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Effectiveness of a conductive cementitious mortar anode for cathodic protection of steel in concrete

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Abstract

The paper reports a study on the behaviour of a cementitious conductive overlay anode used for cathodic protection (CP) of steel in concrete. The anode is made of nickel-coated carbon fibres in a cementitious mortar. Tests were carried out on concrete specimens with two layers of rebars that simulated reinforced concrete slabs. Anodic current densities in the range 10–100 mA/m^2 with respect to the anode surface were imposed. Steel and anode potentials, as well as feeding voltage, were monitored. Four-hour decay and the distribution of current and potential were regularly measured. Galvanostatic polarisation tests were also carried out on the anode material immersed in saturated calcium hydroxide solutions. The maximum anode current output was evaluated. The effectiveness of patch repair of the anode, on areas damaged by excessive current output, is also discussed.

Keywords: Durability; Electrochemical properties; Cathodic protection

1. Introduction

Cathodic protection (CP) has proved to be an effective and reliable technique for the protection of reinforced concrete structures that are damaged by chloride induced corrosion, such as marine structures or road structures exposed to the action of de-icing salts [1–3]. It consists in the application of a cathodic current density of 5–20 mA/m^2 to the steel reinforcement in order to reduce its corrosion rate to negligible values [2–5]. Because of the high resistivity of concrete and the complex geometry of reinforcing bars, CP is usually applied by using an extended inert anode laid on the surface of the concrete and a current feeder in order to impose the required current (impressed current anode systems) [4,5]. Galvanic anodes can also be used for particular applications [6,7].

Inert extended anodes are normally used for reinforced concrete structures in the form of an expanded mesh of titanium activated by oxides of different metals (mainly ruthenium and iridium) or a conductive organic paint containing carbon particles [4,5]. Activated titanium anodes show very long service life and can supply high current densities (up to 100 mA/m^2), but they are rather expensive [8–10]. Furthermore, these anodes have to be embedded in an overlay that adds weight to the protected structure. Conductive paints are cheaper, but they cannot supply current densities higher than 20 mA/m^2 for long times; the experience on their use is limited to 10–15 years, mainly in Northern climates [11].

The development of new types of anodes for the protection of reinforced concrete structures is a subject of great technological interest. A new anode system made of a cementitious conductive overlay has been proposed [12]. This system can be easily and economically applied by spraying 10- to 20-mm thick layer of a polymer-modified mortar on the surface of the concrete. Carbon fibres, coated with a thin and homogeneous layer of corrosion resistant metal, are added in order to provide a continuous network with electronic conductivity (resistivity is lower than 0.1 Ω·m). Activated titanium strips are embedded in the overlay as primary anodes with the purpose of distributing the current along the conductive overlay. Parallel strips are normally placed at distance of 1–2 m. The anodic reaction, necessary to produce the electrolytic current that flows through the concrete to-

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wards the reinforcing steel, is expected to take place on the surface of the fibres and thus to be distributed all over the surface of the overlay [12].

This paper discusses the results of a research aimed at studying this type of conductive mortar as anode for CP in chloride contaminated concrete. The maximum current density that can be supplied by the anode was evaluated both on reinforced concrete specimens and in alkaline solutions.

2. Experimental procedure

Tests were carried out on the reinforced concrete specimens shown in Fig. 1. Concrete was mixed with 350 kg/m^3 of Portland cement, water-to-cement ratio of 0.5, 1850 kg/m^3 of aggregate with maximum size of 15 mm; it was moist-cured at ambient temperature for 28 days. Each specimen had 22 parallel steel bars, 20 mm in diameter, placed at 20 and 140 mm from the anode, respectively, for the upper and lower bars. External copper wires electrically connected all the bars. An activated titanium pseudo-reference electrode (MMO [13]) was embedded in each specimen, on the central upper bar. At the end of curing, the specimens were exposed outdoor unsheltered. A layer of 8–10 mm of a commercial conductive mortar for CP anode was applied on the surface of the specimens. An activated titanium strip was embedded in the conductive mortar as primary anode (Table 1). The ratio between the surface of concrete covered by the overlay and the surface of the primary anode was 20; the ratio between the surface of concrete covered by the overlay and the total surface of the steel bars was 0.36.

Concrete specimens were chloride contaminated both by adding $CaCl_2$ to the mixing water of the concrete or conductive mortar and by ponding with a 5% NaCl solution on the upper surface of the specimens (Table 1). The ponding was applied by maintaining 20 mm of solution on the surface of the specimens during the first 2 months. Afterwards, the specimens were monthly sprayed with 250 ml of a saturated NaCl solution, equivalent to about 1.5 kg/m^2 of chlorides.

Table 1
Testing conditions

Mixed-in chlorides (by mass of cement)	Specimen	Chloride ponding	Anodic current density (mA/m^2)	
			1–3 months	4–24 months
3% in the overlay	1	no	10	10 (50)[a]
	2	no	50	50
	3	no	100	20[b]
None	4	yes	10	10
	5	yes	50	20[c]
	6	yes	100	20[b]
2% in the concrete	7	no	100	20[b]
	8	yes	100	20[b]
	9	yes	50	10[b]

[a] After 15 months, the current density was increased to 50 mA/m^2.

[b] The overlay was damaged during the first 3 months of testing, and the primary anode was substituted with a patch repair.

[c] Specimen 5 was replaced with a new specimen instead of being repaired.

CP was energized about 3 months after casting. Constant currents in the range between 10 and 100 mA/m^2 referred to the concrete surface covered by the anode were applied for a total of 24 months, divided in two periods (Table 1). The feeding voltage was monitored. The potentials of the steel and the anode were measured versus the fixed activated titanium electrode embedded in each specimen.

Ohmic drop-free measurements were carried out 1 ms after switching the current off during depolarisation tests. The 4-h decay of steel potential was also calculated during these tests.

The current distribution through the bars of each specimen was occasionally measured. Ohmic drop along the anode was also measured as a function of the distance from the primary anode by using two saturated calomel reference electrodes (SCE) placed on surface of the conductive mortar.

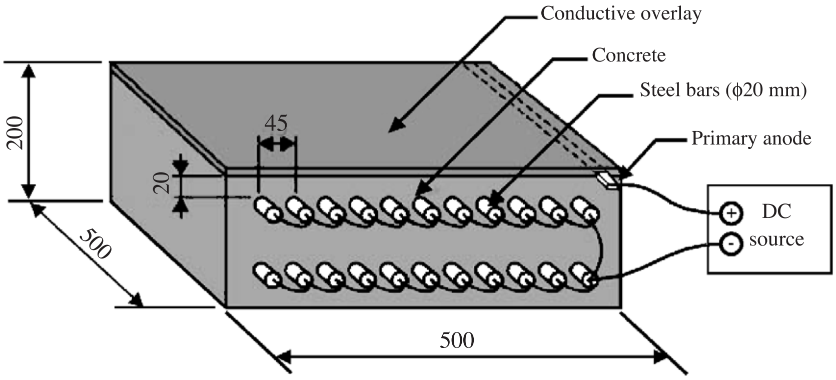

Fig. 1. Reinforced concrete specimens used for CP tests (dimensions are in mm).

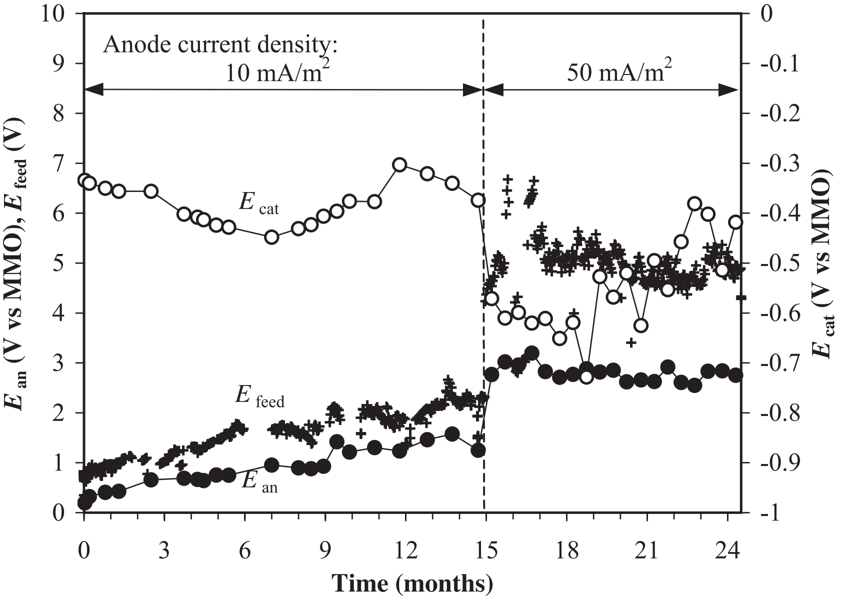

Fig. 2. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 1, containing 3% chlorides by mass of cement in the conductive mortar.

After the damage of the anode that occurred on the specimens energized at high current densities during the first 3 months of testing, the conductive overlay was repaired. The conductive mortar was removed and replaced for about 50 mm around the primary anode. A lower current density was then applied to these specimens (Table 1). The damaged anodes were analysed by scanning electron microscope (SEM) in order to investigate on the causes of deterioration.

The anodic behaviour of the conductive mortar was also studied with galvanostatic tests on small specimens immersed in saturated solutions of $Ca(OH)_2$ both without chlorides and with 1% NaCl. Cylindrical specimens, 35 mm in diameter and 30 mm in height, were cast with the conductive mortar. A primary anode, made of a 1.5-mm wire of titanium or activated titanium, was embedded in axial position. The upper and lower surfaces of the cylinders were then masked with epoxy resin. For these specimens, the surface ratio of the overlay and the primary anode was 20. Current densities ranging from 10 to 100 mA/m^2, referred to the surface of the specimen in contact with the testing solution, were applied. Feeding voltage and anode potential were monitored; the

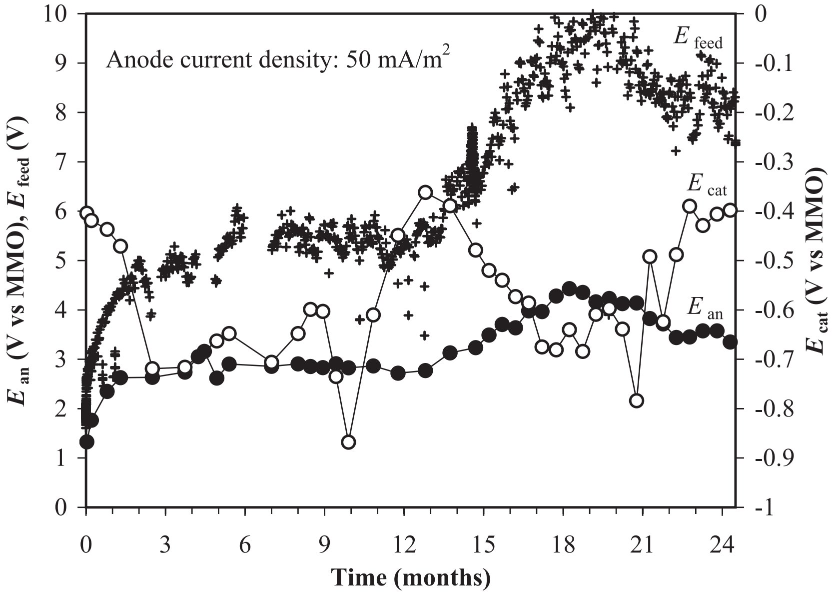

Fig. 3. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 2, containing 3% chlorides by mass of cement in the conductive mortar.

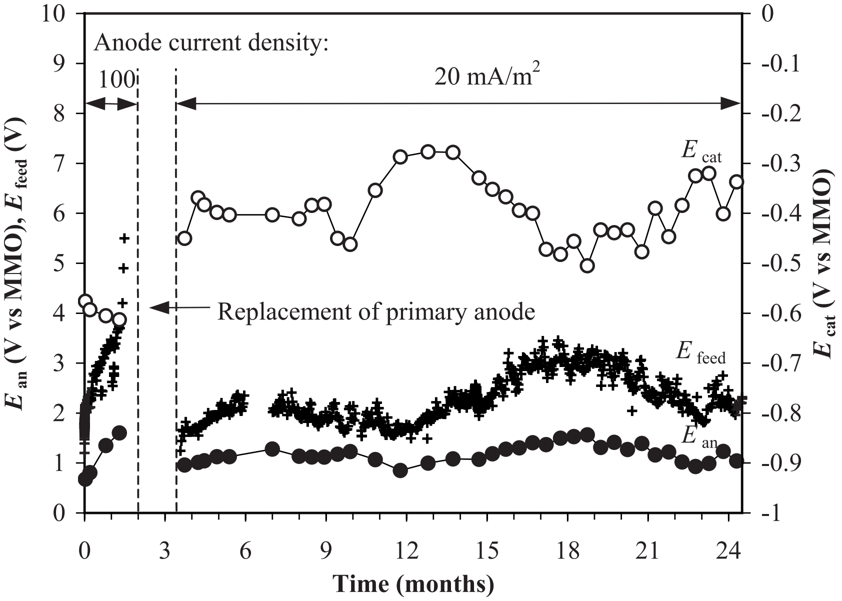

Fig. 4. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 3, containing 3% chlorides by mass of cement in the conductive mortar.

current was periodically interrupted to measure the ohmic drop contributions.

3. Results

3.1. Reinforced concrete specimens

Figs. 2–10 show the results of potential measurements. The figures plot the feeding voltage (E_{feed}), the anode potential (E_{an}), and the steel potential (E_{cat}) as a function of time. The results of the depolarization tests are summarised in Figs. 11 and 12. The ohmic drop contribution in the anode potential (Fig. 11) was estimated as the instantaneous change in the potential of the anode measured by the reference electrode placed on the central upper bar when the current was switched off. This potential change includes ohmic drop through the concrete cover and within the conductive mortar. The 4-h decay (Fig. 12) is the difference between the potential of the

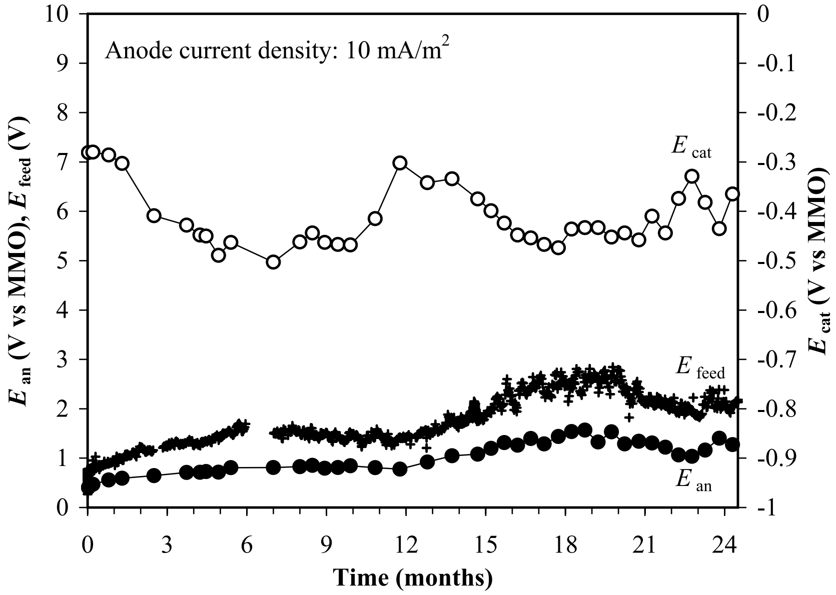

Fig. 5. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 4, subjected to ponding by chloride solution.

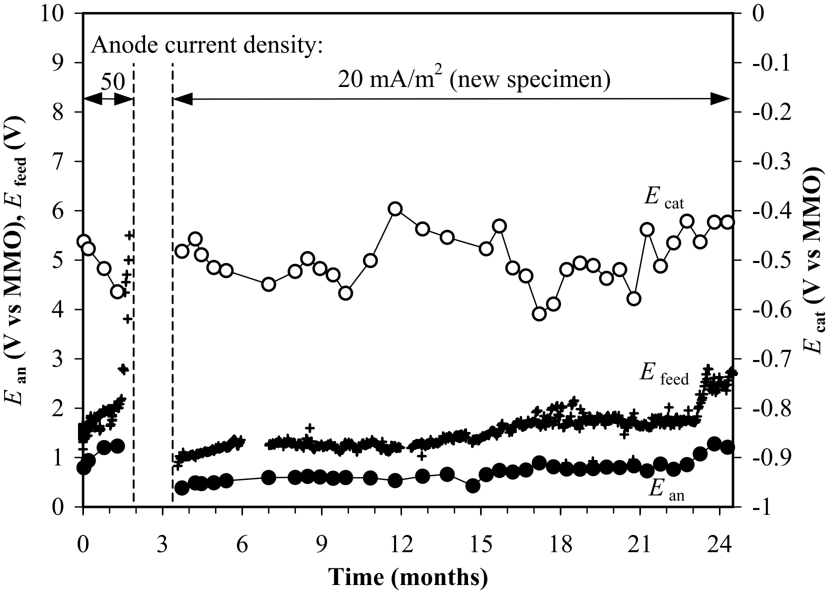

Fig. 6. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 5, subjected to ponding by chloride solution.

steel (cathode) measured after 4 h of interruption of the current and the instant-off potential.

Specimens subjected to anode current density of 10 mA/m^2 showed feeding voltages only slightly higher than 2 V (Figs. 2 and 5). Anode current densities of 50 and 100 mA/m^2 led to an increase with time of the feeding voltage to values more than 5 V. This occurred in the first month of application of CP in the specimens that were not subjected to chloride ponding (Figs. 3, 4, and 8). Specimens with chloride ponding initially showed feeding voltage values of 2–3 V. After about 2 months, when the ponding solution was removed, a sharp increase in the feeding voltage was observed and values higher than 5 V were soon reached (Figs. 6, 7, 9, and 10). When the feeding voltage increased, an increase both in the anode potential (instant-off values in Figs. 2–10) and in the ohmic drop at the anode (Fig. 11) also occurred.

The lowering of the steel potential (i.e., the cathodic polarization) increased as the anode current output increased. However, the potential of the polarized steel (E_{cat}) was rather constant. Only the typical seasonal variations were observed, showing lower potential values in wintertime and higher values in summertime. The 4-h decay (Fig. 12) during the first 3 months of testing was higher than 100 mV for all the specimens.

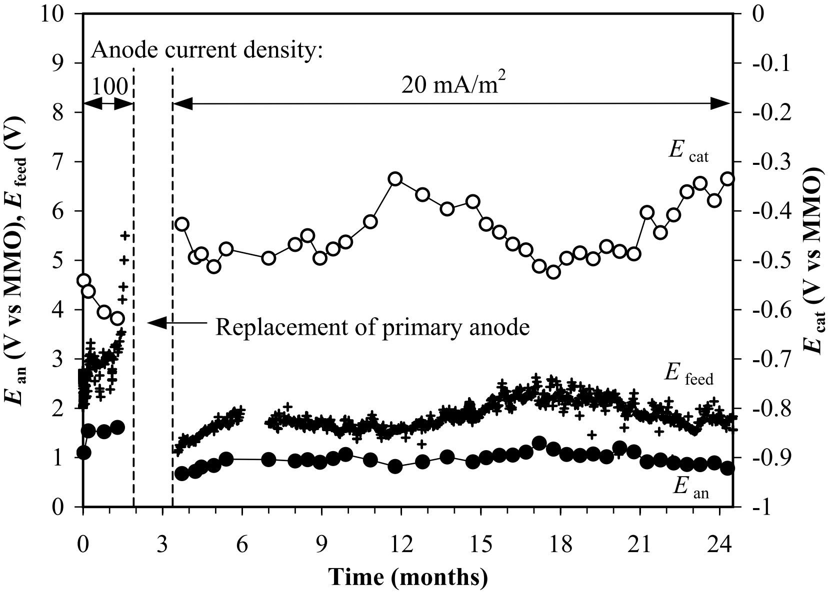

Fig. 7. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 6, subjected to ponding by chloride solution.

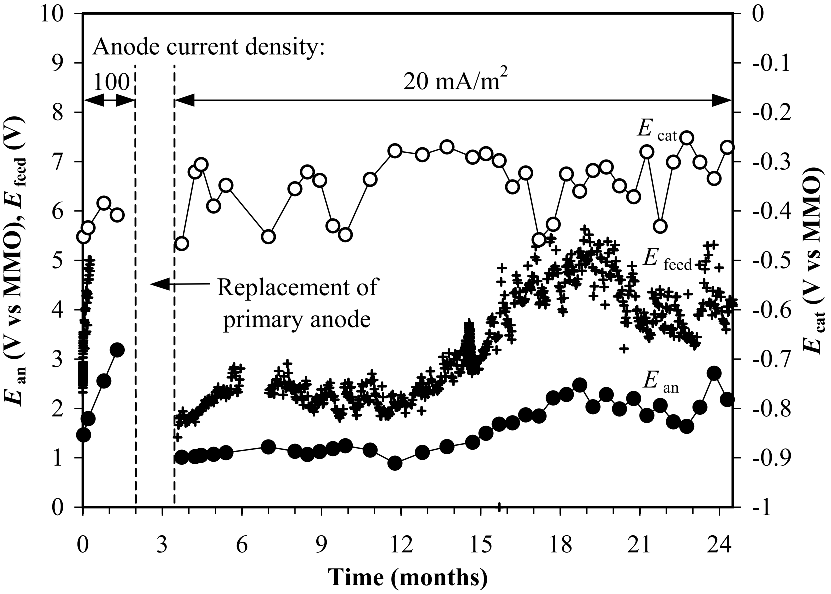

Fig. 8. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 7, with 2% chlorides by mass of cement in the concrete.

Tests on specimens subjected to anodic current densities of 50 or 100 mA/m^2 were interrupted after 2–3 months. A macroscopic deterioration of the conductive overlay was observed in the vicinity of the primary anode. The activated titanium strip that was used as primary anode was removed and substituted. Also, the conductive mortar around the primary anode was replaced. Samples of the damaged overlay were sprayed with phenolphthalein in order to investigate on the causes of the deterioration. Acidification was detected in the conductive overlay in the close vicinity of the primary anode. In these zones, the cement paste matrix appeared to be deeply attacked (Fig. 13). Even where the cement matrix was still present, chemical analyses with an EDS probe showed a remarkable decrease in the content of Ca, Al, and K compared with the cement matrix far from this interface. The content of Si was not affected, while a significant amount of Ni was observed in the damaged zone. Indeed, many fibres showed the almost complete dissolution of the nickel coating (Fig. 14), which was initially present on their surface (Fig. 15). SEM and EDS observations on samples collected from specimens that had been subjected to current densities of 10 mA/m^2 did not show any significant damage.

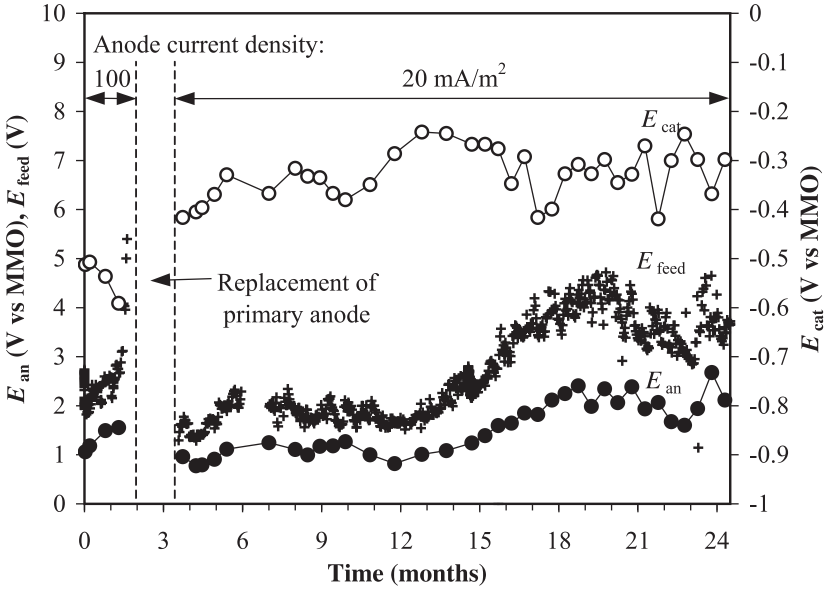

Fig. 9. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 8, with 2% chlorides by mass of cement in the concrete and subjected to ponding by chloride solution.

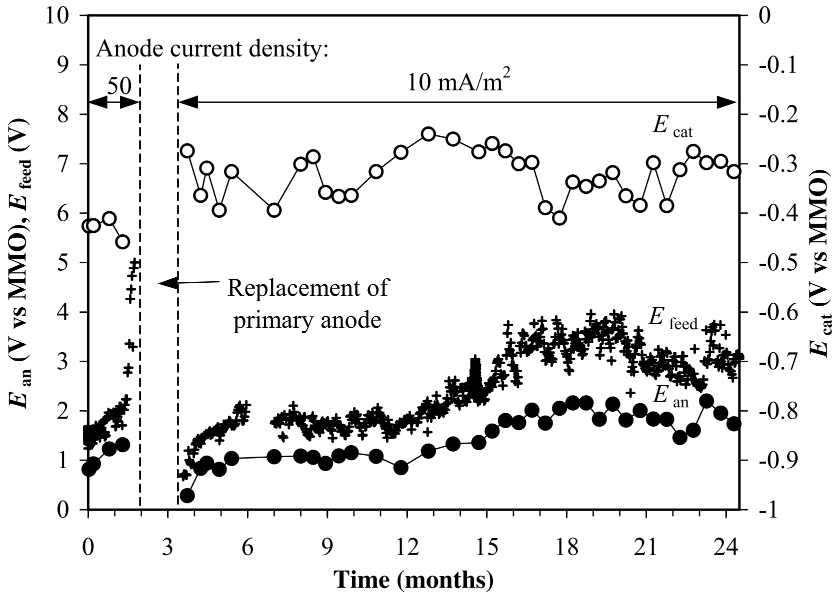

Fig. 10. Feeding voltage (E_{feed}, +) and instant-off values of the potentials of anode (E_{an}, ●) and steel (E_{cat}, ○) in Specimen 9, with 2% chlorides by mass of cement in the concrete and subjected to ponding by chloride solution.

In specimens where the primary anode was replaced, the current densities were reduced to 20 or 10 mA/m^2. However, these specimens still showed feeding voltages slightly higher compared with the specimens where the same value of current density was applied since the beginning of the tests. The ohmic drop contribution in the measurements of the anode potential was initially lower than 1 V; it approached values of 2 V in wintertime during the second year of tests (Fig. 11). The current supplied by the anode was high enough to bring about a 4-h decay higher than 100 mV in the passive steel in chloride-free concrete. It led to lower decays in the corroding bars of Specimens 7–9, where concrete was contaminated with 2% of chloride by mass of cement (Fig. 12).

3.2. Tests in alkaline solution

Fig. 16 shows the potential measurements on small specimens of conductive mortar with primary anodes of activated titanium or titanium, which were immersed in saturated $Ca(OH)_2$ solutions and were subjected to current densities of 10–100 mA/m^2. Specimens that supplied a current density of 10 mA/m^2 maintained potential values

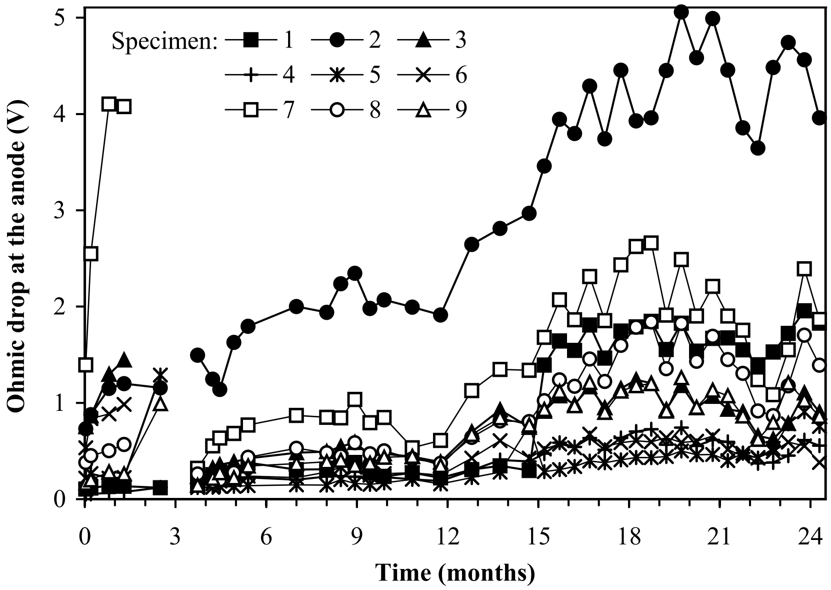

Fig. 11. Ohmic drop at the anode in the different specimens as a function of time.

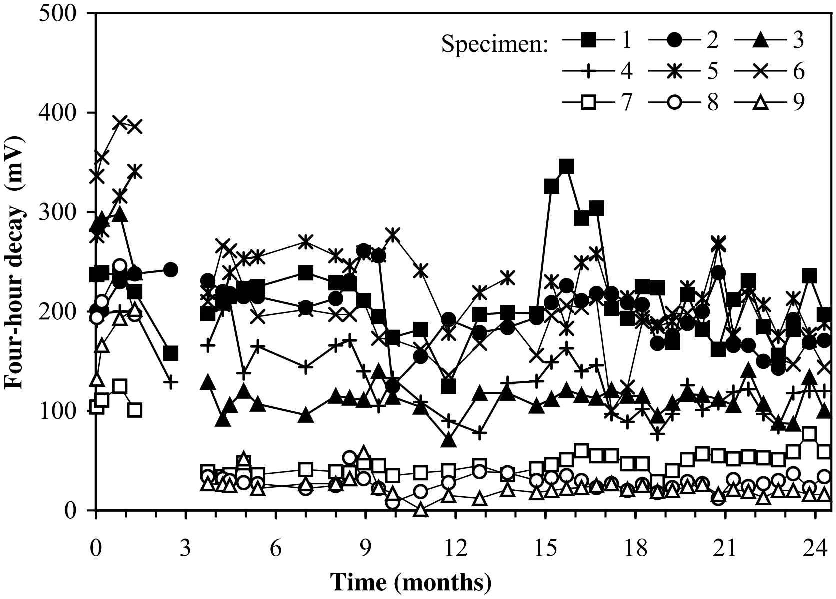

Fig. 12. Four-hour decay measured on the steel bars as a function of time.

lower than 1 V for more than 3 months. In specimens subjected to current density values of 50 and 100 mA/m^2, a sharp increase in the potential was observed after 20–30 days of tests. This increase was essentially due to the increase in the ohmic drop contributions in the anode potential (Fig. 17). No significant differences were observed in specimens with different types of primary anode. The increase in potential was delayed in the tests in solutions with NaCl, especially during tests with the current density of 100 mA/m^2 (Fig. 16).

4. Discussion

Fig. 18a depicts the mechanism by which the conductive overlay anode is expected to supply the protection current to the steel reinforcement. The current generated by the DC source flows through the primary anode and the conductive fibres. This is an electronic current (i.e., it is carried by electrons), and the flow is allowed by the contact of the nickel-coated carbon fibres dispersed in the cement matrix and the primary anode. The anodic reaction (e.g., $4OH^- \rightarrow 2H_2O + O_2 + 4e$) that transforms the electronic current into the ion current that flows through the concrete takes place on the surface of the fibres and thus is distributed on the surface of the cementitious anode. This current then flows through the concrete cover and reaches the steel bars where the cathodic reaction takes place.

The flow of the (electronic) current through the conductive mortar generates an ohmic drop along the anode that increases as the distance x from the primary anode increases. This ohmic drop was measured as the potential difference ΔV between two reference electrodes placed on the surface of the conductive overlay, as shown in Fig. 18a. If the content of conductive fibres is high enough to guarantee a three-dimensional network, the electrical resistivity of the

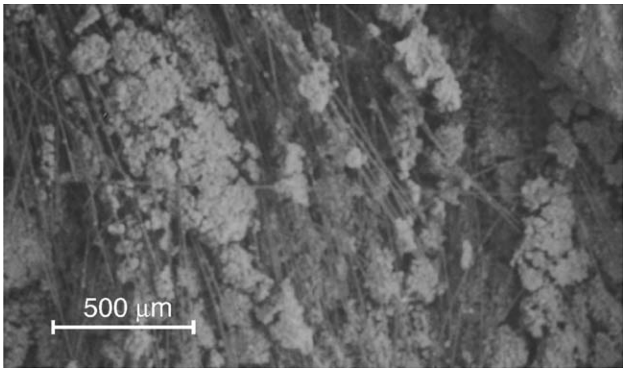

Fig. 13. SEM analysis on damaged areas of the conductive mortar surrounding the primary anode (Specimen 8).

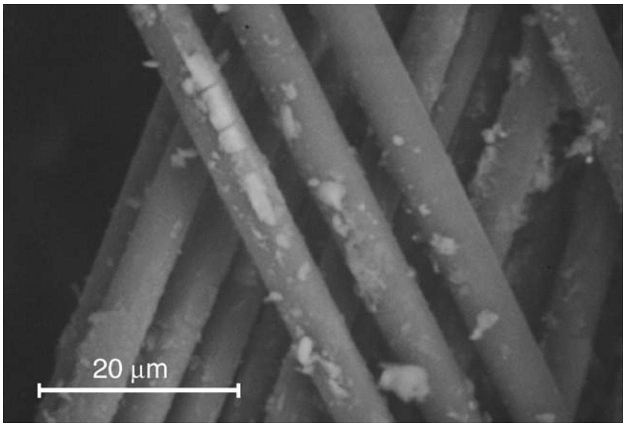

Fig. 14. Detail of a group of fibres of Fig. 13 showing the dissolution of the nickel coating (which was also confirmed by EDS analysis).

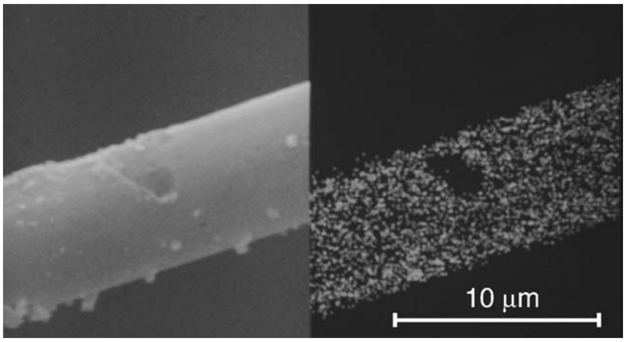

Fig. 15. SEM and EDS analysis of the element Ni of a fibre of Specimen 4 showing the surface coating of nickel.

mortar is low and ΔV should be negligible for the usual distances between primary anodes (about 1–2 m). As a consequence, the current distribution should be uniform and the steel bars farther from the primary anode should benefit of the protection current similarly as those close to it.

Fig. 19 shows, as an example, the current distribution measured on specimen 4 after 2 months of testing. A current density of 10 mA/m^2, referred to the surface of concrete covered by the anode, was applied to this specimen. The average current density referred to the surface of the steel was 3.6 mA/m^2. The actual current density picked up by the bars ranged from 6 to 8 mA/m^2 in the upper bars near the primary anode to 1.5–3 mA/m^2. ΔV was about 100 mV within a distance of 10 cm from the primary anode. The higher current picked up by the bars nearest to the primary anode and the potential drop measured in this region of the anode show that part of the protection current was fed directly by the primary anode. This means that a significant fraction of the anodic reaction took place on the activated titanium strip. Nevertheless, a reasonable current distribution could be obtained since the current density on the remote bars was usually at least 50% of the average value. The anode maintained a good behaviour in time, as shown by monitoring data in Fig. 5. Low values of the feeding voltage and the anode potential can be observed. The current supplied by the anode was able to maintain the 4-h decay around 100 mV throughout the testing period (Fig. 12) and thus to guarantee protection of the bars [4]. A good performance of the conductive anode subjected to a current density of 10 mA/m^2 was also observed in Specimen 1 (Fig. 2).

A different behaviour was observed at current densities of 50 and 100 mA/m^2. The feeding voltage quickly reached very high values as well as the anode potential (Figs. 3 Figs. 4 and Figs. 6–10). This can be explained by a local damage of the conductive mortar in the vicinity of the primary anode. Acidity that was generated by the anodic reaction taking place on the primary anode led to the dissolution of both the cement matrix and the nickel coating of the fibres, as shown by Figs. 13 and 14. This brought about the loss of electrical continuity between the primary anode and the conductive fibres. All the anodic reactions were then concentrated on the primary anode, as shown in Fig. 18b. As a consequence, ΔV became very high in the vicinity of the primary anode, while the current distribution on the steel bars became uneven.

For instance, Fig. 20 shows the measurements carried out after 2 months of tests on a specimen with a current density of 100 mA/m^2 on the anode. A potential drop of about 3 V was measured within a few centimetres from the primary anode, showing the presence of a high current density in this area. In the hypothesis that the primary anode supplied all the anodic current, a current density higher than 2 A/m^2 can

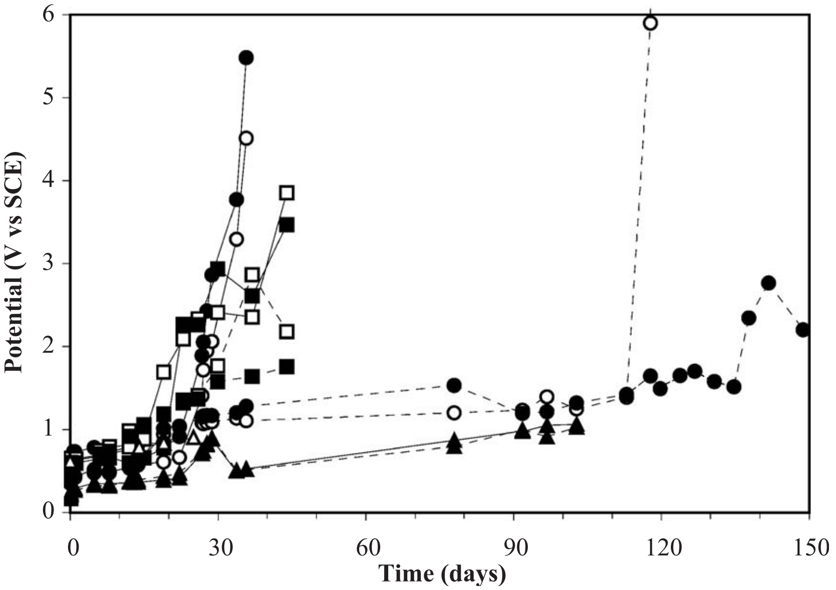

Fig. 16. Anode potential during tests in saturated $Ca(OH)_2$ solutions without chlorides (continuous lines) and with 1% NaCl (dashed lines) on specimens with primary anode made of activated titanium (filled symbols) or titanium (empty symbols) subjected to anodic current densities of Δ (10 mA/m^2), □ (50 mA/m^2), and ○(100 mA/m^2).

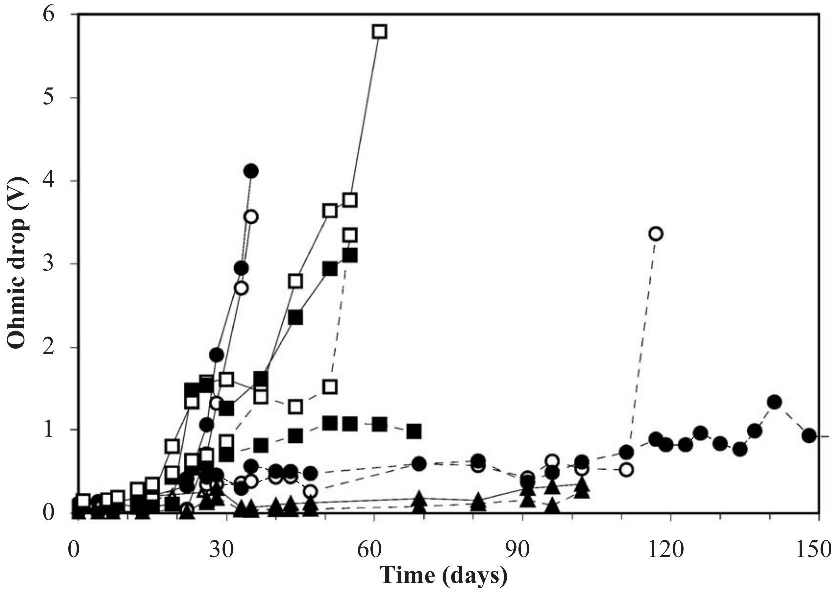

Fig. 17. Ohmic drop in the anodes during tests in saturated $Ca(OH)_2$ solutions without chlorides (continuous lines) and with 1% NaCl (dashed lines) on specimens with primary anode made of activated titanium (filled symbols) or titanium (empty symbols) subjected to anodic current densities of Δ (10 mA/m^2), □ (50 mA/m^2), and ○ (100 mA/m^2).

be calculated on the activated titanium strip. Such a high current density is enough to justify the destruction of the cement paste observed in Fig. 13. In fact, it was shown [8,9] that the acidity produced on the surface of activated titanium that supplies an anodic current density of 2 A/m^2 can lead to pH values of 1.5–2 in the pore solution and thus can damage of the cement hydrates (normally a safe upper limit of 100 mA/m^2 is considered for long term application of activated titanium anodes).

After the damage of the anode, a very uneven current distribution was measured on the reinforcing bars. In the upper layer, the bar immediately below the primary anode was subjected to a cathodic current density of about 300 mA/m^2, while the bars at 40–50 cm had a current density of only 2–3 mA/m^2 (Fig. 20). Low current densities were also measured on the bars of the lower layer [14].

It should be observed that even after being damaged, the anode may function satisfactorily if, due to the exposure conditions of the protected structure, the current can fortuitously find a high conductivity path. For instance, Fig. 21 shows that when a concentrated saline solution was placed above the anode of Specimen 6, the potential drop in the anode became negligible (only a few tens of mV). The current distribution was much more uniform and even the bars distant about 50 cm from the primary anode could pick up a very high current density of 40–50 mA/m^2.

Under dry exposure conditions, the high current density on the primary anode subsequent to its damage increases the feeding voltage due to the increase of the potential drop in the conductive mortar, as well as the anodic polarisation of the primary anode. Thus, the feeding voltage can be assumed as a simple parameter for monitoring the evolution of the damage of the anode. Fig. 7 shows that a sharp increase in the feeding voltage occurred in Specimen 6 during the second month of testing. In a few days, the feeding voltage increased from about 3 V to values higher than 5 V (tests were then stopped since the maximum output of the DC source was reached).

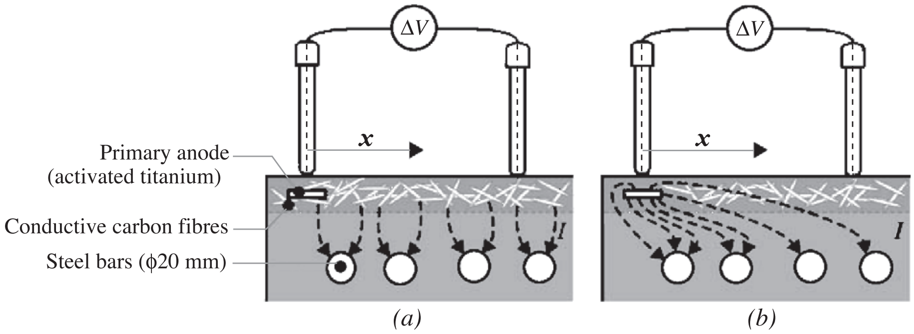

Fig. 18. Schematic representation of the anodic current fed by the conductive mortar overlay (a) and conditions produced after the damage of the interface zone with the primary anode (b).

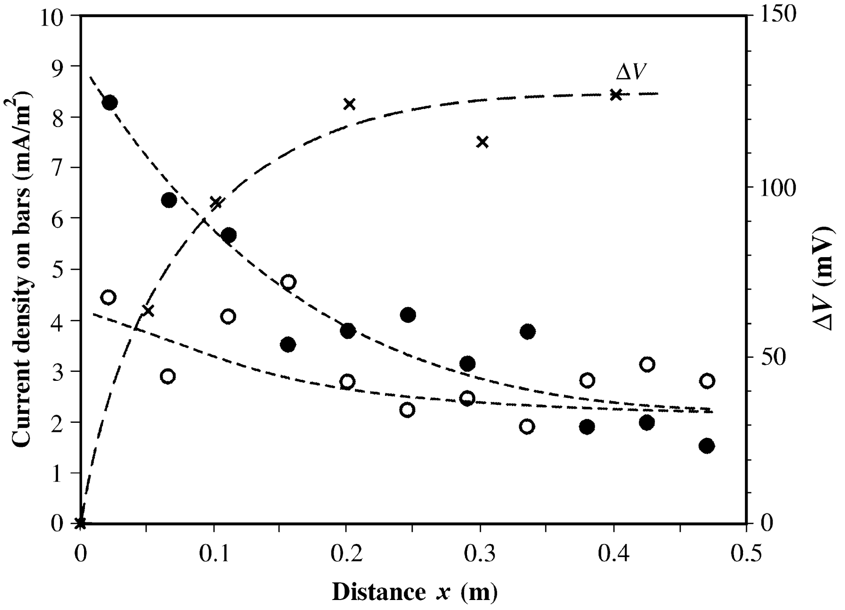

Fig. 19. Current distribution in the upper (●) and lower (○) steel bars and ohmic drop (Δ*V*) in the anode (×) as a function of the distance from the primary anode, measured in Specimen 4 after 2 months of application of 10 mA/m^2 on the anode.

In order to compare the results obtained under different test conditions, Fig. 22 plots the time to reach a feeding voltage of 5 V (conventionally assumed as a measure of the anode damage). All the slabs with an anodic current density of 50 or 100 mA/m^2 showed the increase in the feeding voltage in few months. No significant differences were observed in the slabs subjected to different chloride contamination. Similar results were obtained during the tests in solution showed in Figs. 16 and 17, which confirmed that current densities of 50 mA/m^2 or higher are critical for the cementitious conductive anode. A primary anode of nonactivated titanium was also tested and results were similar to those obtained with activated titanium.

Because the damage of the anode due to excess current output appeared to be localised in the area of the primary anode, it should be possible to repair the structure by simply substituting the primary anode and the surrounding conductive mortar. This was done in all the specimens that during the first months were subjected to high current density. Subsequently, low current densities of 10–20 mA/m^2 were

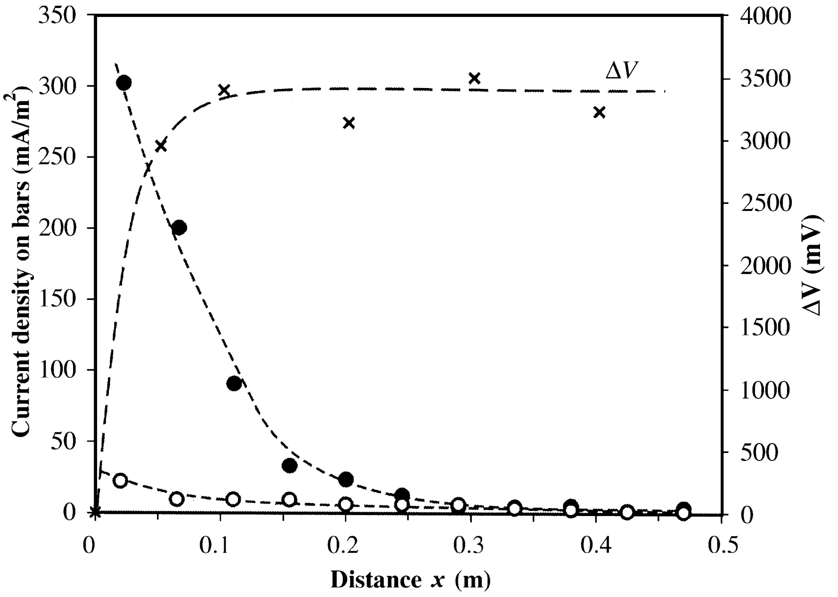

Fig. 20. Current distribution in the upper (●) and lower (○) steel bars and ohmic drop (Δ*V*) in the anode (×) as a function of the distance from the primary anode, measured in Specimen 6 after 2 months of application of 100 mA/m^2 on the anode.

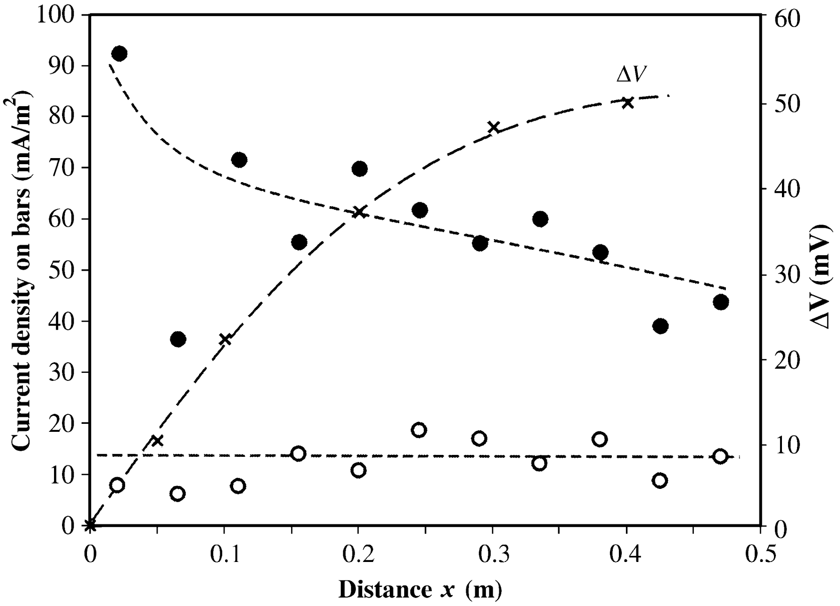

Fig. 21. Current distribution in the upper (●) and lower (○) steel bars and ohmic drop (Δ*V*) in the anode (×) as a function of the distance from the primary anode, measured in Specimen 6 after 3 months of testing in the presence of 5% NaCl solution on the anode.

applied. Although the feeding voltage remained usually in the range of 2–4 V for 20 months, the current distribution on the steel bars was not satisfactory. Fig. 23 shows the current distributions measured in the upper layer of bars after 15 months of testing. To compare tests with different values of current density, the ratio of the cumulate value of the current flowing through the bars placed beyond distance *x* from the primary anode to the total current supplied is shown. The dashed line would represent a theoretical uniform distribution. Only the specimens that were subjected to current density of 10 mA/m^2 since the beginning show current values that approach the uniform distribution. In the other specimens, the repair of the conductive anode and the replacement of the primary anode did not restore the efficiency of the anode. Thus, the current distribution remained uneven in spite of the reduction of the anode current density to values of 10–20 mA/m^2 and the bars placed at more than 20 cm from the primary anode received only a negligible current density.

In order to compare the current distribution found in the tests performed at different current density, a factor α has been introduced. This has been calculated as the ratio of the area below the curve that shows the current distribution in the specimen to the area below the curve that describes the

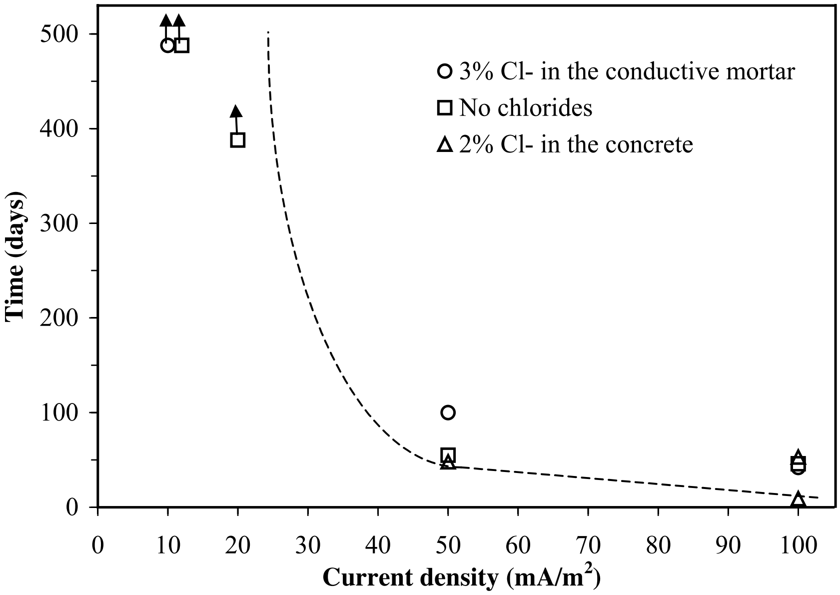

Fig. 22. Time to reach a feeding voltage higher than 5 V as a function of the anode current density.

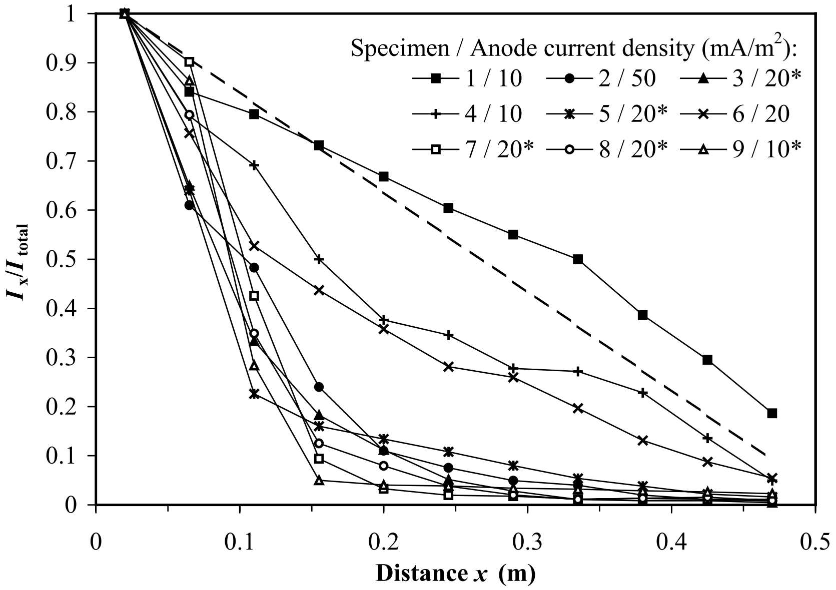

Fig. 23. Current distributions measured in the upper layer of bars after 15 months of testing. I_x is the cumulate current flowing in the bars at a distance from the primary equal or higher than x (* specimens in which the anode had been repaired).

even distribution (dashed line in Fig. 23). The lower the factor α is, the more uneven is the current density; α approaches unit if the current distribution is uniform. Fig. 24 shows the factor α calculated for the different tests as a function of the current density applied to the anode. Results obtained after the repair of the anode are also shown. It can be observed that a value of α of .7–1 could be obtained for current densities of 10 and 20 mA/m², while much lower values were calculated on the specimens with higher current density. Low values of α were also observed in the specimens where the primary anode was replaced. This confirms that the simple substitution of the primary anode and the patch repair of the conductive mortar where it is embedded was not able to repair the damage produced by a prior application of high current density.

5. Conclusions

The results of the tests confirm that a cementitious mortar embedding conductive fibres can be properly used as anode for CP of steel reinforcements in concrete structures. The cementitious conductive coating for CP studied in this work showed a satisfactory behaviour when a current density up

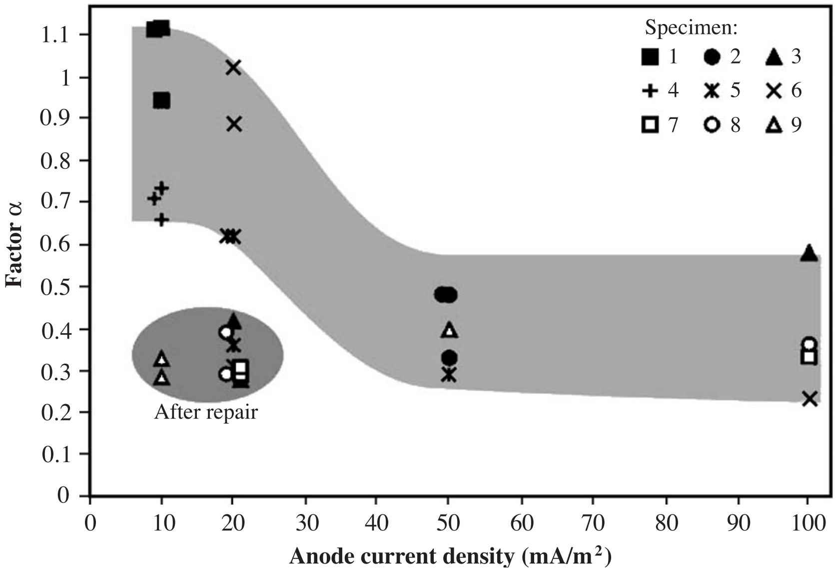

Fig. 24. Factor α measured at different times on the cathodically protected specimens, plotted as a function of the current density applied to the anode.

to 20 mA/m^2 was applied for 2 years. Vice versa, when current densities of 50 or 100 mA/m^2 were applied, the cementitious matrix of the anode was destroyed in the vicinity of the primary anode due to the acidity produced by the anodic reaction after only 1–2 months of functioning.

Based on these results, a maximum current density of 10–15 mA/m^2, referred to the surface of concrete covered by the anode, and a distance of 1 m between primary anodes can be suggested for a safe design.

Substitution of the primary anode and patch repair of the surrounding conductive mortar could not remedy to the damage of the anode induced by high current supply. Repaired anodes could not guarantee a suitable current distribution on the steel bars even for low current densities of 10–20 mA/m^2.

Acknowledgements

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