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Factors controlling cracking of concrete affected by reinforcement corrosion

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ABSTRACT

The present paper tries to contribute to quantifying the relationship between the amount of corrosion and cover cracking. The variables studied were: cover/diameter (c/ø), proportions of cement, w/c, cast position of the bar, transverse reinforcement and corrosion rate. The corrosion is accelerated by applying constant currents causing the rebar to act as an anode. The results indicate that the cracking process develops in two steps: generation and propagation. Radius losses of about 15-50 µm are necessary to generate the first visible crack (< 0.1 mm width). The propagation follows a behaviour of the type: w (crack width in mm) = a + bx (radius loss in µm).

RÉSUMÉ

Ce travail tente de quantifier la relation entre le degré de corrosion et la fissuration du recouvrement de l'armature. Les variables étudiées ont été : recouvrement/diamètre (c/ø), dosage du ciment, eau/ciment, position de l'armature, armature transversale, et degré de corrosion. La corrosion est accélérée par l'application des courants constants qui font agir l'armature comme une anode. Les résultats indiquent que le processus de fissuration se développe en deux temps : génération et propagation. Une réduction du rayon de l'armature d'environ 15-50 µm est nécessaire pour produire la première fissure visible (ouverture < 0.1 mm). À la propagation, le comportement suit l'expression : w (largeur de la fissure en mm) = a + bx (réduction du rayon en µm).

1. INTRODUCTION

When steel corrosion develops, the corrosion products first accumulate at the bar surface and try to fill the closest voids. Then, they spread throughout the material and mix with the hydrated products of cement [1-4]. They slowly stress the concrete cover until it relaxes in a crack initiated at the bar surface towards the concrete surface.

Concrete cracking which occurs due to corrosion products (oxides) has a higher volume than the basic metal [5-10]. This volume depends on the type of oxide and on its degree on hydration.

The oxides generated during active corrosion of rebars induce a pressure on the sourrounding concrete, which in most cases leads to cover cracking along the rebar. These longitudinal cracks may affect the load-bearing capacity of the structural elements presenting this distress, and in consequence, may shorten their service life, in addition to opening a path for a quicker arrival of aggressive elements to the reinforcement.

A preliminary review of the service life of concrete structures suffering from corrosion leads to the general conclusion that service life is considered finished when the depassivation of the bar is reached [11, 12]. This statement sometimes seems conservative, and in consequence, other authors prefer to identify the service life with the time for cover cracking to appear [10, 13-15]. However, there are few references attempting to quantify this last proposal [16-19].

On the other hand, the loss in steel cross-section due to corrosion, and the consequent cover cracking, is related to ULS (Ultimate Limit State) [20, 21], as it affects the structural safety due to the possible loss of steel/concrete bond [10, 22], or the loss in load-bearing capacity. It also relates to SLS (Service Limit State) by the generated cracks themselves and the possible increase in deflections. The final consequence of cover cracking is the spalling of the concrete cover [23]. The rate at which the corrosion evolves is then the key factor, which may depict the evolution pattern of residual safety and serviceability.

Editorial Note
Dr. M.-C. Alonso and Dr. C. Andrade work at the Instituto de Ciencias de la Construccion "Eduardo Torroja", Spain, a RILEM Titular Member. Dr. Alonso is a Senior Member of RILEM and a member of TC 154-EMC. Dr. Andrade is Vice President of RILEM and a member of the Bureau. A RILEM Senior Member and a RILEM Fellow, Dr. Andrade is Chairlady of TC 154-EMC (Electrochemical Techniques for Measuring Metallic Corrosion in Concrete) and TMC (Testing and Modelling Chloride Penetration in Concrete) and participates in the work of TC 116-PCD (Permeability of Concrete as a Criterion of its Durability). J. Rodriguez and J. M. Diez work at Geocisa, Spain, a RILEM Titular Member.

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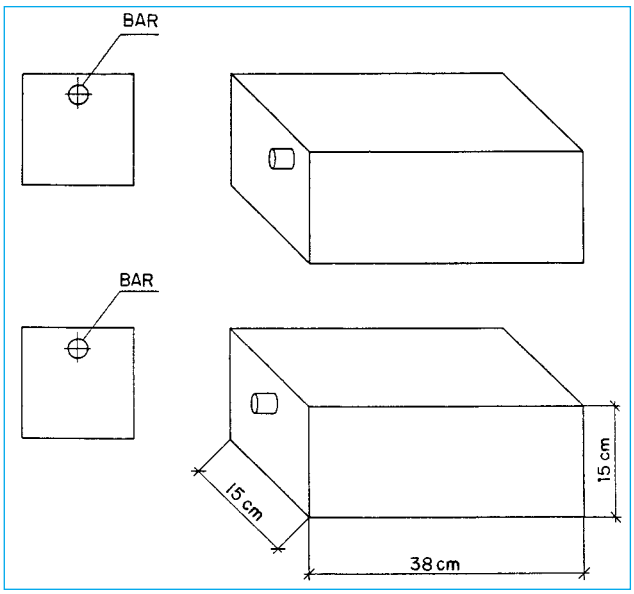


Fig. 1 – Series-1 specimens.

In spite of the very numerous studies devoted to the corrosion of steel in concrete, it is surprising that very few of them [10, 14, 16, 19, 24] have tried to determine the amount of corrosion needed to produce the first crack or how the progressive rebar corrosion induces the crack growth. In fact, this lack of knowledge is one of the basic reasons why the quantification of the residual service of damaged structures has not yet been fully achieved.

The work presented here tries to fill this gap by a detailed study of the influence of different variables on the time elapsed between steel depassivation and cover cracking.

2. EXPERIMENTAL WORK

2.1 Materials and specimen types

Specimens of 15 × 15 × 38 cm in size, shown in Fig. 1, Series-1, were used. The bars embedded were 3, 8, 10, 12 and 16 mm in diameter. They were tested centered or placed in a corner as Fig. 1 shows. The concrete covers tested were of 10, 15, 20, 30, 50 and 70 mm. These specimens were fabricated with a cement type I OPC and siliceous aggregates. The concrete mixes contained 270, 300 or 370 kg/m^3 of cement and water/cement ratios of 0.65, 0.60 or 0.52 were used. The maximum aggregate size was 12 mm. The splitting tensile strength ranged between 2.40 and 3.85 MPa and the porosity in volume between 4 and 9%. The specimens were cured 24h in the moulds and 28 days under water. Finally, they were held at 50% RH, 20 ± 2°C until testing.

The other types of specimens tested, Series-2, were 30 × 30 × 30 cm in size, with and without transverse reinforcement. The concrete materials were: blended cement type A II Z/35, crushed coarse aggregate, sand, water and a plasticizer. The amount of cement was 350 kg/m^3 and the w/c = 0.5. Each specimen had four embedded rebars located in the corners and longitudinally to the specimen.

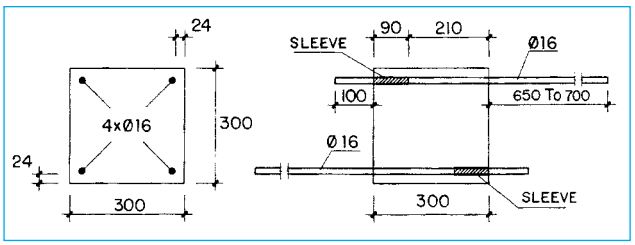


Fig. 2 – Series-2 specimens.

The cover used was of 25 mm. Rebars of 6 or 8 mm ø were employed for transverse reinforcement (three, spaced 100 mm). The splitting tensile strength of these specimens ranged between 3.4 and 4.0 MPa. These specimens were first cured 24 hours in the mould, and later wet continuously at room temperature.

2.2 Accelerated corrosion/cracking test

In order to provoke the active corrosion, 3% $CaCl_2$ by cement weight was always added to the mix, and an electrical current (galvanostatic test) was applied to the bars to accelerate the corrosion process.

The accelerated corrosion procedure employed for both series of specimens consists of a galvanostat that applies a nominal constant current density through the counter-electrodes placed at the concrete surface of each specimen. This testing method was previously used and described in [25, 26]. The electric contact between the specimen and the counter-electrodes was provided by sponges moistened by a dropping system. Whereas in the series-1 tests the current was applied through a counter-electrode placed underneath the specimen, in series-2, the current was applied through four short-circuited counter-electrodes, placed on each face of the specimen.

The usual nominal current intensity applied was 100 μA/cm^2. This current allows quick testing, but causes an induced corrosion in the highest limit of the "natural" values found in the laboratory; that is why some series-1 specimens were tested with nominal intensities of 3 or 10 μA/cm^2, which are more common corrosion rate values in real-size corroding concrete structures.

The concrete surface strain caused by oxide pressure to locate the crack apparition was made similarly to that described in [25]. Crack evolution was measured by a magnification lens of which the smallest reading was 0.01 mm. The evolution of each crack width was recorded as well as their trends on the different surfaces of the specimen. Crack patterns were collected over time.

The test is considered to end when a target cracking size is reached. After this, the specimen is disconnected from the corrosion equipment and is broken in order to study the types of oxides, their colours and their spread through the concrete surroundings. Then, the bars are cleaned, dried and weighed. The difference of weight with respect to the initial weight is the gravimetrical loss of the base metal. This measurement allows calculating the attack penetration depth or radius loss of the bar, x, considering the following hypotheses: 1) uniform pene-

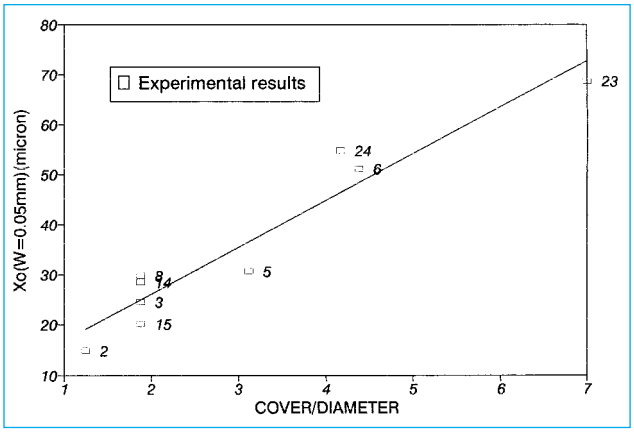


Fig. 3 – Relation between attack penetration which produced the first visible crack (w = 0.05 mm) and cover/diameter ratio.

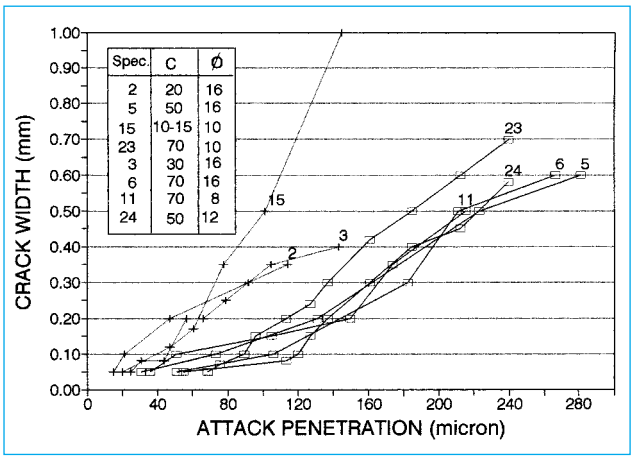


Fig. 4 – Crack width evolution versus radius loss: c/ø ratio influence.

tration, 2) the bar is a cylinder and 3) linear loss over time.

The conversion of corrosion rate into radius loss is performed using a formula based on Faraday's law [21]:

$$x = 0.0116 \cdot Icorr \cdot t$$

where x = attack penetration (mm), Icorr = corrosion intensity in $\mu A/cm^2$, t = time in years elapsed since the current was switched on, and 0.0116 = conversion factor ($\mu A/cm^2$ to µm/year) in the case of homogeneous corrosion.

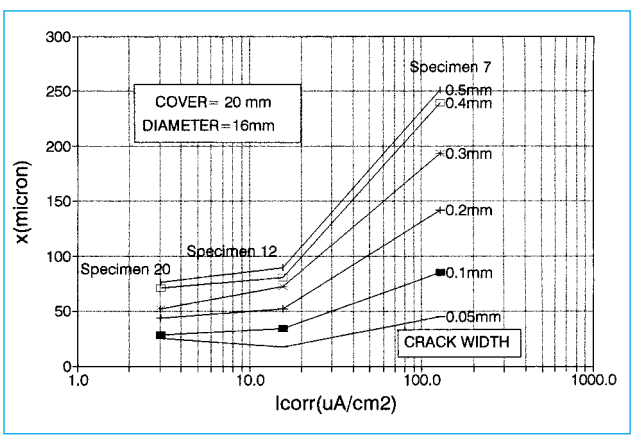


Fig. 5 – Crack width evolution versus radius loss: I_{corr} influence.

In principle, the radius losses were calculated from each applied current (nominal corrosion current) according to Faraday's law. That is, all the current is assumed to be spent in the oxidation of the steel, and therefore, 100% of current efficiency is reached. The losses so calculated are named "theoretical steel losses" (nominal). However, this ideal behaviour was not produced and the "actual" radius losses in many cases were higher than the theoretical ones. This fact was verified by comparing the gravimetrical loss produced at the end of the experiment and the theoretical loss.

3. RESULTS

3.1 Influence of cover/diameter ratio (c/ø)

Most of the series-1 specimens had been devoted to studing the effect of this parameter, considered in principle to be the most influential one in cracking initiation (*i.e.* cracks < 0.05 mm). In all series-1 specimens with the centered bar, the first crack appeared in the nearest surface (the upper surface), except for the 70 mm cover, where the cracks appeared in the lateral faces (due to previous shrinkage effects). When the bar was placed in the corners, the first cracks appeared in both faces.

Fig. 3 depicts the c/ø ratio versus the attack penetration that produced a crack width of 0.05 mm (x_o in µm) of some series-1 specimens. It is possible to deduce from the figure that, for the first crack, there is a lineal relationship between c/ø and x_o of the type:

$$x_o = a + b\ c/ø$$

where: a = 7.53, b = 9.32, r^2 = 0.92 (from the regression).

For c/ø values ranging between 2 and 3, which are normal in concrete structures, 15-35 µm of attack penetration cause the initiation of cracking at the concrete surface.

Most of the series-1 specimens were also prepared to detect the influence of the c/ø in the evolution of crack width. Fig. 4 displays the crack width evolution versus the radius loss, for several c/ø. Two ranges of influence of c/ø values can be established: a) values of cover depth lower than 30 mm and values ranging between 50 and 70 mm. Although the crack appearance is delayed for larger covers, the slope of the propagation curves does not have a significant variation for the various c/ø values.

3.2 Influence of the corrosion rate

Fig. 5 represents the radius losses to obtain several crack widths (from 0.05 to 0.5 mm). It can be seen that higher attack penetrations are necessary when applying 100 $\mu A/cm^2$ than when applying 10 $\mu A/cm^2$ (in nominal values), to get a specific crack width. Also, Fig. 5 represents the results for the specimen tested at 3 $\mu A/cm^2$.

The corrosion rate is a basic parameter in crack evolution. Thus, the results significantly change if the corrosion rate decreases by a factor of 10. Fig. 6 shows a higher slope of the propagation curve with the lower corrosion rate.

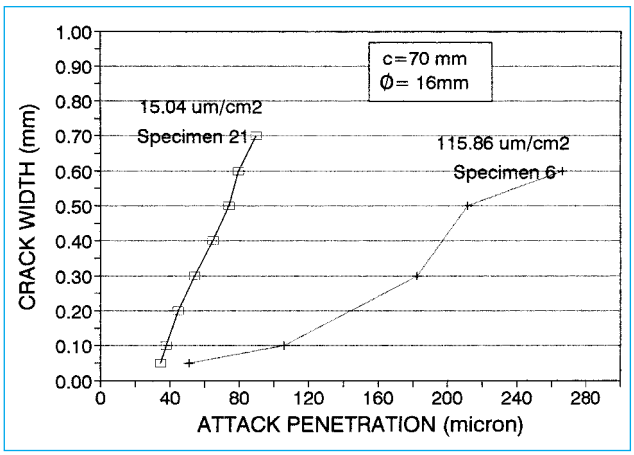


Fig. 6 – Crack width evolution versus radius loss: nominal I_{corr} (100 μA/cm², 10 μA/cm²).

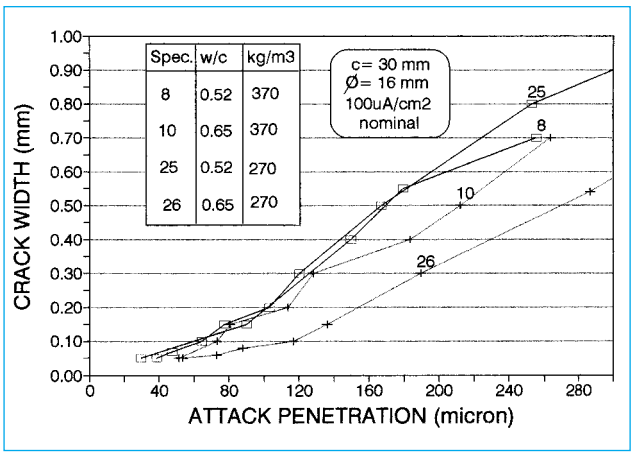


Fig. 7 – Crack width evolution versus radius loss: concrete quality influence.

This means that the crack width increases faster with an actual value of 15.04 μA/cm² (nominal 10 μA/cm²) than with 115.86 μA/cm² (nominal 100 μA/cm²). This may be interpreted mechanically by considering that a slower "load" application induces higher deformations [27].

The fitted slopes for specimens with a nominal corrosion rate of 10 μA/cm² are approximately three times higher than the slopes for those with a nominal corrosion rate of 100 μA/cm², when the concrete cover is 20 mm, and nearly six times when the cover is 70 mm.

However, the influence of the corrosion rate is less significant in the first crack appearance, as can be also observed in Fig. 5 near the horizontal curve for w = 0.05 mm.

3.3 Influence of concrete quality

The effect of concrete quality on crack initiation and propagation was studied by means of: a) bars embedded in concrete with different compositions, b) bars embedded in the same concrete but in different cast positions (top and bottom).

As Fig. 7 shows, an increase of porosity (that is, an increase of w/c ratio) supposes a delay in the generation of the crack. This can be interpreted as due to the higher void space available to accomodate the oxides without pressing the surrounding concrete. Figs. 8 and 9 present the differences found between top and bottom cast bar positions of the bars in series-2 specimens without stirrups. Similar results were found in specimens with stirrups. It can be observed that the top cast position delays the cracking propagation.

3.4 Efficiency of the current

When currents are used for inducing chemical reactions, the normal efficiency is smaller than 100% due mainly to simultaneous heat generation. In the present case, gravimetrical losses were measured in order to find out the relationship between theoretical weight losses, by means of Faraday's law, and actual weight losses. The results indicated current efficiencies higher than 100%, as Table 1 shows.

These results can be explained as due to two effects: a) the acidification developed by the progressive corrosion is so important that the spontaneous corrosion generated induces a simultaneous additional corrosion. A

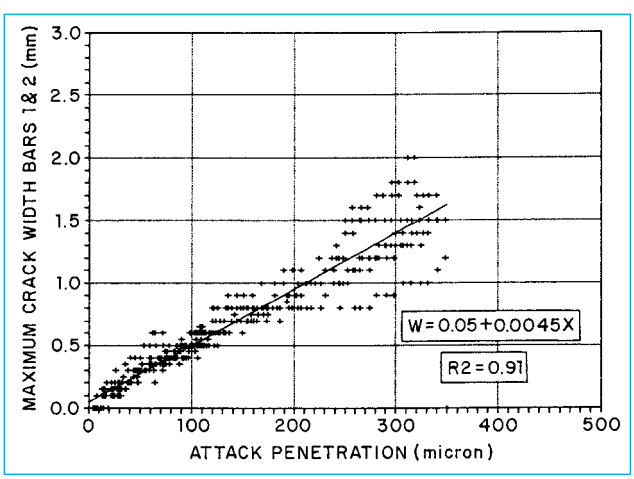


Fig. 8 – Maximum crack width versus real radius loss (100 μA/cm²) without stirrups. Top bars of specimen series-2.

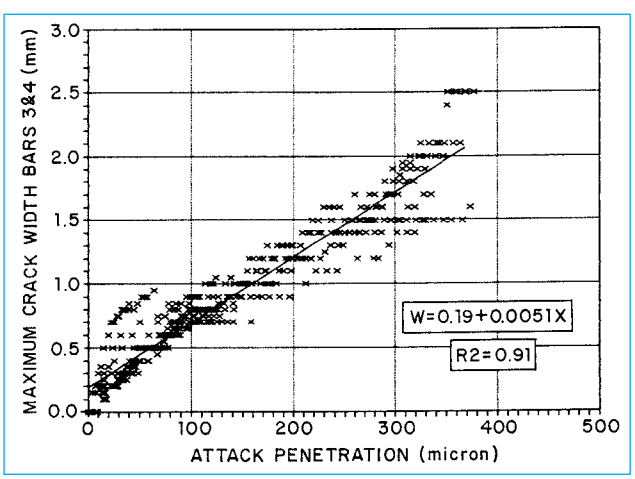


Fig. 9 – Maximun crack width versus real radius loss (100 μA/cm²) without stirrups. Bottom bars of specimen series-2.

Table 1 – Comparison of theoretical and gravimetrical losses of specimens series-1

Gravim. (G) (g)	Theoretical (E) (g)	G/E (%)	Test time (days)
35.15	29.43	119	73
33.31	29.43	113	73
32.05	27.39	117	68
34.46	27.44	125	68
4.51	5.62	80.3	75
32.99	29.06	113.5	72
13.49	14.85	90.8	72
11.15	7.81	142.76	190
32.53	28.91	112.52	71
23.24	22.61	102.78	112
14.97	14.71	101.76	71
51.27	42.00	122.07	103
21.66	20.76	104.33	103
12.76	9.02	141.46	221
36.68	36.53	100.40	91
11.63	7.60	153.02	190
19.15	17.27	110.90	70
22.65	21.04	107.65	70
37.59	28.70	130.97	70
42.59	28.50	149.43	70
35.93	36.50	98.40	70

pH measured with pH-paper resulted in a value around 3 [28]; b) there are parts of the metal (inclusions) that do not dissolve electrolitically but that spall out from the metal surface when the surrounding material is oxidizing. Both effects lead to actual losses higher than the theoretical ones.

This evidence leads to two consequences: 1) gravimetrical losses are always necessary to correct theoretical values of daily "attack penetration", and 2) all results have to be recalculated and converted into actual values of radius loss. This has been performed in the case of the present work.

4. DISCUSSION OF RESULTS

4.1 Testing methodology

The testing procedure followed here differs from that used by other authors [17, 18] since a galvanostatic and not a potentiostatic method of current application was used. Galvanostatic control enables a careful monitoring of constant corrosion rates throughout the test, while potentiostatic tests suppose a variation of the dissolution rate (current recorded) over the testing time.

Another feature which was revealed as very important is the intensity of the applied current. With high corrosion rates (nominal intensity of 100 $\mu A/cm^2$), the attack penetration needed to propagate a crack is higher than with low corrosion rates (nominal intensity < 10 $\mu A/cm^2$). This means that for an equal crack width, lower radius losses are needed if the corrosion rate is lower too. The latter being normal in natural conditions, accelerated tests may induce erroneous quantification if extrapolated to the behaviour of real structures. The different behaviour is attributed to the hydration degree of iron oxides and their relative volume.

Wetting and drying cycles should have some effect on oxide hydration and volume. The thermal movements (shrinkage) also contribute to the cracking of concrete. In real structures, those surfaces directly exposed to the sun crack earlier and quicker.

4.2 Process steps of cover cracking

In most cases, two steps (I and II) in the cracking process were identified with a lineal relationship: I) generation and II) propagation of the crack (lineal relationship between crack width and attack penetration).

In some cases a further third step (III) was identified, when a change of the slope of step II is produced, perhaps due to an easier diffusion of oxides through the generated crack.

C/ø ratio and concrete porosity seem to control step I (crack generation). Steps II and III are controlled mainly by corrosion rate and the concrete porosity.

In addition to the influence of these parameters, it has also been noticed, although not properly quantified, that the following are also influencing parameters: a) the local shrinkage, b) the applied loads, c) the thermal and moisture gradients and d) the concrete inhomogeneities.

4.3 Crack width/attack penetration

In the present paper, the significant influence of the parameter c/ø in the attack penetration needed to generate the first crack has been confirmed. In previous work [25] such influence was not identified.

Assuming a generalized corrosion, it may be stated, in agreement with other authors [11, 29-31], that for c/ø ratios > 2, radius losses of around 50 µm induce crack widths of about 0.05mm, while for c/ø ratios ≤ 2, only attack penetrations of 15-30 µm are necessary.

For c/ø ratios ≥ 2 crack widths of 0.3 mm appear for radius losses of about 100-200 µm, and of 1 mm for about 300 µm. For larger crack widths, the scatter is very high as the oxides diffuse out of the concrete and the pressure decreases significantly.

4.4 Cracking and residual service life of concrete structures

It has been confirmed, as well, that the time elapsed between steel depassivation and appearance of the first crack in the surface is comparatively very short (step I). After the generation of the crack, the growth of its width (step II) seems to follow a lineal trend with the attack penetration until levels of around 200-300 µm. Afterwards (step III), the prediction of the evolution of the crack is more difficult, because the geometry and

size of the element start to be the crucial factor. The final state is the spalling of the cover, which seems to be, respective to the period of crack generation, a much longer process. The amount of rebars becomes another important factor in the spalling.

The present results are intended to assist in quantifying the service and residual life of concrete structures. Therefore, the influence of the cover cracking in the SLS and ULS has to be analyzed in the light of the loss in the load-bearing cross-section (either of the steel or of the concrete), on the increase in deflection that it induces, and on the cracking itself that appears.

5. CONCLUSIONS

The influence of several parameters on the generation and evolution of crack widths is summarized as follows:

variable	Time of evolution of the crack for the same attack penetration	
	generation	propagation
increases Icorr	indifferent	longer
increases c/ø	longer	low to high influence
increases porosity	longer	high influence
stirrups (isolated)	indifferent	indifferent

In addition, it may be drawn from the results that:

1) Radius losses of 15-50 µm are necessary to generate crack widths of 0.05-0.1 mm, and widths of 0.2-0.3 mm are obtained for attack penetrations of 50-200 µm depending upon the c/ø ratio.

2) There seems to exist a lineal relationship between crack width (w) growth and radius loss (x) of the type $w = a + bx$ during the propagation period of the crack until a certain limit of attack. This evidence will enable quantification of the service life from the design phase.

3) The corrosion rate has a very significant influence in these limits. A slower corrosion rate generates earlier cracking for the same attack penetration.

4) Finally, with regard to the testing procedure used, the strain gauges have been very informative for the very early stages of the crack evolution. In addition, the galvanostatic procedure has proved to be an important tool in maintaining a constant rate of oxidation, although only the final gravimetrical losses can give reliable results for the metal losses.

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