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Corrosion induced cracking: Effect of different corrosion rates on crack width evolution

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HIGHLIGHTS

- The influence of a range of distinct corrosion rates on the crack growth rate was tested.
- The results obtained show a two stage crack width growth process, where a bilinear curve enveloping relation between crack width evolution and the attack penetration of the steel bar is a fair approximation to adopt for prediction purposes.
- An empirical relation was found between the ratio crack width/steel attack and the corrosion rate applied for the first stage of cracking.
- A formulation that relates the crack width evolution through time with the corrosion rate was developed.

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ABSTRACT

Reinforcement corrosion leads to several damage types that influence the structure service lifetime, among which can be mentioned the cracking of concrete cover due to the increase in volume of the oxides with respect to the original volume of the parent steel. The relation between crack width and corrosion level has been studied by some authors while its analytical or numerical modelling is attracting increasing interest. In the modelling attempts, it has not been found the consideration of the corrosion rate effect, which, on the other hand was experimentally demonstrated more than 20 years ago. In the present paper the impact of different corrosion rates on the crack width development of reinforced concrete (RC) was studied. Identical RC prisms were subjected to accelerated corrosion in galvanostatic conditions with distinct electrical currents each, in order to monitor the superficial crack width growth of every specimen. Crack width growth with steel attack penetration is analysed as a two stage bilinear process where the crack width grows faster in the first stage. An empirical relation is found between the ratio crack width/steel attack and the corrosion rate applied for the first stage of cracking. With the new-found relation, a formula relating crack width evolution through time with the corrosion rate is presented. This study shows that it is crucial to take into account the strong influence of the corrosion rate on the crack width/steel attack ratio variation in order to successfully predict corrosion induced cracking.

1. Introduction

Reinforcement corrosion is the most common deterioration mechanism of structural concrete. As the rebar corrodes, the iron in the steel is oxidised to produce rust, that occupies a larger volume than the original material. This expansion causes tensile stresses in the concrete which eventually lead to cracking. Predicting reinforced concrete (RC) deterioration through modelling is gaining interest due to its economic consequences. However, not many models focus on the crack propagation period, as much of the interest is focused in the reproduction of the initial cover cracking due to the expansive character of the iron oxides.

The vast majority of experimental studies on corrosion induced crack initiation and propagation, that were conducted previously [1–5], use the same corrosion rates or only a few different ones in their tests. Andrade et al. and Alonso et al. already expressed before the importance of the corrosion rate as a basic parameter in crack evolution [1,2] as higher steel attack penetrations are necessary when applying higher corrosion rates to obtain the same crack width values. Vu et al., in their model, proposed to minimize the prediction error when extrapolating accelerated corrosion test results to the behaviour of real RC structures by means of a correction factor for the rate of loading [5]. However, few authors went deeper on this subject.

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Consequently, one of the limitations in existing models [6–10] resides in quantifying the influence of a large range of distinct corrosion rates on the crack growth rate. As such, present day formulation has not included the corrosion rate as one of the parameters to predict in a proper way how corrosion induced cracking of RC develops in natural conditions.

The tests designed for this study focused on obtaining results for crack width growth on the surface of RC specimens at different imposed corrosion rates. The main objective of the test set is to contribute in clarifying the relation of corrosion rate I_{corr} and crack width growth.

I_{corr} as a basic parameter in corrosion induced cracking is often treated in a very simplistic way by neglecting its influence, resulting in incorrect predictions of the consequent concrete cracking. The usual approach is to determine the damage produced in the steel, by means of attack penetration and to relate it in a direct proportional way to cracking disregarding the corrosion intensity applied. Ignoring the corrosion rate in this approach leads to large prediction errors, as will be understood after the analysis of the results obtained.

An empirical relation between I_{corr} and the crack width growth rate is presented for imposed corrosion, as an additional step contributing to the comprehension of the phenomenon and development of prediction models.

A better knowledge of the corrosion rate influence on crack width growth rate is fundamental to the development of new corrosion induced cracking models and adjustments of current ones.

2. Experimental procedure

2.1. Concrete specimens' characteristics

11 prisms of reinforced concrete were casted with the following dimensions: 15 cm × 15 cm × 50 cm. Each concrete prism was reinforced longitudinally with a single corrugated steel bar with length of 60 cm and 16 mm diameter. Two concrete covers *c* were tested: 20 mm and 40 mm. A scheme of a prism is presented in Fig. 1. The concrete mix has a water/cement ratio of 0.55 and contains 360 kg/m^3 of CEM II 32,5 B/V cement. The maximum aggregate size is 12 mm. $CaCl_2{\cdot}2H_2O$ was added to the mix in order to ensure a 3% mass ratio of Cl^- to cement. The presence of chloride in the mix enables a correct accelerated corrosion process.

The prisms were casted in two batches: Batch 1, containing specimens P1 to P5, which were submitted 147 days to moist curing, and Batch 2, comprising the prisms P7 to P12, submitted 28 days to moist curing. After curing, both batches were left 28 days in laboratory conditions before the application of accelerated corrosion. The average results of standard compressive strength and modified diametric splitting tests [11] characterizing the batches are given in Table 1. Batch 1 was more mature and resistant than Batch 2 when the imprinting of electrical current started.

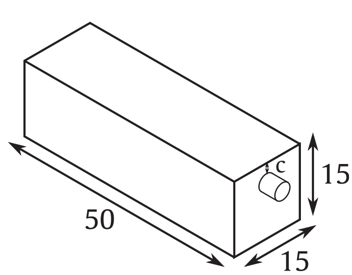

Fig. 1. Scheme of a RC prism (all units in cm). *c* is the concrete cover.

Table 1
Mechanical characteristics of the concrete.

		28 days moist curing	147 days moist curing + 28 days lab condition
Batch 1	$f_{cm,cube}$ [MPa]	32.47	54.71
	f_{ts} [MPa]	–	3.90
Batch 2	$f_{cm,cube}$ [MPa]	37.47	–
	f_{ts} [MPa]	2.18	–

2.2. Impressed controlled current setup for accelerated corrosion

The accelerated corrosion setup is illustrated in Fig. 2. A controlled current source applies a constant electrical current to the rebar through the counter electrode, a stainless steel mesh. The electrical contact between the concrete and the stainless steel mesh is assured by a wet sponge cloth. The sponge was maintained wet all the time through recurrent watering. An additional large sponge was placed covering each RC piece to keep the moisture inside. Each RC prism was placed inside a plastic tray (height approx. 2 cm), to avoid electrical interferences, and also as an additional way to minimize the drying rate of concrete. Both lateral sides of the RC prism are covered by the steel mesh, in order to obtain the most homogeneous electrical field possible around the steel rebar.

The intensity of current passing by each circuit/specimen was monitored with a data logger unit every 15 min, at most. The nominal current densities applied are expressed in Table 2, ranging from 5 to 500 μA/cm^2.

2.3. Crack width measurement

In order to quantify the crack widths throughout the test, several polycarbonate reference points were glued with epoxy adhesive along the concrete surfaces. The crack width value was obtained as the evolution of distance between reference points at opposite sides of the crack. The distances between each pair of polycarbonate points were obtained periodically using a digital calliper. In addition, to obtain more accurate crack width values in smaller ranges, polyester wire strain gauges were added on the upper face of Prisms P9, P10 and P11 (Fig. 3). The electrical resistance of the strain gauges was recorded by the data logger unit every 10 min. Influence of temperature variation and cable resistance was taken into account by placing an additional strain gauge on a non-reinforced reference specimen. The measurements obtained with the digital calliper and the strain gauge were cross-checked between themselves and also with additional ones obtained with a crack width microscope.

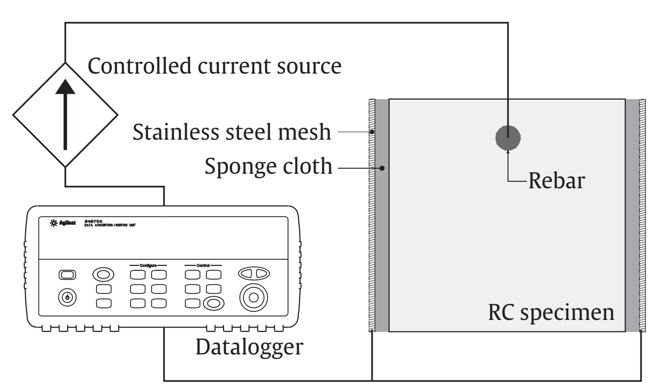

Fig. 2. Impressed current setup for accelerated corrosion.