

CORROSION OF STEEL AND GALVANIZED STEEL REINFORCING BARS IN CONCRETE SIMULATING FIELD CONDITIONS

T. Bellezze⁽¹⁾, R. Fratesi⁽¹⁾, G.A. Plizzari⁽²⁾ and F. Tittarelli⁽¹⁾

(1) Department of Materials and Environmental Engineering and Physics, University of Ancona, Via Breccie Bianche, 60131 Ancona - Italy

(2) Department of Civil Engineering, University of Brescia, Via Branze 38, 25123 Brescia, Italy

ABSTRACT

A correct concrete technology can help to increase the structure service life but it cannot ensure an overall protection against reinforcement corrosion, especially in aggressive environments. Among the possible solutions to this problem, the use of galvanized reinforcing bars has recently received great consideration for increasing the durability of structures.

Although successful practical results have been obtained with the use of galvanized reinforcement against corrosion, some questions concerning the protection of bars still remain unanswered. The major concerns are related to the presence of coating discontinuities such as cut bar-ends, to the areas with zinc coat flaking (produced during bending procedures) or to welded areas where the zinc coating is missing. Furthermore, laboratory tests often performed on unloaded bars in uncracked concrete, do not represent the condition of the reinforcement in a real structure where the bars are stressed and microcracks could be present in the concrete.

In this paper, experimental results concerning the corrosion behavior of bars with a properly simulated discontinuous zinc coating are presented. Furthermore, results from corrosion tests on post-tensioned bars to a stress typical of service conditions are compared with the results relative to unloaded bars.

KEYWORDS: Galvanized bars, reinforced concrete, zinc coating discontinuities, flaking, bending, cathodic protection, concrete microcracking, post-tensioned bars.

1 INTRODUCTION

The limits of durability of reinforced concrete structures have led to a considerable impulse towards research, aimed at establishing an adequate level of knowledge on the properties of this material. When concrete technology is correctly applied, it is possible to increase the service life of reinforced structures, even if it is difficult to ensure an absolute protection from aggressive agents, in particular when concrete cracking or accidental causes of degradation occur. Therefore, in critical corrosion conditions, the durability of the structure can only be guaranteed by providing additional protection to the steel reinforcement.

Among the possible methods for improving the corrosion resistance of reinforcement in concrete, new consideration has been given to the use of galvanized rebars, in view of their relatively low cost compared to other protection systems. It is clear that the galvanized bars increase the initial cost of the concrete structures but, during their whole service life, this is not a major cost considering the rising costs of restoration and maintenance. However, although good practical results are present into the literature [1-4], the benefits of using galvanized steel in reinforced concrete structures is still uncertain because of some controversial laboratory test results [5-9].

Swamy [10] stated that the results of laboratory tests must be viewed with caution due to the fact that the simulated environment does not fully match the actual conditions. It has been observed, however, that zinc coating delays the onset of corrosion of reinforcing steel, as it was explained with a conceptual model proposed by Yeomans [11].

One of the unanswered questions concerning the use of galvanized reinforcements, is the risk of corrosion where zinc coating discontinuities are present owing to bending of the bars or during welding procedures which leave uncoated spots.

Major corrosion problems are especially present when cracks appear in concrete structures, because they determine a preferential pathway for aggressive agents (chlorides, oxygen, carbon dioxide, etc.) [12]. The effectiveness of the zinc coating in protecting steel rebars in the presence of cracks is subject to controversy, and contradictory results [10, 13-16] have been presented by different researchers.

In this work, the corrosion behavior of galvanized reinforcement, both in the case of zinc coating discontinuities and in the case of microcracked concrete due to the post-tensioning of ribbed bars, was studied. To this aim, several reinforced concrete specimens were manufactured. In the first case, the coating discontinuities were simulated by a small piece of black bar assembled with two lateral galvanized bars, electrically isolated from each other, in order to externally measure the galvanic corrosion current; these specimens were submitted to wet-dry cycles by ponding both with tap water and with a sodium chloride solution. In the second case, results obtained from corrosion tests carried out by wet-dry cycles with a sodium chloride solution on post-tensioned black and galvanized bars were performed and compared with those related to unloaded bars.

At the end of the tests, all the specimens were autopsied to visually assess the corrosion attack, if any.

2 EXPERIMENTAL

2.1 Concrete specimens with simulated coating discontinuities

Sixteen prismatic specimens (14x12x44 cm) were manufactured using CEM II/A-L 42.5 R cement with a water-cement ratio of 0.70. The specimens were reinforced, in the longitudinal direction, with a bar (diameter=12 mm; cover=15 mm) obtained by assembling three electrically isolated bars: two lateral galvanized bars (anodic parts) of the same length and a small piece of black bar (cathodic part) in the center. Four different types of bars were produced with anodic surface (Sa) to cathodic surface (Sc) ratios as shown in Table 1.

Figure 1 shows two assembled bars (Sa/Sc = 20 and 7.5) ready for the cast. The assembly and electrical insulation were performed with a PVC insert (not shown in the figure) and epoxy resin

between the two lateral galvanized bars and the central black bar. In Figure 1, the electrical cables for the external current and potential measurements are also clearly visible. The Sa and Sc values were well defined by masking the bars with epoxy resin.

Table 1. Assembled bars with 4 different Sa/Sc.

Sa/Sc	Lateral galvanized bars (cm)	Central black bar (cm)
80	16+16	0.4
40	18+18	0.9
20	15+15	1.5
7.5	15+15	4.0



Fig.1. Two assembled bars with Sa/Sc=20 (top) and Sa/Sc =7.5 (bottom), used to study the galvanic protection on discontinuities.

Four concrete specimens were prepared for each value of Sa/Sc (Table 1): two for each type of exposure condition. All the specimens were demoulded 3 days after casting. The exposure conditions were respectively: wet-dry cycles with tap water and wet-dry cycles with 5% NaCl solution. The wet-dry cycles were applied to the specimens after 28 days of air curing and they consisted of 5 days of drying and 2 days of wetting. During the experimentation period, there were some longer drying periods.

During the whole test period (about 270 days), the galvanic coupling between the galvanized bars and the black bar was externally obtained by short-circuiting the electrical cables soldered to the single parts (Fig. 1). The short circuit current between the anodic part (the two galvanized bars) and the cathodic part (black bar) was monitored using a zero resistance ammeter. Furthermore, potential measurements were performed with a calomel electrode (SCE) both during the coupling conditions and in free corrosion conditions; in this last case, the external electrical contacts between the bars were removed, and the free corrosion potential measurements were performed after 1.5 hours at open circuit.

Two further specimens, of the same type but without reinforcement, were manufactured and submitted to ponding with 5% NaCl solution, in order to periodically determine the depth of chloride penetration during the wet-dry cycles.

In the two different exposure conditions, concrete resistivity was also evaluated to study a possible ohmic control of galvanic corrosion. To this aim, four cubic specimens (15x15x15 cm) were cast, two per type of exposure, with the same cement and the same water-cement ratio mentioned above. Two stainless steel plates (18x15 cm) were embedded in these specimens and positioned vertically

at a distance of 11 cm. Measurements of conductivity were performed during the whole corrosion test period, using a 50 mV sinusoidal amplitude signal and a frequency of 1 KHz. The results presented were obtained by finding the average of the measured data at each exposure condition.

2.2 Concrete specimens with post-tensioned bars

Twenty concrete prismatic specimens (25x20x10 cm) were manufactured using CEM II/A-L 42.5 R cement with a water-cement ratio of 0.66. Ten were reinforced with a black steel ribbed bar and the other ten with a galvanized steel ribbed bar, both with a diameter of 20 mm and a concrete cover of 40 mm.

After 28 days of curing in air at room temperature, half of each type of bar embedded in concrete was tensioned and maintained under a stress of 180 MPa by means of an external metallic framework for the whole duration of the corrosion tests (Fig. 2). In summary, the specimens were grouped in the following way: 5 specimens with black steel bars post-tensioned; 5 specimens with black steel bars unloaded; 5 specimens with galvanized steel bars post-tensioned; 5 specimens with galvanized steel bars unloaded.

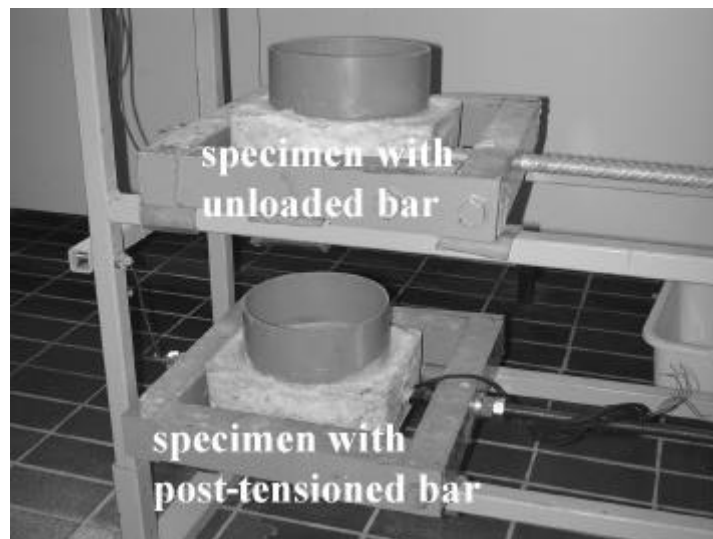


Fig. 2. Specimens with galvanized steel unloaded bar (top) and galvanized steel bar post-tensioned (bottom).

All the specimens were submitted to wet-dry cycles by ponding with 5% NaCl solution, consisting of 8 days drying and 1 day wetting.

On two concrete specimens for each group, free corrosion potential and corrosion rate were monitored for about 100 days, while the remaining 3 specimens were autopsied after 300 days of ponding treatment. The corrosion rate was measured by linear polarization technique under galvanostatic control (scan rate = 0.5 μ A/sec). A calomel reference electrode and a graphite counter electrode were used.

The corrosion potential and corrosion rate data presented were obtained by averaging the values related to the two specimens submitted to the electrochemical test for each group.

3 RESULTS AND DISCUSSION

3.1 Galvanic coupling simulating zinc coating discontinuity

Just after the concrete cast, the galvanized steel was in an active state and its free corrosion potential was -1350 ÷ -1400 mV, while the black steel corrosion potential was -400 ÷ -520 mV (Fig. 3); after galvanic coupling of the anodic and cathodic parts, the galvanized steel cathodically polarizes black steel, which assumed potential values in the range -850 ÷ -1050 mV, very close to the

thermodynamic immunity conditions for the steel. One day after the cast, the zinc coating became passive and the relative corrosion potential was $-750 \div -850$ mV; the galvanic corrosion was under cathodic control in the cases of $Sa/Sc = 80$ and $Sa/Sc = 40$; it became slightly anodic for $Sa/Sc=20$ and completely anodic for $Sa/Sc=7.5$ (Fig. 3).

The short circuit currents were very high only during the early days after the cast and they changed from a minimum value of $300 \mu\text{A}$ up to a maximum value of $1000 \mu\text{A}$ as the ratio Sa/Sc decreased. The wet-dry cycles started after 28 days of curing.

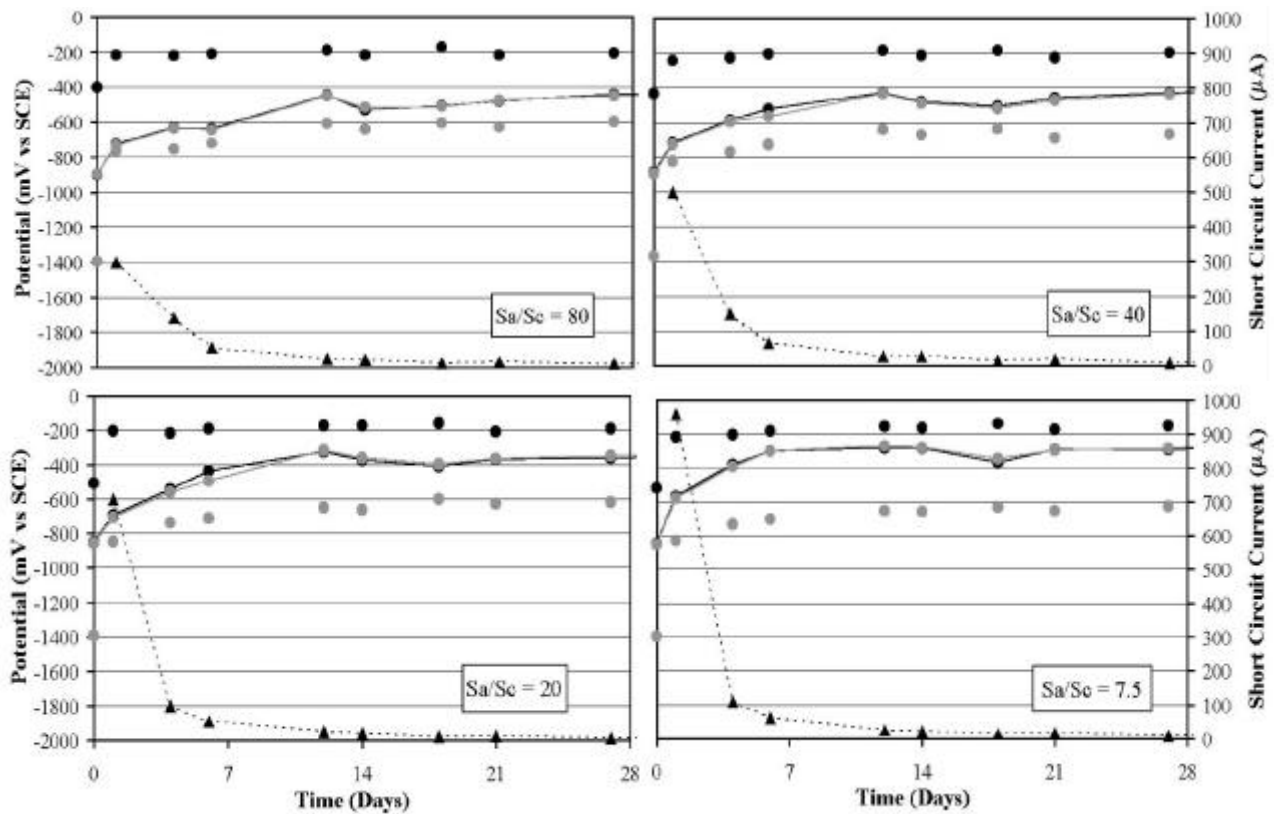


Fig. 3. Trend of the free corrosion potential, short circuit potential and short circuit currents, during 28 days of curing in atmosphere: ● free corrosion potential of black steel; ● free corrosion potential of galvanized steel; ●— short circuit potential of black steel; ●— short circuit potential of galvanized steel; ...▲... short circuit current.

3.1.1 Wet-dry cycles with water

During cycles with water, the specimens showed an anodic macrocell control in the case of $Sa/Sc=20$ and $Sa/Sc=7.5$, while for $Sa/Sc=40$ the cathodic polarization was almost equal to the anodic polarization. For $Sa/Sc=80$ there was a cathodic macrocell control; this last result is quite clear considering the low value for the black steel surface. As a consequence, the cathodic protection is much more effective for a small defect in the zinc coating.

The short circuit currents became very low with time and assumed values lower than $10 \mu\text{A}$.

The resistivity was low and ranged between 5 and 20 ohm cm during wetting periods, and between 20 and 75 ohm cm during normal drying periods. Due to the low values of the short-circuit current and low values of resistivity of concrete, the ohmic drop control of galvanic corrosion has to be excluded.

During wet-dry cycles, the values of free corrosion potential ranging between $-100 \div -200$ mV and $-500 \div -600$ mV were monitored for black and galvanized bars, respectively.

3.1.2 Wet-dry cycles with 5% NaCl solution

Compared to the previous case, it was observed that, for the specimens subjected to ponding in 5% NaCl solution, the galvanic corrosion was under cathodic control for the different Sa/Sc values (Fig.

4). These experimental results can be explained by the damage of the zinc coating passive film, which becomes unable to control the galvanic corrosion. In particular, after 3 wet-dry cycles, the galvanized bars exerted “cathodic prevention” [17] toward the chlorides attack, with respect to the coupled black bars. In fact, considering that at a depth of 15 mm (equal to the assembled bars cover) the measured chloride concentration (by weight of cement) was slightly under 4%, the short circuit potentials of the black bars, for the different Sa/Sc values, were under -300 mV vs SCE (Fig. 4), which approximately corresponds to the pitting potential of a black bar embedded in concrete with a chloride concentration of 4% by weight of cement [18]. This effect was much more evident when Sa/Sc value was 80, which simulates the smallest defect in the series. After 10 wet-dry cycles, the “cathodic prevention” exerted by the galvanized bars, was probably still effective because the short circuit potential of the black bars was very low in all cases (under -600 mV vs SCE), even if this potential must be compared with a pitting potential lower than -300 mV, due to the measured chloride concentration being slightly higher than 4%.

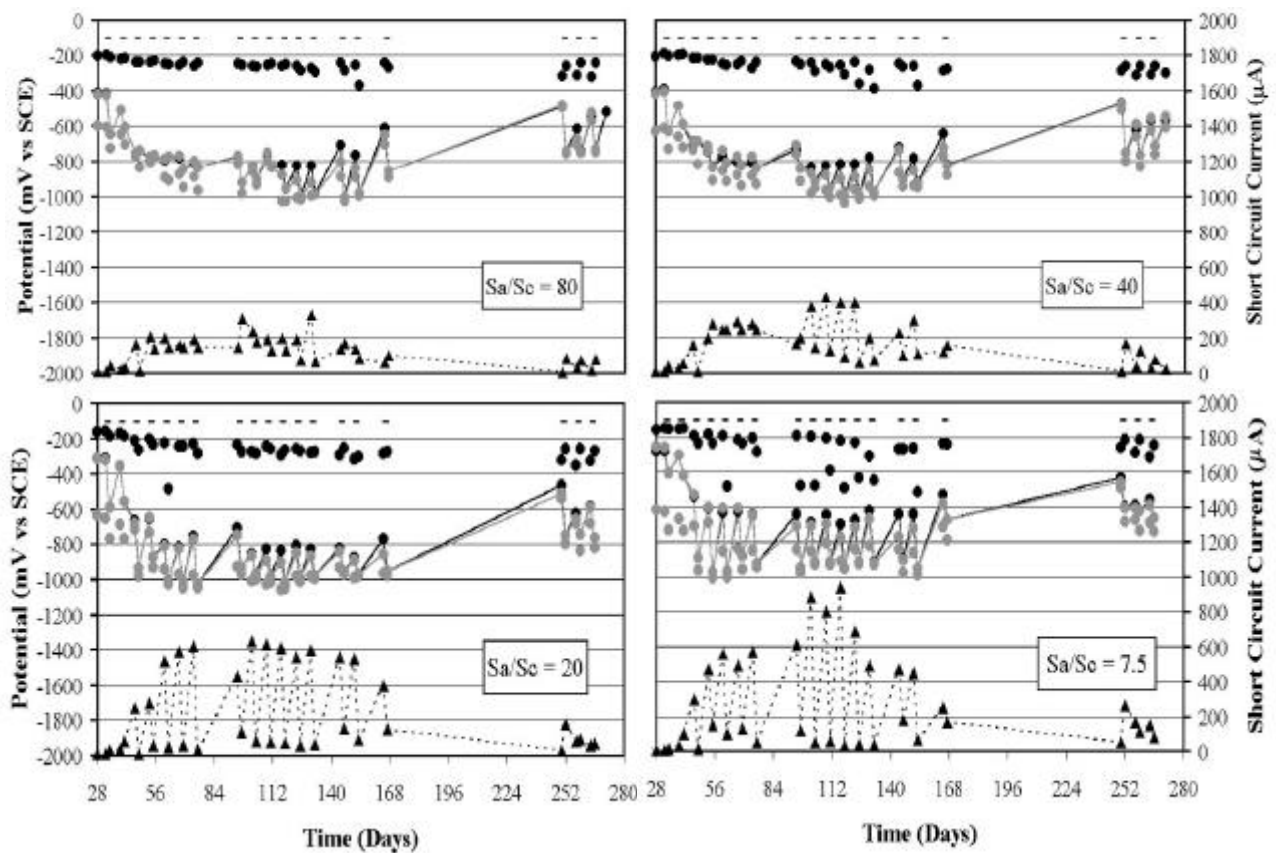


Fig. 4. Trend of the free corrosion potential, short circuit potential and short circuit currents, during wet-dry cycles with 5% NaCl solution: ● free corrosion potential of black steel; ● free corrosion potential of galvanized steel; —●— short circuit potential of black steel; —●— short circuit potential of galvanized steel; ...▲... short circuit current; — wetting periods.

During wet-dry cycles, free corrosion potentials ranging between $-200 \div -400$ mV and $-700 \div -1000$ mV were monitored for black steel and for galvanized steel, respectively. In this case, the low values of free corrosion potential of zinc coating indicate its weak passive state.

The short circuit currents were much higher than the previous case (Fig. 4) due to the higher electromotive force between the galvanized steel and bare steel, and also because the zinc coating is not well passivated in the presence of chlorides. Furthermore, the short-circuit current increases as the Sa/Sc decreases; this means that an increase in the bare steel surface leads to a higher consumption of the adjacent zinc coating.

The resistivity, which contributes to the possible ohmic drop control, was very low: $3 \div 5$ ohm cm during wetting periods and $5 \div 15$ ohm cm during drying periods. Therefore, even if the short-circuit currents in this case are significantly high, the ohmic drop control of the galvanic corrosion has to be considered ineffective.

3.1.3 Autopsy of the reinforcement

At the end of the exposure period, all bars were autopsied in order to compare their visible corrosion conditions with the data obtained by means of the electrochemical measurements.

On all the pieces of black bars embedded in the manufactured specimens, exposed both to wet-dry cycles with water and to wet-dry cycles with NaCl solution, no red rust was observed. These simulating discontinuities were protected against corrosion by means of the cathodic protection even though the potential values did not reach thermodynamic immunity.

The galvanized bars embedded in the specimens exposed to wet-dry cycles with water, were not corroded, with the exception of those bars coupled with largest black bars ($S_a/S_c = 7.5$). In this case, near the bars joints, the galvanized bars were dark due to the consumption of the external pure zinc layer of the coating (η phase). Therefore, the underlying Zn-Fe alloy layer was visible on the surface.

These observations demonstrate that for a larger simulated discontinuity, the cathodic protection of bare steel determines a slight corrosion of the adjacent zinc coating.

In the presence of chloride ions, the corrosion attack of the zinc coating close to the pieces of black bars, was well detected in the specimens with $S_a/S_c = 7.5$. Indeed, in this case the zinc coating close to the joints with black steel was heavily corroded and the localized attack had penetrated into the Zn-Fe alloy layers leading to local destruction of the zinc coating. This phenomenon was also found for galvanized reinforcements in concrete with chlorides without galvanic coupling [7,19].

These experimental results demonstrate the beneficial effect of the zinc coating when discontinuities as large as 4 cm are present. In general, a larger discontinuity produces a higher corrosion in the adjacent zinc than a smaller discontinuity does; in addition, the galvanized rebars offer a more effective cathodic protection in this last case, especially when a critical level of chlorides is present. In fact, in the presence of chlorides, a discontinuity of about 4 cm can be considered critical for the surrounding zinc consumption.

3.2 Corrosion behavior of the specimens with post-tensioned bars

The trends of free-corrosion potential and of the corrosion rate measured on specimens both with loaded and unloaded bars are shown in Figure 5. In the wet-dry cycles, the corrosion rate increases during the wetting periods and decreases during the drying periods. The sudden increase of the corrosion rate of the post-tensioned bars after the initiation of wet-dry cycles is also evident, as well as the higher values of corrosion rates related to the post-tensioned bars with respect to the unloaded ones. This is mainly due to the microcracks developed in concrete surrounding the bars after loading the bar. These microcracks permit the chloride solution to reach the bars quickly and to start the corrosive attack.

In the presence of high chloride concentrations, zinc coating corrodes with the formation of non-protective corrosion products [20]. This explains the high values of corrosion rate registered on the post-tensioned galvanized bars with respect to the bare steel bars, when submitted to the same conditions (Fig. 5b).

Corrosion rate values of both unloaded galvanized and bare steel bars up to 100 days of testing are lower with respect to the correspondent post-tensioned ones, due to the fact that the chloride ions can reach the bar only by diffusion and capillary suction through a sound concrete cover.

The autopsy of the bars after 300 days agree with the results found by electrochemical measurements (Fig. 6).

For the unloaded bars, no attack in the case of black steel (Fig. 6a) and a slight attack in the case of the coating of the galvanized bars was observed (Fig. 6b). This is due to the initial reaction between the pure zinc phase and cement paste during concrete hardening. The post-tensioned galvanized

bars showed almost complete dissolution of the zinc coating and even corrosive attack of the steel substrate where the zinc is missing (Fig. 6d). The post-tensioned steel bars showed a heavy layer of corrosion products as a demonstration of the severe corrosive attack (Fig. 6c).

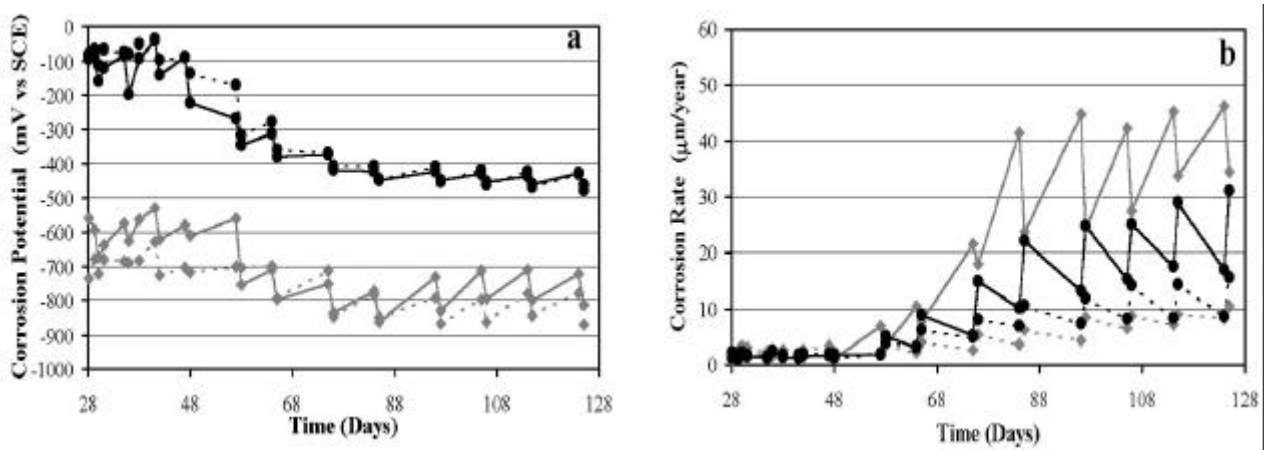


Fig. 5. Corrosion potential (a) and corrosion rate (b) of the post-tensioned and unloaded bars: —●— black steel bar post-tensioned; ...●... black steel bar unloaded; —◆— galvanized steel bar post-tensioned; ...◆... galvanized steel bar unloaded.

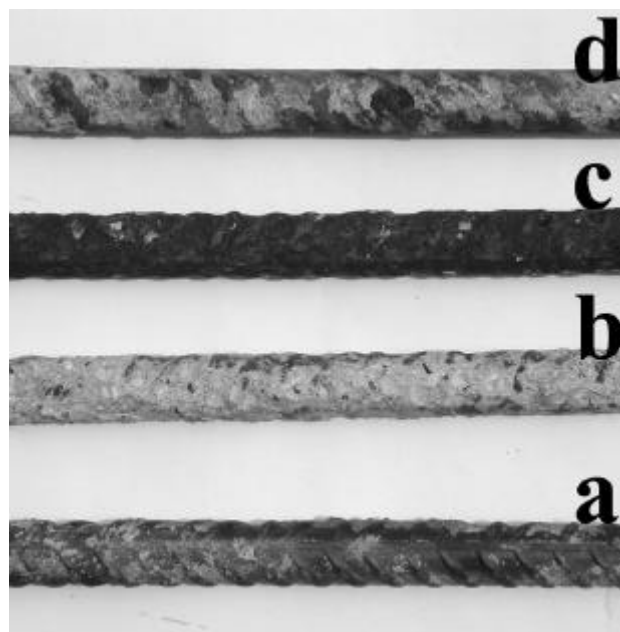


Fig. 6. Photo of the bars after 300 days of wet-dry cycles with 5% NaCl solution: (a) unloaded black steel bar; (b) unloaded galvanized steel bar; (c) post-tensioned black steel bar; (d) post-tensioned galvanized steel bar.

4 CONCLUSIONS

Experimental tests were performed to simulate field conditions for reinforcing bars in concrete structures.

Pieces of bare steel immersed in free-chloride concrete and in contaminated concrete with chlorides was coupled with galvanized steel with the aim of simulating the bending or welding of galvanized bars that might be cathodically protected by the adjacent zinc coating. The damage of this coating depends on the aggressiveness of the concrete surrounding the bars and on the dimensions of the bare steel simulating the spots.

The short circuit potentials measured indicate that the zinc of the galvanized steel exerts the “cathodic prevention” against the chlorides attack on bare steel. However, in chlorides containing concrete, a spot of 4 cm in length seems to be a critical size for the surrounding zinc consumption. Microcracks produced by the stress of the reinforcement in concrete represent a short cut for the access of chlorides toward the bars and as a consequence galvanized and bare steel corrodes easier.

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