Stainless and Galvanized Steel, Hydrophobic Admixture and Flexible Polymer-Cement Coating Compared in Increasing Durability of Reinforced Concrete Structures

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Abstract: The use of stainless or galvanized steel reinforcements, a hydrophobic admixture or a flexible polymer-cement coating were compared as methods to improve the corrosion resistance of sound or cracked reinforced concrete specimens exposed to chloride rich solutions. The results show that in full immersion condition, negligible corrosion rates were detected in all cracked specimens, except those treated with the flexible polymer-cement mortar as preventive method against corrosion and the hydrophobic concrete specimens. High corrosion rates were measured in all cracked specimens exposed to wet-dry cycles, except for those reinforced with stainless steel, those treated with the flexible polymer-cement coating as restorative method against reinforcement corrosion and for hydrophobic concrete specimens reinforced with galvanized steel reinforcements.

1. INTRODUCTION

Concrete has been world-widely applied in civil engineering structures thanks to its excellent mechanical and economic performance but loading, shrinkage, creep, thermal and flexural stress and mechanical shocks crack concrete. Cracks greatly increase the concrete surface permeability, since they represent preferential paths for penetration of aggressive ions such as sulphates and chloride in polluted area and coastal zone [1]-[2]-[3] promoting concrete deterioration and corrosion of embedded reinforcements.

The corrosion of reinforcing steel in concrete reduces the service life of the structures. Since the cost of repairing reinforced concrete structures during the induction period of the corrosion process is usually much lower than the rehabilitation cost during the propagation one, concrete technology is always developing methods to mitigate deterioration of reinforced concrete structures.

The prevention of reinforcement corrosion is primarily achieved by using high quality concrete, adequate concrete cover and suitable casting and curing [4]. Additional prevention methods are adopted when severe and/or extreme environmental conditions occur on structures requiring very long service life. Obviously, the costs needed to obtain durable concrete

structures rise with the required durability level, but it is important to provide an adequate level of protection in relation to the structure service life, avoiding unnecessary expenses.

Methods proposed for corrosion mitigation include cathodic protection, where current is impressed to polarize the reinforcement or a sacrificial anode is placed to protect the rebar, penetrating corrosion inhibitors and natural bioactive agents [5]; galvanized reinforcement, which provides protection through sacrificial corrosion, and stainless steel rebars, which is highly corrosion resistant but very expensive [6]-[7]-[8]-[9]; concrete protection through flexible polymer-cement coatings [10], or surface hydrophobic coatings due to their ability to make concrete less susceptible to water saturation [11]-[12]. Good results obtained by polymer-cement coatings are based on their water-proof property, bond strength, and flexibility, which allows the coating to bridge the possible cracks on the concrete substrate. On the other hand, the effectiveness of hydrophobic surface treatment in time depends on their penetration depth, resistance to atmospheric agents, and the integrity of the structure. Therefore, to optimize the utilization of hydrophobizing agents, they have been introduced also in the concrete bulk directly in order to make both the surface and the whole concrete bulk hydrophobic [13].

Generally, literature reports results on the efficacy of a single particular corrosion protection method but does not compare the efficacy of several different methods at the same experimental conditions.The aim of this work, indeed, is to compare the efficiency of more traditional methods used to mitigate chloride induced corrosion of cracked reinforced concrete, such as the use of galvanized or stainless steel, with more innovative ones, such as coating the concrete surface with a polymer-cement based mortar, used either as a preventive or as a restorative method, or the introduction in the concrete mix of a hydrophobic admixture.

2. EXPERIMENTAL

2.1 Materials

A commercial Portland cement type CEM II/A-M 32.5 R, crushed gravel (15 mm maximum size) and natural sand (2 mm maximum size) were used as binder and aggregates, respectively. The hydrophobic admixture was a 30% aqueous emulsion of butyl-ethoxy-silane. The mixture proportions for the polymer-cement coating were 1 part of 2-ethylhexyl acrylate polymer latex (50% water), 1 part of Portland cement type CEM II/A-L 42.5 R and 2 parts of fine sand (0-0.2 mm). Then the w/c of this coating as well as the polymer/cement was 0.50. Different steel plates were used to reinforce the concrete specimens: bare steel plates,stainless steel plates (AISI 304) and hot dip galvanized steel plates.

2.2 Mixture Proportions

Concrete with w/c = 0.80 was prepared for all the specimens mixing 288 kg/m^3 of cement, 230 kg/m^3 of water, 600 kg/m^3 of sand and 1167 kg/m^3 of coarse aggregate.

Hydrophobic concrete was manufactured by adding in the concrete mixture 2% of the hydrophobizing active ingredient by mass of cement. In order to obtain similar microstructure exposed to the aggressive environment, the strength loss due to the hydrophobic admixture was compensated by reducing the w/c to 0.75 [14].

2.3 Specimens Preparation

Prismatic specimens (100 x 100 x 400 mm) of highly porous concrete (w/c = 0.80), in order to

highlight the different corrosion behaviour, were manufactured: 6 specimens were reinforced with bare steel plates, as reference; 6 specimens were reinforced with galvanized steel plates; 6 specimens were reinforced with stainless steel plates; 12 specimens were protected by a polymer-cement coating and reinforced with bare steel plates; 6 hydrophobic concrete specimens were reinforced with bare steel plates; 6 hydrophobic concrete specimens were reinforced with galvanized steel plates. The coating, if any, was applied after 1 month of air drying of the concrete specimens.

   For each group, half of the specimens, kept uncracked to act as cathodes for the short-circuit current measurements, were reinforced with single steel plates (70 × 1 × 360 mm) embedded at mid depth (Fig. 1). The other half of the specimens, acted as evaluation test, were cracked by flexural stress (crack width of about 1 mm) after an additional week, and then were reinforced with two steel plates not in contact with each other. The two steel plates (70 × 1 × 360 mm and 70 × 1 × 120 mm, Fig. 1) were placed at 70 mm and 30 mm, respectively, from the specimen side containing a preformed notch, whose function was to initiate a crack reaching the smallest plate under flexural loading. This plate acted as the anode during the experiment, while the longer steel plate served to control the crack width. The electrical connections required for corrosion monitoring through electrochemical measurements were carried out as described in previous works [14].

   In order to estimate the efficiency of the polymer-cement coating as a restorative method against corrosion, three specimens were cracked before coating. In order to estimate the efficiency of the surface coating as a preventive method against corrosion, the other three specimens were coated before cracking. All the specimens were kept for 48 hours at 100% R.H. and, after demoulding, they were air dried for 1 month at room temperature. The coating, if any, was then applied on the specimens. After an additional week of air-curing, half of all the specimens were stressed by flexural stress, by loading the specimen surface opposite the notch (Fig. 1) to initiate the development of a crack. Crack width of 1 mm was obtained with enough accuracy by slowly varying the applied load.

   Concerning with specimens protected with the polymer-cement coating before cracking (as a preventive method against corrosion), no failure of the polymer-cement coating was visible after the concrete substrate was cracked, thus apparently confirming the good flexibility properties of the coating. Moreover, after the flexural loading, the produced crack width could not be measured, but its size could be reasonably assured by the load reached to crack the concrete specimen.
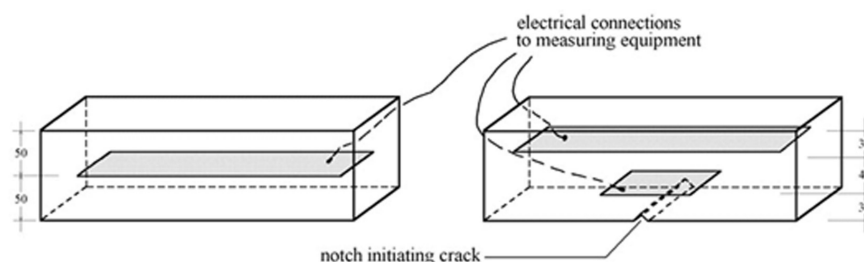

Fig. 1. Reinforced specimens

2.4 Specimens Testing

After the drying period, all specimens, sound or cracked, were then exposed to increasingly aggressive environments: at first a full immersion in a 3.5% NaCl aqueous solution for 40 days, taking care to maintain constant atmospheric oxygen saturation through adequate recycling and then exposure to weekly wet-dry cycles, characterized by two days of full immersion in a 10% NaCl aqueous solution followed by 5 days of air drying, up to about 6 months.

The corrosion resistance of the different steel plates was monitored by measuring their corrosion potential with respect to reference saturated calomel electrode (SCE). Moreover, during the immersion period, the short-circuit current was measured between the smallest plate (anode), embedded in the cracked specimen and reached by the crack tip, and the same type of steel plate (cathode) placed in the corresponding sound specimen. The reported values are the averages of the measurements carried out on three specimens of each type.

3 DISCUSSION OF TEST RESULTS

3.1 Steel Reinforcements

Fig. 2a shows the free corrosion potential of the anodic steel plates embedded in the cracked specimens as a function of the test time. By assuming that potential values lower than -450 mV/SCE indicate a relatively high corrosion risk of steel, stainless steel and the polymer-cement coating applied after cracking guarantee adequate protection whatever the aggressive exposure condition. This is not detected, as expected, with the reference bare steel or with bare steel in hydrophobic concrete. On the other hand, when the concrete specimen is preventively protected by a polymer-cement coating applied before cracking, the corrosion risk does not seem to be reduced, demonstrating that the corrosion behaviour is not consistent with the apparent coating integrity observed.

The short-circuit currents (Fig. 2b) measured in the full immersion condition are, in any case, very low as a consequence of the low oxygen availability, which slows down the kinetics of the corrosion process [15] with the exception of those related to reinforcing steel bars in hydrophobic concrete. This different behaviour is explained because the gaseous oxygen diffuses better through the open pores of the hydrophobic concrete with respect to the water saturated pores of the reference mixture, feeding in this way the cathodic reaction of the corrosion process [14]. They remain negligible in the wet-dry cycles condition only for stainless steel, thus assuring prevention of corrosion, and for the concrete protected by polymer-cement coating applied after cracking, thus confirming the efficiency of this application as a successful repair method. On the other hand, the short-circuit current values measured in this condition obviously become unacceptably high for bare steel, but they also appear too high for the bare steel anodic plate embedded in the concrete specimen protected with the polymer-cement coating applied before cracking. In fact, some corrosion products already appeared at the end of the full immersion period of these specimens, thus indicating that coating stretching induced by flexural loading can compromise the efficiency of this preventive method against corrosion. Steel plates in hydrophobic concrete do not modify significantly the short circuit currents values when the exposure condition changes from full immersion to wet-dry cycles in the chloride solution.
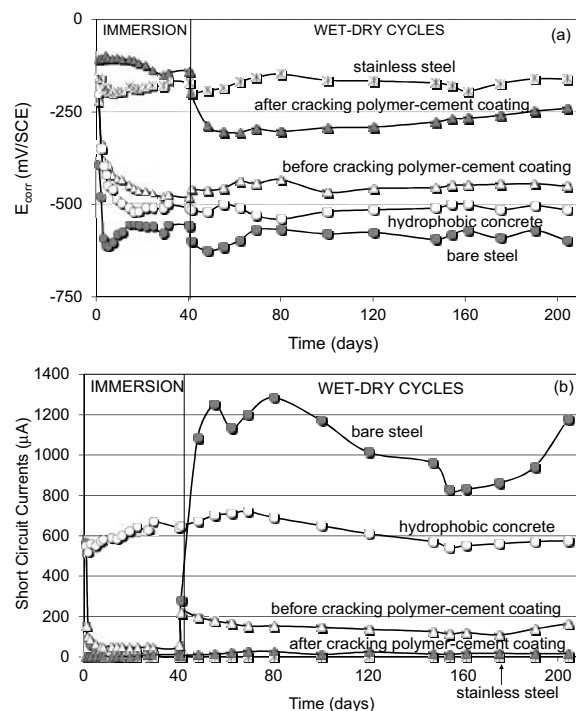
Fig. 2. Free corrosion potential (E_{corr}) of the anodic steel plates embedded in cracked concrete specimens (a) and short circuit currents of steel plates embedded in cracked concrete specimens as a function of the test time (b).

3.2 Galvanized Steel Reinforcements

Fig. 3a shows that the active corrosion potential assumed by the galvanized steel plate during the full immersion period moves towards passivation values when embedded in hydrophobic concrete. When the cracked concrete specimens reinforced with galvanized steel are exposed to wet-dry cycles the anodic potential rises in any case even if the potential values become rapidly typical of the passive state only in the case of hydrophobic concrete.

The short-circuit currents measured in the full immersion condition for galvanized steel embedded in hydrophobic concrete (Fig. 3b), rapidly decrease and remain at negligible values after the cracked concrete specimens are transferred to the wet-dry cycles environment. On the other hand, the negligible currents measured in the full immersion condition for galvanized steel in ordinary concrete, due to poor oxygen availability in water saturated concrete, suddenly rise to very high values before gradually decreasing as long as the anodic galvanized steel plate reaches less negative potential values when exposed to wet-dry cycles.
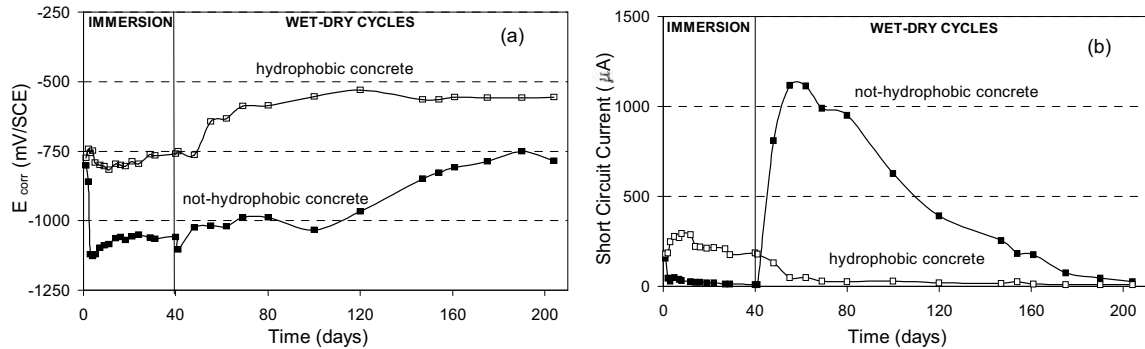
Fig. 3. Free corrosion potential (E_{corr}) of the anodic galvanized steel plates embedded in cracked concrete specimens (a) and short circuit currents of galvanized steel plates embedded in cracked concrete specimens (b) as a function of the test time.

3.3 General Comparison

The comparison is drawn on the basis of the short-circuit current evaluation as a function of the potential difference between the steel plates respectively acting as anode (cracked specimen) and cathode (uncracked specimen). In the full immersion condition (Fig. 4a), at equal potential difference (electromotive force) of the corrosion process, the highest corrosion currents are monitored for bare and galvanized steel embedded in hydrophobic concrete. Lower currents are found in all other concrete specimens, except for those protected with the polymer-cement coating applied before the specimen cracking.
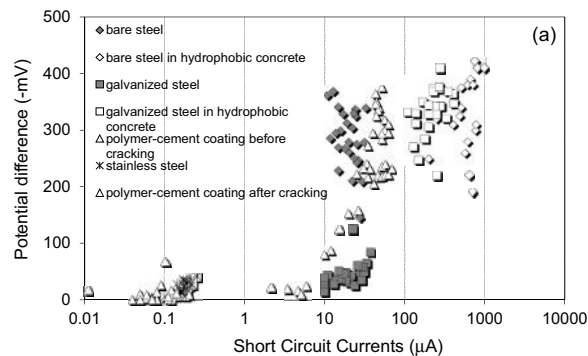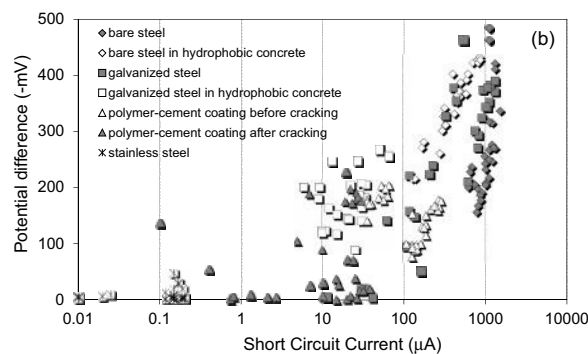
Fig. 4. Potential difference versus short-circuit current for the full immersion (a) and wet-dry cycles conditions (b).

In the wet-dry cycles condition (Fig. 4b), a very high current was recorded for bare steel; it is high for galvanized steel, up to its corrosion potential reaches more positive values, and for bare steel in hydrophobic concrete; it is unacceptable for bare steel embedded in concrete protected by the polymer-cement coating applied before concrete cracking; it is definitely low when this protection is applied after the concrete cracking and in the case of galvanized steel embedded in hydrophobic concrete; it is practically insignificant for stainless steel.

4 CONCLUSIONS

The use of stainless or galvanized steel reinforcements, a hydrophobic admixture or a flexible polymer-cement coating is compared as methods to improve the corrosion resistance of sound or cracked reinforced concrete specimens exposed to chloride rich solutions. The obtained results show that:

- the use of stainless steel is the most efficient method to mitigate chloride induced corrosion of steelin cracked concrete;
- the good behaviour of cracked concrete protected by a polymer-cement coating is not fully confirmed when this technique is applied as a preventive method to reinforced concrete before cracks occur due to coating stretching which compromises its water-repellentpropertiesthrough the occurrence of visually undetectable micro-cracking;
- the hydrophobizing admixture makes significantly worse the corrosion behaviour of both bare and galvanized steel in full immersion conditions;
- the hydrophobizing admixture increases surprisingly the corrosion resistance of galvanized steel reinforcement in cracked concrete when exposed to the very aggressive, and more common, wet-dry cycles conditions;
- despite the poor efficiency observed in certain situations, the use of galvanized steel reinforcement in hydrophobic concrete shows good prospects especially when technical-economic considerations are taken into account.

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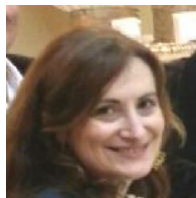
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Corrigendum:
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The published references are not correct.

Please replace with:

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