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EFFECTIVENESS OF CRACK CONTROL AT EARLY AGE ON THE CORROSION OF STEEL BARS IN LOW MODULUS SISAL AND COCONUT FIBRE-REINFORCED MORTARS

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ABSTRACT

This is the second part of a two-part paper involving the study of the free plastic shrinkage and cracking sensitivity at early drying of mortars reinforced with low modulus sisal and coconut fibres, and the evaluation of the effectiveness of crack control at early age on the corrosion of steel bars, which is sensitive to the presence of cracks in the matrix. The incorporation of fibres in the mortar is proposed to control cracking and, therefore, to provide a more homogeneous composite material. Whether such addition improves the compactness of the mortar by reducing crack propagation at early age and the corrosion of the embedded steel bars with time is the subject addressed in the present work. Mortar samples with reinforcing bars were submitted to early drying after casting, to develop cracks in the vicinity of the rebars, and then held at 100% RH and room temperature until 40 days when they were exposed to a chloride solution to enhance the corrosion rate of the steel bars. The corrosion of the steel bars was monitored by electrochemical measurements and observations of crack development.

Natural fibres perform well in controlling cracking in mortars and also seem to delay slightly the initiation of the corrosion of embedded steel bars. Self-healing of cracks is more effective in smaller ones and, therefore, in natural fibres, reinforced mortars present a higher self-healing behaviour. *© 1998 Elsevier Science Ltd*

Introduction

Deterioration of reinforced concrete is rarely due to one isolated cause; however, corrosion of embedded steel is invariably a principal one. To prevent steel corrosion, several codes specify a minimum concrete cover and a maximum permissible crack width as a function of the exposed environment (1). Although many researchers find no direct relation between crack width and corrosion, it appears that, by increasing the permeability of concrete and

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TABLE 1
Average properties of coconut fibre.

Physical and mechanical properties of coconut fibre							
Diameter (mm)	Density (g/cm^3)	Natural moisture content (%)	Water absorption after 5 min. under water (%)	Water absorption at saturation (%)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Strain at failure (%)
0.25	0.8	13.5	28	110	150	3	27

exposing it to numerous physical-chemical processes of deterioration, the presence of cracks would eventually have a deleterious effect.

The reinforcement of concrete by a small volume of low modulus fibres has been shown to be quite effective in reducing crack tendency in the plastic stage (2,3). The main objective of the present study is to verify whether the control of crack appearance and propagation at early age is useful in reducing long-term corrosion of embedded steel bars. Mortar mixes reinforced with 0.5% by volume of sisal and coconut fibres were cast in a special ring-shaped mould with steel bars. The specimens were then submitted to early drying to develop plastic cracking by restrained shrinkage in the vicinity of the steel bars. The specimens were afterwards held at 100% RH and room temperature until 40 days, and then exposed to a corrosive environment to enhance the corrosion rate of the steel bars. The corrosion of the steel bars was monitored by electrochemical measurements and observations of crack development. The performance of the mixes with naturally occurring sisal and coconut fibres and without fibres was then compared.

Experimental

Materials and Mix Composition

The matrices used in this work were all made with a water/cement ratio of 0.5 and a cement:sand ratio of 2:1. The fibre content was 0 and 0.5% by volume of sisal, coconut, and polypropylene fibres. The properties of the ordinary Portland cement, sand, and sisal fibres are presented in (4) and the properties of coconut fibres are presented in Table 1. The length of the natural fibres was 25 mm. Fibres were dispersed with the aggregates in the mixer before cement and water addition.

Deformed steel bars, normally used in construction (400-CIET), 6 mm in diameter and 80 mm in length, with a composition of 0.19% C, 0.64% Mn, 0.28% Si, 0.021% P, and 0.052% S were used.

Testing Procedure

The testing method proposed by Sanjuán, Andrade, and Bentur (5) was used to study the effect of crack control at early age in sisal and coconut fibre-reinforced mortars on the

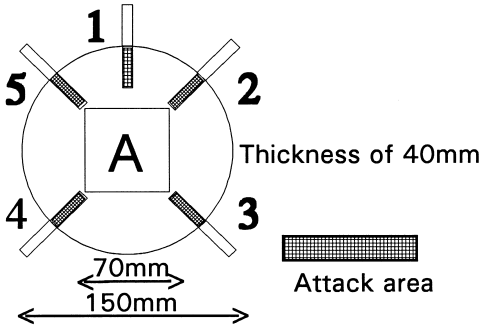


FIG. 1.
Test setup.

corrosion of steel bars in concrete. The test setup is presented in Figure 1. A ring-shaped specimen of 40-mm thickness and 150-mm diameter with a 70-mm solid cubic core was employed.

Five steel bars 6 mm in diameter and 80 mm in length were embedded in each mortar specimen in order to measure the corrosion of the rebars with time. Prior to casting, these steel bars were cleaned in a 1:1 water:HCl solution containing 3 g/L of hexametilentetramine, $(CH_2)_6N_4$, as a corrosion inhibitor, then rinsed in acetone, dried, and weighed. Their ends were coated with a plastic insulating tape to limit the attack area to 5.75 cm^2.

After casting, the specimens were subjected to an air flow of 0.4 m/s at 40°C to create conditions for the crack formation at early age. Air flow started half an hour after casting and lasted for 4 h. The specimens were then kept covered in plastic bags for 3 days, and subsequently were held at 100% RH and room temperature for 37 days; then they were subjected to a 0.5 M NaCl solution contained in a pond placed on the top of the specimen. The mould remained around the specimen throughout the experiment.

Corrosion potential (E_{corr}), ohmic drop (R_{ohm}) and corrosion rate (I_{corr}) of the embedded steel bars were monitored during the test. A potentiostat with electronic compensation of the ohmic drop (R_{ohm}) between reference and working electrode was employed to measure the I_{corr} values, which were obtained by means of linear polarisation resistance measurements (6). An external saturated calomel electrode was used as reference, to give the corrosion potential. The I_{corr} value was calculated assuming values of B equal to 26 mV for the corroding steel and 52 mV for passive steel (7), using Stern-Geary equation:

$$I_{corr} = \frac{B}{Rp} \tag{1}$$

The electrochemical values were then compared with the crack width observed on the upper face of the samples near the steel bars. A passive state of the steel bars can be assumed when E_{corr} values are above −200 mV. Decreasing this value, higher corrosion rates may be expected. The most efficient measurement, however, is the I_{corr}, for which there is a well established threshold of about 0.1–0.2 A/cm^2. Below this limit the corrosion rate is negligible. Values higher than 0.2 A/cm^2 mean active corrosion, whereas values about 1 A/cm^2 indicate significant corrosion but not severe. Above 10 A/cm^2 a severe attack is expected. Values much higher than 10 A/cm^2 never have been recorded in practice.

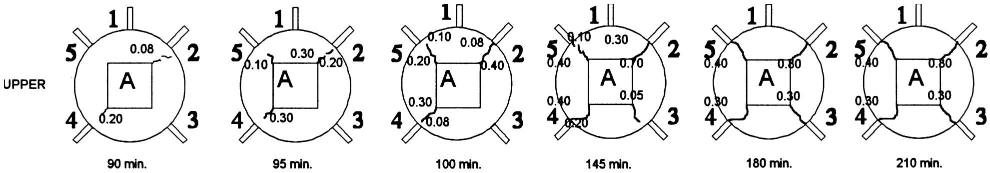


FIG. 2.
Crack pattern of Specimen A at early age.

Results

Crack Evolution

The crack appearance time and evolution at early age, prior to the exposure of the specimens to salts and also after several months in the corrosive environment, was measured by means of a magnification optical lens and registered. The first crack appeared on the plain mortar (Specimen A), 90 min. after the mix had been placed. The cracks on the upper face of the specimen started from the corners of the central block on Bars A2 and A4. After 95 min. a new crack appeared on Bar A5, and after 145 min. one appeared on Bar A3. Figure 2 shows the crack pattern (crack width in mm is shown next to it) on the plain mortar at up to 210 min., which is due to restrained shrinkage at early age.

Specimens B and C were reinforced with sisal and coconut fibres, respectively. Figure 3 shows the early age crack evolution in these samples at up to 210 min. It can be seen that the first crack appeared after 180 min. in both samples. The results show that both fibres are quite effective in retarding the first crack development and in reducing the inherent cracking tendency at early age.

Crack development was recorded until the age of 160 days. Crack width evolution is presented in Figure 4. Air flow started 30 min. after casting and lasted for 4 h. The specimens, which were previously stored in plastic bags for 3 days and then held at 100% RH and room temperature for 37 days, were then subjected to a 0.5 M NaCl solution contained in a pond placed on the top of the specimen. As can be seen, self-healing in Specimens B and C was almost complete by 40 days; this is before NaCl exposure.

Figure 4 shows that the crack pattern and width did not change considerably from 3 days to 160 days. In the specimen reinforced with sisal fibres, a new crack of about 0.05 mm appeared after 3 days at Bar B2. On the other hand, the crack on Bar B4 started to heal after 3 days and was completely self-healed after 40 days. The specimen reinforced with coconut

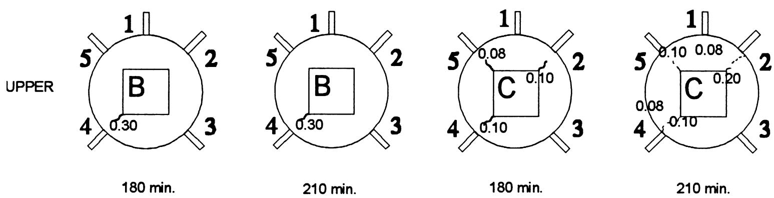


FIG. 3.
Crack pattern of Specimens B (sisal fibres) and C (coconut fibres) at early age.

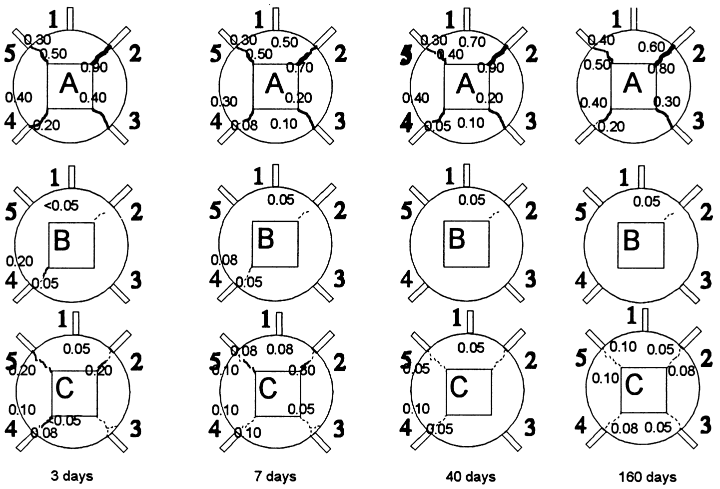


FIG. 4.
Crack pattern of Specimens A, B, and C up to 160 days.

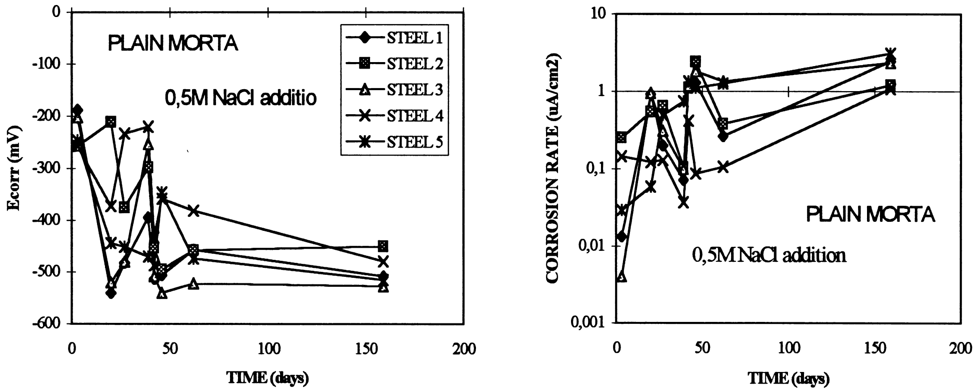
fibre showed a new crack at Bar C3 after 3 days and slightly increased width of the existing ones. After 7 days, the tendency to self-heal the cracks began to be observed on this sample.

Steel Bar Corrosion Resistance

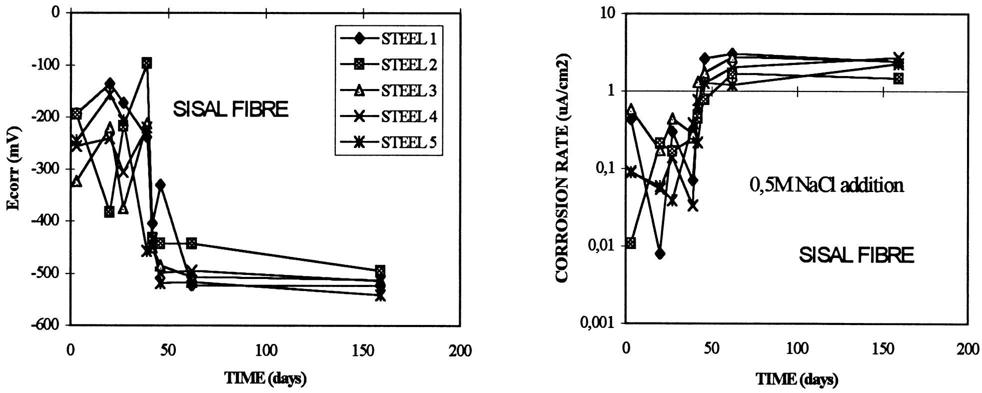
Corrosion potential (E_{corr}), ohmic drop (R_{ohm}), and corrosion rate (I_{corr}) were monitored during the whole test, and the results are presented in Figures 5 and 6. The results are discussed to explain the differences observed between specimens, and within each specimen prior to and after the addition of the 0.5 M NaCl solution (40 days after casting). These parameters show the corrosive state of the steel bars, which is affected by the aggressivity of the environment as well as by the accessibility of the aggressives through the mortar.

The first measurement of the electrochemical parameters was made after 3 days of casting when the specimens were kept covered by plastic bags just before exposure to 100% RH. The initial E_{corr} values were about −250 mV in all the steel bars, ranging from −188 to −257 mV for the bars embedded in the plain mortar and from −185 to −320 mV for the bars embedded in the fibre-reinforced mixes. Then, when the specimens were stored at 100% RH, the range of values became wider. As soon as the 100% RH exposure began, the E_{corr} dropped to more negative values and the corrosion process developed quickly on the cracked cover specimens.

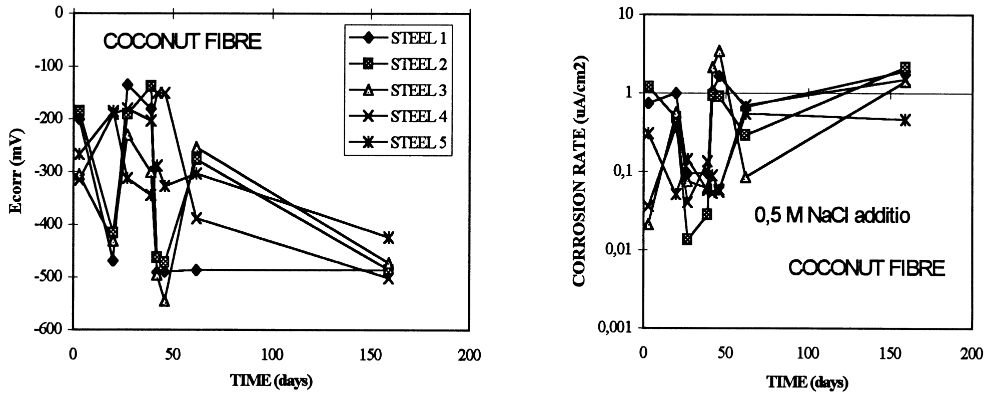
After 39 days of exposure, the E_{corr} of the bars of the plain mortar (except bar 2) drastically dropped to values reaching −550 mV, indicating that the corrosion process had developed rapidly. This tendency is confirmed by the I_{corr} values, which initially ranged between 0.006 and 0.4 A/cm^2, and at 39 days increased to values ranging between 0.7 and 1.5 A/cm^2. Until the age of 39 days, the specimens reinforced with sisal and coconut fibres presented a general tendency to reduce the I_{corr} values observed at 3 days. This evolution could be correlated with the reduced cracking (Fig. 4) due to fibre reinforcement. This seems to indicate some influence of the crack width on the initiation of the corrosion, because of its oxygen



(a) Plain mortar



(b) Sisal fibre reinforced mortar



(c) Coconut fibre reinforced mortar

FIG. 5.

Corrosion potential (Ecorr) and corrosion rate of the rebars embedded in the specimens. *a*) Plain mortar; *b*) sisal fibre-reinforced mortar; and *c*) coconut fibre-reinforced mortar.

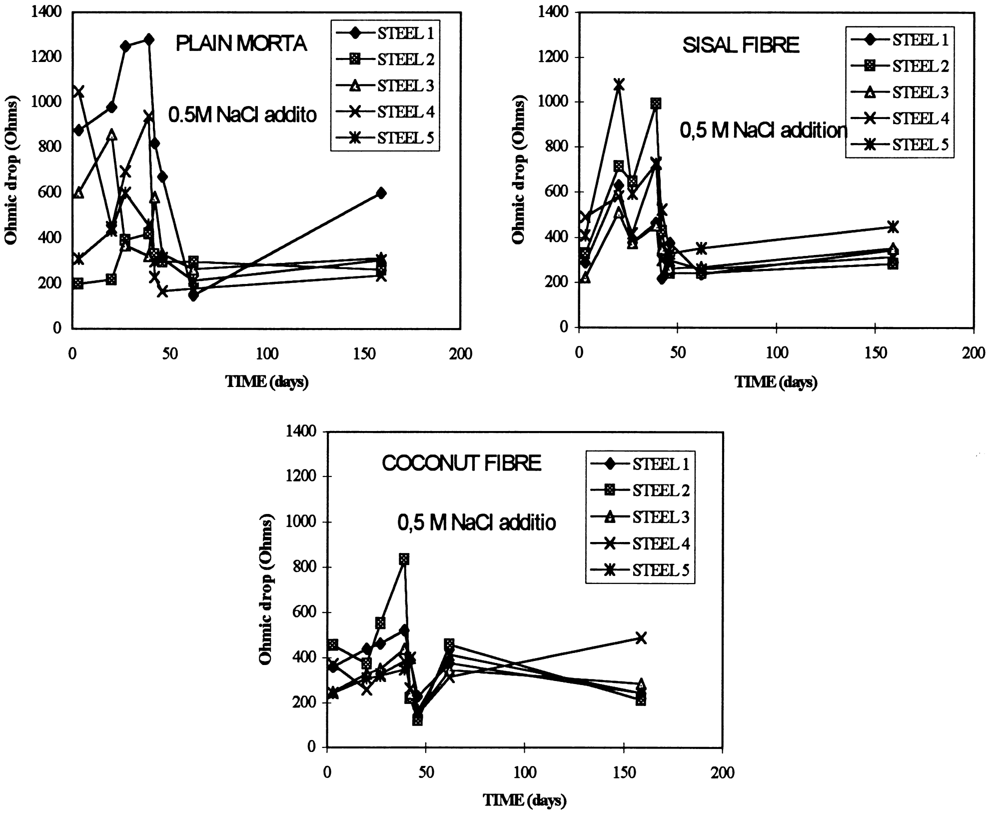


FIG. 6.
Ohmic drop measurements.

accessibility. Individual values for a given steel bar vary because of the cracking state of the cover, leading to an easier path for the chloride ions to come into the material. The development of E_{corr} and I_{corr} for the three specimens is similar. However, E_{corr} and I_{corr} values do not correlate because E_{corr} depends strongly on the environmental conditions.

Ohmic drop values ranging between 200-1300 Ω were registered in the bars of the plain specimen in this period. More uniform and smaller values of ohmic drop were measured in the samples reinforced with fibres, in particular in the specimen with coconut fibres that presented values ranging between 220–580 Ω (Fig. 6). Ohmic drop values are dependent on the microstructure of the mortar. Thus, bigger voids lead to more spaces filled with solution, and lower ohmic drops are expected. A similar trend was found for plain mortar and sisal fibres but not for coconut.

At 40 days, the specimens were subjected to the NaCl solution, and, despite the better initial behaviour of the fibre-reinforced samples, corrosion rates above 1 A/cm^2 were reached in all the fifteen steels with the exception of the Bar 4 and 5 in Specimen C, even though they had presented cracks since the age of 3 days. On the other hand, it was noticed that the high corrosion rate on Bars 1 and 3 (Specimen C) did not exhibit any visible crack at 40 days. This fact suggests that the internal cracks played an important role in the corrosion process which

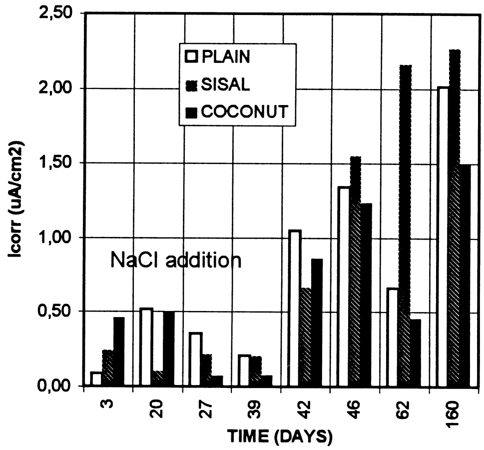


FIG. 7.
Average corrosion rate of the rebars embedded in the specimens at 160 days.

cannot be quantified by this experiment. E_{corr} values about -500 mV were observed in all the bars after the addition of NaCl, indicating an active corrosion.

The average I_{corr} values given in Figure 7 were calculated from the five steel bars embedded in each mortar specimen. From the beginning, the passive layer of the steel showed a significant corrosion rate below 0.5 A/cm^2. After 27 days, the steels embedded in the plain mortar presented the highest corrosion rate. Once the NaCl solution was added, the average I_{corr} values increased over 0.5 A/cm^2, increasing with time up to values over 1.5 A/cm^2, which means a significant corrosion.

There is also a slight correlation either I_{corr}-E_{corr} (Fig. 8) or E_{corr}-R_{ohm} (Fig. 9) at 160 days of testing. This fact shows the relation of high corrosion rates with low potentials and low ohmic drops (Fig. 10).

Finally, no relationship has been found between crack width and corrosion rate, as shown in Figure 11.

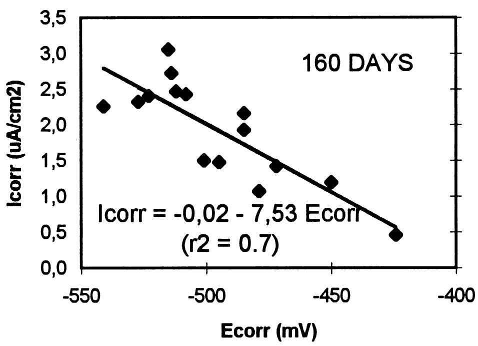


FIG. 8.
Corrosion rate vs. corrosion potential.

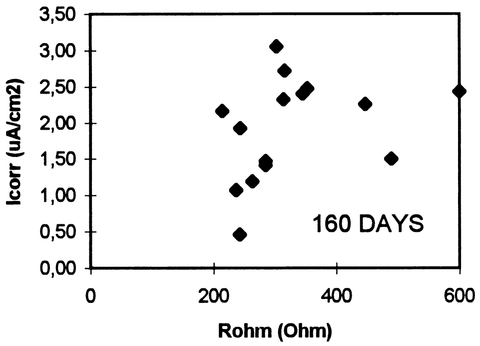


FIG. 9.
Corrosion rate vs. ohmic drop.

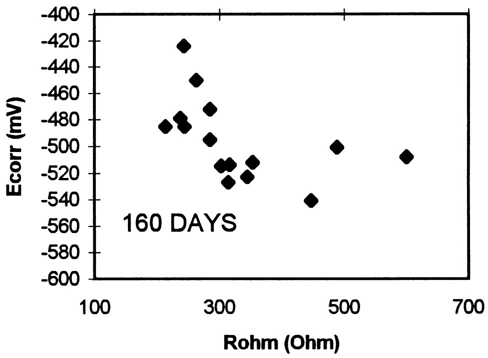


FIG. 10.
Corrosion potential vs. ohmic drop.

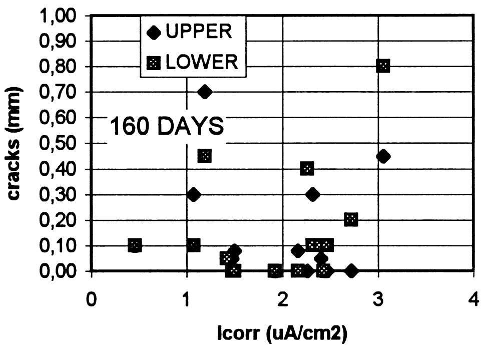


FIG. 11.
Crack width vs. corrosion rate.

Discussion

Non-uniform cracking as well as differences between the upper and lower faces were expected. Therefore, the wide crack width range observed in Specimen A from 0.05 to 0.90 mm is not surprising. In contrast, a smaller range was observed in the fibre-reinforced mortars (0.05–0.50 mm), which means the fibre addition was helpful in reducing cracking. Crack pattern in natural fibre-reinforced mortars is quite different depending on the fibre type, and it can be said that, in general, sisal-reinforced mortar cracks are thinner than those of mortars reinforced with coconut fibre.

Self-healing of concrete has been observed since long ago (8) and is a characteristic that may endow the material with better durability properties (9). Self-healing seemed to decrease with the age of the concrete. That is, the most important closing of the cracks occurs at the beginning of the life of a concrete structure, due to the hydration process itself whose products refill the crack. However, a more notable observation is that the smaller the initial crack width, the faster the self-healing. Then, the crack control provided by the natural fibres will lead to a more effective self-healing effect. Furthermore, self-healing itself could increase the pullout resistance of fibres in mortars (10). With regard to the saline testing environment, a marked crack healing in concrete exposed to sodium chloride solutions such as sea water has been experienced before (11). However, the plain mortar in these experiments did not show this phenomena.

Electrochemical parameters provided an indirect measurement of the total amount of effective cracks from the point of view of their penetrability. Thus, we can qualitatively evaluate which material is more compact and impermeable and therefore could be more durable with regard to its easy accessibility after plastic cracking.

The corrosion potential did not provide any useful information when the specimens were stored at 100% RH. Nevertheless, this parameter was found to be quite sensitive in detecting the addition of a saline solution. More interesting information was obtained by using I_{corr} measurements. The values of E_{corr} and I_{corr} at the very beginning of the monitoring showed that some of the steels were in active state. Steels embedded in plain mortar corroded fast as a consequence of their cracked cover; whilst the presence of fibres in Specimens B and C led to a delaying of the initiation of the corrosion via crack control. That no clear-cut relationship between crack width and I_{corr} was found means that internal cracks can play an important role among other factors.

With respect to the ohmic drop, it appears that the narrower and more uniform trend of the reinforced mortars than the plain ones at 100% RH suggests that a more homogeneous material has been obtained when fibres are added. This parameter is also useful to detect the ingress of chloride ions through the mortar. In this case, a sudden drop in this parameter is registered.

Comparing the average corrosion rate values of these natural fibres with the values obtained with 0.5% by volume of polypropylene fibres (5), we can observe active values (polypropylene: 1.34 A/cm^2; coconut: 1.50 A/cm^2; sisal: 2.25 A/cm^2) after more than 100 days of exposure to a 0.5 M NaCl solution. Whereas close values are obtained for polypropylene and coconut fibres, higher corrosion rates were recorded for sisal-reinforced mortars. These data have a qualitative nature and further research is necessary to assess it.

An important difference in ohmic drops between synthetic fibres and natural ones was expected as a result of the electrical isolation capability of the former. This fact lead to reach values sometimes about 1000 Ω, while for natural fibres those values only were obtained in environments of 100% RH and ranged between 200 and 400 Ω after steady-state conditions were reached after exposure to the NaCl solution. Moreover, a great dispersion of ohmic drops was found when polypropylene fibres were used. Such dispersion is a consequence of the effectiveness of the fibres in controlling cracks. That is, ohmic drop measurements can be quite useful for checking the effectiveness of crack control when synthetic fibres are employed.

Conclusion

The early age observations showed the comparative effect of the fibre addition on the plastic shrinkage cracking. It has been established that natural fibres have a good performance in controlling cracking in mortars exposed to windy and hot conditions at early ages, and they seem to delay slightly the initiation of the corrosion of embedded steel bars. However, an obvious relationship between corrosion rate and crack width has not been established. Self-healing of cracks is more effective in smaller ones and, therefore, in natural fibre-reinforced mortars.

Larger ohmic drops were obtained in the plain mortar and sisal-reinforced mortars than in the coconut fibre-reinforced mortars, which is related to the material microstructure (micro-cracks and porosity) of the fibres. Therefore, the ohmic drop measurement is presented as a reliable technique to assess the effectiveness of crack control.

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