisms reinforced with a tube, instead of a bar, as those shown in Fig. 1, was investigated. This reinforcement differs from that of real structures, but in the proposed method it has been essential to determine the oxide parameters for a given condition, as will be discussed in the paper; then those parameters could be applied to simulate the behavior of real structures reproducing their geometry. The specimens were designed with a geometry as simple as possible, clear boundary conditions and a dominant mode of failure, consisting of a single main crack through the cover [12,33]; other secondary cracks developed around the reinforcement, but they were much thinner [12]. Besides, accelerated corrosion tests were designed to achieve plane current field, thus,

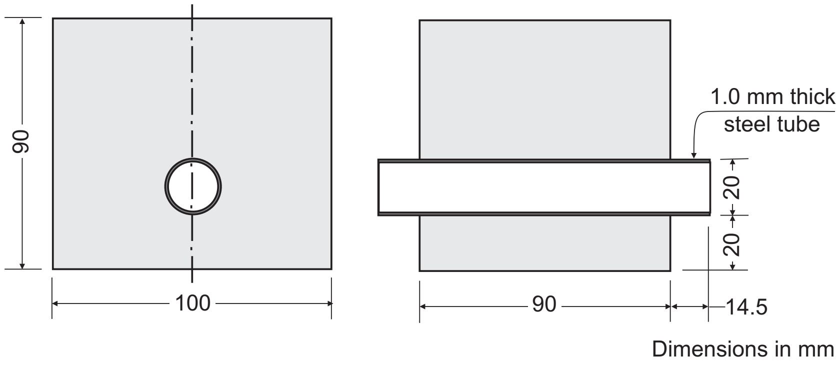

Fig. 1. Specimens used in accelerated corrosion tests.