RESEARCH ARTICLE

Cracking in Reinforced Concrete Structures Damaged by Artificial Corrosion: An Overview

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Abstract:

Background:
Corrosion of the reinforcing steel is a significant issue in construction engineering. As the corrosive attack propagates, the oxides accumulated on the steel-concrete interface cause a radial internal pressure in the structural element and induce a tensile stress state in the concrete with the consequent cracking. Except for few cases, the main outcomes on the behavior of reinforced concrete structures damaged by corrosion come from experimental results on artificially corroded specimens. For many years, the scientific community has been discussing the feasibility of artificial techniques to simulate the corrosion process in structural element. Specifically, the most disputed method is the accelerated electrolytic corrosion test, often characterized by high current intensities in order to reduce the duration of the experimental surveys.

Objective:
In the paper the influence of the current density on the degradation of a reinforced concrete element is investigated with particular reference to the kind of formed oxides and to the crack width.

Methods:
An experimental survey on steel rebars embedded in concrete cylinders and subjected to an electrolytic corrosion has been performed, with different increasing current densities. Furthermore, an analytical model, based on the classical thick-walled cylinder theory already proposed by the authors, is applied for validating the experimental results.

Results:
The oxides produced by artificial corrosion with different current densities are analyzed with X-ray diffractometry measurements. The influence of the current density on the crack widths is also pointed out.

Conclusion:
The analyses of the obtained results show that for the analysed specimens and current density range, no significant differences are found for the oxides composition. On the contrary the influence of the current density on the crack width is pointed out, and an upper limit of this parameter is indicated.

Keywords: Corrosion, Reinforced concrete, Cracking, Experimental survey, Current density, Analytical model.

1. INTRODUCTION

For several years the reinforced concrete was considered an invulnerable material and all the factors related to the environmental actions and the relative consequences were ignored.

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Therefore, the study of the durability and the service life of reinforced concrete structures is of great importance (e.g. [1 - 4]). As an example, in EU a great number of the concrete highway bridges are deteriorated and are considered to be substandard: the 39% for France, the 37% for Germany, the 30% for United Kingdom and the 26% for Norway [5]. More than 30% of the American highway bridges have been declared deficient by the U.S. Department of Transportation [6].
In the estimation of life-cycle costs and optimization of repair and maintenance strategies for RC structures, severe cracking and spalling are considered as limit states (e.g. [7 – 9]). The definition of the maximum crack width depends on individual conditions and asset owner policies. Actually, a crack width between 0.3 to 0.4 mm is defined as the limit value for a durability limit state [10, 11]. The problem of the relationship between the corrosion phenomenon and the corresponding crack opening has been discussed [12].

In the paper, the topic of the cracking in reinforced concrete structures subjected to the corrosion process is firstly outlined by means of a brief review of the most significant literature results. Except for few cases, the principal findings come out from experimental surveys based on artificial corrosion procedures. Since the corrosion products amount increases with the increase of the current intensity, there is a great influence of the current intensity on the crack width is clear, the oxides must have the time to spread in the concrete. The amount of the oxides (and then the radial pressure) increases with the time proportionally to the current intensity; consequently, the cracks widen and a strong localization of the corrosion at the crack occurs.

Since the simulation of a realistic degradation is strictly related to the effective concrete porosity, to the cover depth and to the current intensity, the accelerated electrolytic corrosion tests have to be carried out by applying low current intensity values. Then, an experimental survey is carried out to estimate the influence of the current intensity on the corrosion morphology, oxides typology and cracking. The classical electrolytic corrosion technique was applied to embedded rebars in order to attain a level of 5% in mass loss, applying different corrosion rates. The experimental results suggest that the current density, in the analysed range of up to 4000 μA/cm², does not influence the typology of the corrosion products - mainly ferrous hydroxide - in agreement with other authors (e.g. [13 - 15]). On the other side, the increase of the corrosion rate induces a significant corrosion localization, with an increase of the crack width.

Finally, to assess the upper limit of the current density for simulating a realistic degradation morphology, an analytical model, based on the classical thick-walled cylinder theory and able to provide the crack opening as a function of the corrosion level, the concrete mechanical properties, the cover/reinforcement-diameter ratio and the oxide typology, is also applied.

2. LITERATURE REVIEW

Many experimental and theoretical researches are focused on the assessment of the time in which the concrete cracks, due to the corrosion process.

The theoretical models typically define the stress state in the concrete through the thick-walled cylinder model (internally delimited by the reinforcement bar and, externally, by the concrete cover) subjected to an internal pressure caused by the expansion of the corrosion products. Complex models take into account the reduction of the reinforcement cross-section, the presence of a thin porous layer around the reinforcements (in which the oxides settle without stress the concrete) and the diffusion of the oxides in the cracks. The first conceptual model for the prediction of the service life of corroded structures was developed by Tuutti [16], which distinguished two periods of the corrosive phenomenon (Fig. 1a), in the first stage CO₂ or Cl⁻ ions spread and activate the corrosive process; in the second, the corrosion propagates up to the cover cracking. Weyers et al., [17], stated that between the initiation and the propagation period there is a further phase during which the corrosion products are arranged at the steel-concrete interface and do not exert any pressure on the surrounding concrete (Fig. 1b).

The model proposed by El Maaddawy [14] is based on the assumption that the concrete surrounding the reinforcement behaves like a perfectly elastic thin-walled cylinder. In this hypothesis, the time necessary for the concrete cracking (T_cr) is evaluated according to the Faraday’s relationship and requires the knowledge of the corrosion products amount.
Cracking in Reinforced Concrete Structures

The effective Young's modulus, \( E_{\text{ef}} \), is used in the proposed expression for the time to crack initiation was obtained by many authors who applied very low corrosion rates. Alonso et al., [31] suggested a maximum current intensity of 100 \( \mu \text{A/cm}^2 \) for practical applications. Even if nominal intensities of 3-10 \( \mu \text{A/cm}^2 \) represent the common corrosion rate detected in real-size corroding concrete structures, higher values can be applied: Alonso et al., [31] developed galvanostatic tests characterized by nominal constant current density of 100 \( \mu \text{A/cm}^2 \), El Maaddawy [32] proposed a current density level above 200 \( \mu \text{A/cm}^2 \) as a limit in the accelerated electrolytic corrosion test on reinforced concrete elements. With this in mind the results obtained by many authors should be critically reviewed.

Reliable indications have been provided by the Spanish researchers, who applied very low corrosion rates. Alonso et al., [31] developed galvanostatic tests characterized by nominal constant current density of 100 \( \mu \text{A/cm}^2 \) and found crack widths of 0.05-0.1 mm for radius losses of 15-50 \( \mu \text{m} \) and widths of 0.2-0.3 mm for penetrations of 50-200 \( \mu \text{m} \). Similar results were obtained by Rodríguez et al., [33] on RC beams subjected to accelerated electrolytic corrosion. Moreover, a formulation relating the pit penetration needed for cracking initiation \( x_p \) expressed in \( \mu \text{m} \), the concrete cover \( (c \text{ expressed in mm}) \) and the inner bar diameter \( (\varphi \text{ expressed in mm}) \) was proposed (EQ. 7).

\[
x_0 = 7,53 + 9,32 \frac{C}{\phi_0} \quad (7)
\]

An alternative formulation was defined by Rodríguez [34] to account for the splitting tensile strength \( (f_{csp} \text{ expressed in MPa}) \):

\[
x_0 = 83,8 + 7,4 \frac{C}{\phi_0} - 22,6 f_{csp} \quad (8)
\]
Moreover, Rodríguez [34] proposed a relationship between the crack width ($w$ expressed in mm), the attack penetration ($x$ expressed in μm) and $x$:

$$w = 0.05 + \beta(x - x_0)$$  \hspace{1cm} (9)

where, $\beta$ is a coefficient that account for the reinforcement position ($\beta$=0.01 for top cast bars and 0.0125 for bottom cast bars).

In EQ.9 the attack penetration $x$ may be evaluated as:

$$x = \frac{\phi_0}{\alpha} \left[1 - \sqrt{1 - \frac{\Delta A_s}{A_s}}\right]$$  \hspace{1cm} (10)

where $\phi_0$ is the initial reinforcement diameter and $\alpha$ is a coefficient to account for the corrosion morphology (2 for uniform corrosion and 4-8 for pitting corrosion). $\Delta A_s$ and $A_s$ are the corroded and the initial cross section of the reinforcement, respectively.

An interesting study was performed by Vu and Val [35, 36], who experimentally and numerically investigated the crack initiation and propagation, quantifying also the corrosion products dissipated within the cracks. Eight 700x1000x250 mm$^3$ slabs, reinforced only on the top with four 16 mm diameter round steel bars spaced 150 mm, were subject to an accelerated corrosion process characterized by a current density of 100 μA/cm$^2$. The first visible crack had a width of about 0.05 mm; the cracks propagated (in width and length) along a longitudinal fracture approximately 0.25-0.4 mm wide (Fig. 2).

On the basis of the obtained experimental results, Vu [35] defined an empirical relationship (EQ. 11) able to establish the time necessary to obtain a limit crack width as a function of the concrete quality:

$$t_{serv} = A \left(\frac{c}{wc}\right)^B$$  \hspace{1cm} (11)

where, $c$ represent the concrete cover, $wc$ the water/cement ratio. $A$ and $B$ are parameter specifically defined in Table 1 for the considered limit crack widths ($w_{lim}$).

![Fig. (2). Crack propagation in the experimental test [35].](image)
To predict the penetration of corrosion products into the crack, the experimental results were also simulated by mean FEM models. In Fig. (3) the ratio of the volume of corrosion products penetrating into cracks after crack initiation with respect to the total cracks volume is represented as a function of the corrosion attack: since the corrosion products gradually fill the cracks, the classical hypothesis of the analytical model can underestimate the predicted crack width.

Finally, it is interesting to mention the results obtained by various authors who submitted structural elements to a natural long-term corrosion process. In their experimental surveys, Ortega et al., [37] finds corrosion cracks already after one year of exposure; during the five-year research, the crack pattern, increased constantly in the time according to a linear law. After a natural corrosion of 14 and 17 years Vidal et al., [38] finds that the Rodriguez’s formulation gives reliable results only for the bottom cast reinforcement and propose a model of crack initiation for the localized corrosion. According to Vidal et al., [38, 39], the cross-section loss $\Delta A_{se}$ can be calculated as

$$\Delta A_{se} = A_s \left[ 1 - \left( 1 - \frac{\alpha}{\phi_0} \left( 7.53 + 9.32 \frac{c}{\phi} \right) \right) \right] 10^{-3} \right] 10^{-3}\right] 10^{-3}\right] 10^{-3}$$

where $A_s$ is the sound steel cross-section (mm2), $\phi$ is the initial reinforcement diameter (mm), $c$ is the concrete cover (mm) and $\alpha$ is the pit penetration depth parameter.

In the Vidal’s model, it is assumed that crack width is directly proportional to the steel corrosion:

$$w = 0.0575 \left( A_s - \Delta A_{se0} \right)$$

(13)

Subsequent studies performed by Zhang [40] on the same beams have shown that the corrosion morphology change (from a pitting corrosion to a generalized corrosion) with the cracking propagation. After 26 years Khan [41] finds that the Rodriguez’s formulation accurately predicts the crack width only if the attack penetration parameter is fixed equal to 8, while the Vidal et al. model appears in a quite good agreement with the experimental results.

### 3. EXPERIMENTAL SURVEY

An analytical model is carried out in order to investigate the effects of the corrosion rate on the cracking, the corrosion morphology, the oxides typology and their diffusion inside the concrete (Table 2). A total of 10 reinforced concrete cylindrical specimens, characterized by a diameter of 50 mm and a length of 200 mm, were cast. At the center of each specimen, a 12 mm diameter bar ($f_y = 500$ MPa) was embedded. The concrete was realized with a CEM I 52,5 Portland cement and a water-to-binder ratio of 0.46; due to the small dimension of the specimens, only the fine aggregates (0.00 - 4.00 mm) were provided according to an aggregate-to-binder ratio of 0.47. The mean compressive strength after 28gg of curing was 20 MPa.

The samples were conditioned for 24h in a 3% electrolyte solution and subjected to an accelerated corrosion test with different current densities, as defined in Table 3. After the test, the samples were dried at a constant temperature of 18° C for 72h and the crack pattern was been accurately acquired and measured (Fig. 4).

<table>
<thead>
<tr>
<th>Limit Crack Width</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{lim} = 0.3$mm</td>
<td>65</td>
<td>0.45</td>
</tr>
<tr>
<td>$w_{lim} = 0.5$mm</td>
<td>225</td>
<td>0.29</td>
</tr>
<tr>
<td>$w_{lim} = 1.0$mm</td>
<td>700</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 1. Parameters for the EQ.11 [35].
Table 2. Corrosion variables for the samples.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Current Density</th>
<th>Theoretical Corrosion Level</th>
<th>Effective Corrosion Level</th>
<th>Crack Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>500 μA/cm²</td>
<td></td>
<td>5.82%</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td></td>
<td>4.57%</td>
<td>0.35 mm</td>
</tr>
<tr>
<td>B1</td>
<td>1000 μA/cm²</td>
<td></td>
<td>4.96%</td>
<td>1.00 mm</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td></td>
<td>3.85%</td>
<td>0.30 mm</td>
</tr>
<tr>
<td>C1</td>
<td>2000 μA/cm²</td>
<td></td>
<td>4.02%</td>
<td>0.35 mm</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
<td>6.64%</td>
<td>1.20 mm</td>
</tr>
<tr>
<td>D1</td>
<td>4000 μA/cm²</td>
<td></td>
<td>6.82%</td>
<td>2.50 mm</td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td></td>
<td>4.68%</td>
<td>1.50 mm</td>
</tr>
<tr>
<td>D3</td>
<td></td>
<td></td>
<td>6.67%</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>D4</td>
<td></td>
<td></td>
<td>4.15%</td>
<td>1.30 mm</td>
</tr>
</tbody>
</table>

Table 3. Corrosion products and their volumetric ratio respect the iron [21].

<table>
<thead>
<tr>
<th></th>
<th>FeO</th>
<th>Fe₂O₃</th>
<th>Fe₃O₄</th>
<th>Fe(OH)₂</th>
<th>Fe(OH)₃</th>
<th>Fe(OH)₃·3H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>α₁</td>
<td>1.80</td>
<td>2.00</td>
<td>2.20</td>
<td>3.75</td>
<td>4.2</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Fig. 4 cont......
The experimental survey shows crack widths varying between 0.30 and 2.00 mm, depending on the current intensity applied. In all the samples, the crack pattern is composed of two opposite longitudinal cracks spreading in all the specimen length and bifurcating at the specimen edges. Increasing the current density, the cracks become wider since the oxides fail to spread in the concrete pore and therefore exert a significant radial pressure, even for low degradation levels. The analysis of the propagation of the oxides inside the specimens shows a random diffusion apparently independent of the current intensity. (Fig. 5). As a matter of fact, the diffusion of the corrosion products is related to the casual arrangement of the aggregates and to the produced macro and micro-cracks.

A concentration of brown rust at the reinforcing bar with degrading colors up to yellow along the surface of the cracks was detected in all the samples. The analysis of the oxides showed two different morphologies, scaly (Fig. 6a) and porous (Fig. 6b) ones, that were analyzed through diffractometry measurements. The results are here reported for the corrosion product formed in the samples subjected to two corrosion rates (500 μA/cm² and 2000 μA/cm²).

In the graphs (Figs. 7-10), the blue curve represents the background noise, while the different peaks, of different colors, represent the phases, that is the different types of oxides formed. Except for the scaly oxide extracted from the sample subjected to the higher corrosion rate (the Iron Chloride Hydrate, H₂Cl₂FeO), all the corrosion products have different phases among which quartz and calcite are prevalent for the presence of the concrete. Specifically, the prevailing phase is the ferrihydrite (Fe₂O₃-0.5H₂O), eventually accompanied by the magnetite. This result is of particular importance because it allows us to define unambiguously the volumetric ratio between the prevalent oxide (characterized by a density of 3.70-3.90 g/cm³ depending on the hydration degree) and the iron, which for the examined cases vary between 2.00 and 2.15.

Finally, the corrosion morphology detected on the bars is analyzed (Fig. 11). As previously stated, higher current densities cause larger crack widths. In this condition, a strong corrosion localization is expected since a part of the reinforcement remains exposed and becomes highly subjected to the corrosive phenomenon. It is clear therefore that a higher corrosion rate corresponds to higher corrosion localization, even for low levels of degradation.

Aim of the experimental research is the evaluation of the effects of high current densities in accelerated corrosion, on the crack pattern, corrosion morphology and (eventually) oxides. Due to the reason, the lower corrosion intensity applied to the sample was 500 μA/cm². Smaller values were already used in the past by the authors in the framework of the experimental analysis of the bond behavior of corroded reinforced concrete elements [42]. In that case, a very low value of current density of about 20 μA/cm² was applied, in agreement with Alonso [31]. For corrosion level slightly lower than 1.00% in terms of mass loss, the specimens presented a crack width of about 0.10 mm (Fig. 12). These results will be discussed and compared with the ones previously described, in the following sections.
Fig. (5). Corrosion products propagation in the samples.

Fig. (6). Corrosion products formed in the samples: (a) scaly oxides; (b) porous oxides.
Fig. (7). X-ray diffractometry measurements on the scaly oxide formed with a corrosion rate of 500 μA/cm².

Fig. (8). X-ray diffractometry measurements on the porous oxide formed with a corrosion rate of 500 μA/cm².
Fig. (9). X-ray diffractometry measurements on the porous oxide formed with a corrosion rate of 2000 μA/cm².

Fig. (10). X-ray diffractometry measurements on the scaly oxide formed with a corrosion rate of 2000 μA/cm².
4. ANALYTICAL MODEL

According to previous studies of the authors [42], the relationship between the internal pressure due to the expansion of the corrosion product and the degradation level may be evaluated by means of the thick-walled cylinder theory modified in order to account for the nonlinear behavior of the concrete in tension [43].

In absence of any external load and cracks, during the corrosion process the oxides occupy a volume:

\[ P_{\text{corr}} = E_c \varepsilon \left( \frac{c^2 + r^2}{c^2 - r^2 + 4} \right) \]  \hspace{1cm} (15)

where \( E_c \) and \( \nu \) are the Concrete Elastic Modulus and Poisson’s ratio respectively; \( c \) is the concrete cover and \( r \) is the reinforcement radius.

The parameter \( \alpha_i \) represents the ratio between the volume of the oxides produced and the volume of iron consumed; its value (Table 3) depends on the oxide that is produced.

Then, in the elastic stage corrosion attack may be defined as:

\[ x_{\text{corr}} = \frac{\phi_{in}}{2} - \frac{\phi_{in}^2}{4} \left( \frac{U_{r}^2 + \phi_{in} U_{r}}{\alpha_i - 1} \right) \]  \hspace{1cm} (16)

where \( \phi_{in} \) is the sound diameter of the specimen, \( U_r \) is the radial displacement due to the expansion of the corrosion products due to an internal pressure that in the elastic stage \( (\varepsilon \leq \varepsilon_c) \) can be defined as:

\[ U_r = \pi x_{\text{corr}} \left( \phi_{in}^2 - x_{\text{corr}}^2 \right) \]

\[ + \pi \phi_{in} (x_{\text{corr}}^2 - x_{\text{corr}}^2) \]

where \( \phi_{in} \) is the sound diameter of the specimen.
Fig. (12). Corrosion degradation for some samples experimented in (Coccia et al., 2016).

Subsequently to the cracking, always assuming the absence of any external load, a certain number of cracks \( n \), characterized by an average crack width \( (w_c) \) and length \( (l_c) \), is introduced in EQ. 14, to account the spreading of the corrosion products. Then, the relationship between the corrosion attack and the average crack width will become:

\[
x_{\text{corr}} = \frac{\phi_m}{2} - \sqrt{\frac{\phi_m^2}{4} \left( \frac{U_r^2 + \phi_m \phi_f}{m w_0} \right) / \alpha_i - 1} \quad (17)
\]

Where the radial displacement \( U_r \) will depend on a radial pressure defined according to the equation EQ. 18 for the partially cracked stage and to EQ. 19 for the entirely cracked stage:

\[
P_{\text{corr}} = \frac{r_c}{r} \left[ f_{\text{cr}} \left( \frac{c^2 - r_c^2}{c^2 + r_c^2} \right) + f_{\text{cr}} \left[ a_i \frac{\pi c}{r} \left( \frac{c - 1}{r} \right) - 1 \right] \right] \quad (18)
\]

\[
P_{\text{corr}} = f_{\text{cr}} \left[ \frac{2 \pi c}{r} \left( \frac{c - 1}{r} \right) + b_i \frac{\pi c}{r} \left( \frac{c - 1}{r} \right) - 1 \right] \quad (19)
\]

In fact, in both the stages the relationship between displacement and pressure depends on the contributions of two concentric cylinders: in the partially cracked phase, a perfectly elastic and a cracked cylinder (characterized by a linear softening behavior) are considered; in the entirely cracked stage, two cylinders will be characterized by two different two branches are introduced. Due to this reason, in EQ. 18 and EQ. 19 the terms \( a_i \) and \( b_i \) \( (i = 1, 2) \) represent the coordinate of the intersection point yields for the two branches of the softening curve with respect to the fictitious crack width \( w \) [44].

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Crack Pattern</th>
<th>Crack width</th>
<th>%( \rho M_{\text{corr,exp}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td></td>
<td>0.10</td>
<td>0.80</td>
</tr>
<tr>
<td>M5</td>
<td></td>
<td>0.15</td>
<td>0.88</td>
</tr>
<tr>
<td>M6</td>
<td></td>
<td>0.20</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table 4. Mechanical properties of the concrete in the experimental specimens.

<table>
<thead>
<tr>
<th>( f_c )</th>
<th>( E_c )</th>
<th>( G_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.26 MPa</td>
<td>17880 MPa</td>
</tr>
</tbody>
</table>
Table 5. Comparison between the analytical and the experimental results in terms of crack width: present work.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Effective Corrosion Level</th>
<th>Crack Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>M1 [42]</td>
<td>0.80%</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>M2 [42]</td>
<td>0.88%</td>
<td>0.18 mm</td>
</tr>
<tr>
<td>M3 [42]</td>
<td>0.94%</td>
<td>0.20 mm</td>
</tr>
<tr>
<td>A1</td>
<td>5.82%</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>A2</td>
<td>4.57%</td>
<td>0.30 mm</td>
</tr>
<tr>
<td>B1</td>
<td>4.96%</td>
<td>1.00 mm</td>
</tr>
<tr>
<td>B2</td>
<td>3.85%</td>
<td>0.30 mm</td>
</tr>
<tr>
<td>C1</td>
<td>4.02%</td>
<td>0.35 mm</td>
</tr>
<tr>
<td>C2</td>
<td>6.64%</td>
<td>1.20 mm</td>
</tr>
<tr>
<td>D1</td>
<td>6.82%</td>
<td>2.50 mm</td>
</tr>
<tr>
<td>D2</td>
<td>4.68%</td>
<td>1.50 mm</td>
</tr>
<tr>
<td>D3</td>
<td>6.07%</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>D4</td>
<td>4.15%</td>
<td>1.30 mm</td>
</tr>
</tbody>
</table>

5. DISCUSSION

5.1. Comparison Between the Analytical Model and the Experimental Results

The analytical model synthesized in the previous section, has been adopted for the evaluation of the influence of the current intensity on the crack width due to corrosion. Indeed, EQ. 17, calibrated on the base of experimental results obtained with very low current density, has been applied to analytically estimate the crack width due to corrosion, for the specimens A1-D4.

The parameters necessary for the application of the model were evaluated according to the Model Code 2010 suggestions, based on the measured compressive strength. The value of the main properties is reported in Table 4.

The volumetric ratio of the oxide, with respect to iron ($\alpha_1$ in Eq. 17) has been assumed equal to 2.00/2.15 since mainly ferrihydrite formed after the corrosion process. The comparison between the experimental and the analytical results expressed in terms of crack width is reported in Table 5, for both the specimens analysed in [42] and the ones discussed in this paper. It can be clearly noted how the crack width measured in specimens corroded with high current densities (higher than 500 $\mu$A/cm$^2$) are greater than the ones obtained by the model, calibrated with reference to low densities, and then simulated the crack width due to natural corrosion.

CONCLUSION

In the present work, an experimental survey finalized to the evaluation of the influence of the current density in an artificial corrosion process is presented. The literature review shows, in fact, that some of the most significant results on the structural behavior of corroded structures come out from artificially corroded specimens, typically subjected to accelerated electrolytic corrosion test with different current intensities.

Steel rebars embedded in cylindrical concrete specimens were cast and subjected to different current intensities. After the corrosion test, the crack pattern was registered, the corrosion level on the reinforcement measured, the degradation morphology of the steel evaluated, and the typology of the corrosion products analyzed. The experimental tests showed that the prevalent corrosion product formed in the specimens was the ferrihydrite, characterized by a volumetric ratio, with respect to the iron, that varies between 2.00 and 2.15. Moreover, increasing the current intensity, then the corrosion rate, the cracks become wider and the corrosion morphology becomes more localized. This occurs because the oxides do not have time to spread in the concrete, so they accumulate at the interface and exert a considerable radial pressure. Therefore, as the current intensity increases, cracking occurs to lower and lower levels of corrosion.

Once the concrete cracks, the corrosion morphology becomes localized, with pits becoming deeper when the corrosion rate is increased.

Finally, an analytical model for the evaluation of crack width, based on the thick-cylinder model and calibrated with results obtained with very low current density is applied for the simulation of the experimental outcomes.

Based on the obtained results it is shown that current densities higher than 500 $\mu$A/cm$^2$ lead to such values of crack widths, which are not representative of the actual conditions of elements subjected to natural corrosion.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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CONFLICT OF INTEREST
The authors declare no conflict of interest, financial or otherwise.

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REFERENCES
[39] [http://dx.doi.org/10.1016/S0008-8846(03)00246-1]


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