J Appl Electrochem (2011) 41:829–837
DOI 10.1007/s10800-011-0302-3

ORIGINAL PAPER

Electrochemical repair techniques in carbonated concrete. Part II: cathodic protection

Elena Redaelli · Luca Bertolini

Received: 25 May 2010 / Accepted: 25 March 2011 / Published online: 9 April 2011

Abstract The role of several factors such as concrete composition, exposure condition and pre-corrosion of steel reinforcement in concrete on the effectiveness of the electrochemical realkalisation (*ER*) technique was discussed in Part I of this article (Bertolini and Redaelli in J Appl Electrochem, doi:10.1007/s10800-011-0301-4, 2011). Here the same factors will be considered in the case of cathodic protection (*CP*). *CP* differs from *ER* since it is a permanent technique with much lower applied current density. It was originally introduced to protect steel from corrosion in chloride-contaminated concrete; however, it can be advantageous even in carbonated concrete, in particular compared to conventional repair. *CP* tests were carried out on reinforced specimens made with six different types of concrete, subjected to accelerated carbonation. *CP* was applied with a current density of 10 mA m^{-2} of steel preceded by a start-up current density of 100 mA m^{-2} for 3 weeks. Reference specimens in the same conditions were also considered.

Keywords Corrosion · Concrete · Carbonation · Cathodic protection · Realkalisation · Repair

1 Introduction

As it was introduced in Part I of this article [1], corrosion of reinforcement due to concrete carbonation is one of the most common causes of damage of concrete structures operating in atmospherically exposed environments and it can be stopped, among others, with electrochemical techniques. Compared to conventional repair, which is based on the replacement of carbonated concrete, electrochemical techniques allow to preserve sound concrete, although it is carbonated [2].

After a pioneer work in the 1950s, cathodic protection (*CP*) in concrete was introduced in the 1970s to stop chloride-induced corrosion and it was mainly used on bridges and garages contaminated by de-icing salts or structures and buildings exposed to marine environments [2–4]. Traditionally, *CP* is applied with impressed current and a distributed inert anode, although other anodic configurations are possible and the use of sacrificial anodes is increasing [5–8]. In particular, localised and sacrificial anodes can reduce the invasiveness of the technique and the alteration of the surface, although their durability is usually lower compared to inert systems due to anode consumption and also the distribution of current has to be verified in advance.

CP in carbonated concrete was introduced in the 1990s by Pedeferri [9], who explained that it acts with a mechanism of "continuous realkalisation" which induces steel repassivation. The applied currents involved in *CP* are around 5–10 mA m^{-2} with respect to steel surface. It was also shown that with a high initial current density of 70 mA m^{-2}, repassivation could be reached faster and then maintained in time with a lower current density [10–14]. Carbonated concrete is a less aggressive environment towards steel compared to chloride-bearing concrete; however, carbonation is a widespread phenomenon and all concrete structures and buildings (unless those permanently immersed in water) are facing it to a certain extent. Today *CP* is considered as one of the possible effective options for the repair of structures, buildings and facades suffering carbonation-induced corrosion.

E. Redaelli (✉) · L. Bertolini
Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", via Mancinelli, 7, 20131 Milan, Italy
e-mail: elena.redaelli@polimi.it

Since *CP* relies on the application of a continuous current, the protection from corrosion needs to be properly monitored in time to check the correct functioning of the system. As a matter of facts, the need of a continuous monitoring characterises *CP* and differentiates it from temporary techniques such as electrochemical realkalisation. Although several methods have been proposed in the literature [15–18], monitoring of reinforcement under *CP* is usually based on measurement of absolute potential or potential decay [19], the latter being more reliable since the absolute potential depends on many factors in concrete. Steel potential has to be measured with on–off techniques to avoid ohmic contribution. It is usually assumed that steel under *CP* can be considered protected from corrosion if the potential decay measured after interruption of the current is higher than 100 mV in a period of 4 or 24 h. This is the so-called 100-mV criterion, which is a semi-empirical criterion, but has proved to be reliable in most circumstances, at least for atmospherically exposed structures. It relies on the increase of steel potential following the interruption of current that is expected after steel repassivation, which is not merely connected with the potential decrease due to the applied current, but also with the chemical changes induced by the current at the steel surface, typically the local increase of concrete alkalinity and the migration of chlorides (if present) towards the anode [20–23].

While many publications investigated the effectiveness of *CP* in chloride-contaminated concrete structures, much less investigation has been devoted to *CP* in carbonated concrete. This article tries to clarify the mechanisms involved in *CP* in carbonated concrete presenting the results of an experimental research on the effects of the composition of concrete (in terms of cement type, water/cement ratio and chloride content), the exposure conditions and the presence of corrosion products at the steel–concrete interface before the application of the technique (i.e. pre-corrosion of the steel bar inside the concrete) on the effectiveness of *CP*. Part I of this article dealt with the electrochemical realkalisation technique [1]; this article presents results obtained with *CP*. Following results obtained from previous tests in carbonated concrete [13], *CP* was applied with an initial current density of 100 mA m^{-2} for 3 weeks and then reduced to 10 mA m^{-2}.

2 Experimental

The experimental set-up is the same as described in Part I, regarding the basic geometry of the specimens, the concrete mixes composition, the accelerated carbonation process, the exposure conditions and pre-corrosion of steel reinforcement before the application of the current [1]. The compositions of the six concrete mixes considered are briefly reported here for clarity (for details see Table 1 in Part I). Four concrete mixes (*A*, *B*, *C* and *D*) were made with limestone portland cement (CEM II/A-LL 42.5R) with water/cement ratios of 0.55 and 0.70 and with or without the addition of chloride (0.4% by mass of cement). The other two concrete mixes (*E* and *F*) were made with ground granulated blastfurnace slag cement (CEM III/B), with *w*/*c* ratios of 0.55 and 0.70.

All the specimens were wet cured for a week and then subjected to accelerated carbonation. Carbonation was checked with phenolphthalein tests on sacrificial specimens, non-destructive measurements of internal MMO electrodes and direct phenolphthalein test on thin slices cut from each specimen. After complete carbonation, the specimens were aged for about 1 year before the beginning of *CP* tests. During the ageing period, some specimens were exposed to a wet environment to promote steel corrosion (*pre-corroded* specimens, only made with concrete mixes *C*, *D* and *F*, that having a higher *w*/*c* ratio, were fully carbonated in a relatively short time), while the others were kept in the laboratory environment.

Before the beginning of *CP* tests, a permanent anodic system was applied on the surface of the specimens, consisting of an activated titanium mesh embedded in a layer of mortar with a thickness of approximately 20 mm. The mortar was prepared with 300 kg m^{-3} of CEM II/A-LL 42.5R, 195 kg m^{-3} of water ($w/c = 0.65$), 1938 kg m^{-3} of limestone aggregates with maximum size of 4 mm and addition of a commercial acrylic superplasticiser to obtain a *S5* consistence class (according to EN 206-1 standard). The final geometry of the specimens is shown in Fig. 1. After the application of the anodic system, the specimens were wet cured for a week at 95% RH and 20 °C.

The tests were carried out in two different environments: the “wet” environment at 98% RH and the “dry” environment at 85% RH. Cathodic protection was applied with a current density of 10 mA m^{-2} preceded by an initial start-up current density of 100 mA m^{-2} for 3 weeks

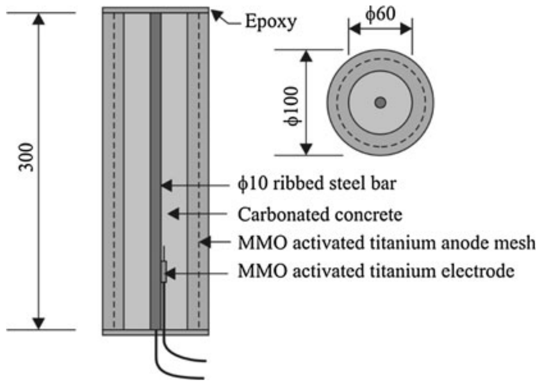

Fig. 1 Geometry of the specimens (mm)

(all current densities are referred to steel surface). All the specimens subjected to *CP* were monitored by means of current and potential measurements. 4-h depolarisation tests were periodically carried out during which the instant-off value of potential ($E_{\mathrm{off},0}$) and the potential after 4 h ($E_{\mathrm{off},4\mathrm{h}}$) were measured. The potential measurements were carried out versus the internal MMO electrode that was calibrated versus an external SCE electrode during the interruption of the applied current. The external SCE electrode was placed on the lateral surface of the specimen, in the vicinity of the internal electrode. The realkalisation thickness around the rebars was evaluated at the end of the start-up period: a layer of the specimen (with a thickness of approximately 30 mm) was cut and the phenolphthalein test was performed.

Also reference specimens were considered, i.e. no current density was applied and they were exposed to the same environments as the others (the anodic system was applied also on the reference specimens to guarantee moisture conditions similar to the other specimens). The reference specimens were exposed to the wet and dry environment immediately after accelerated carbonation. These specimens were used to monitor the free corrosion conditions of the reinforcement by means of potential and linear polarisation resistance measurements of the steel bar, that were carried out as described in [1], except that in this case the MMO mesh inside the mortar was used as counter electrode.

3 Results and discussion

The corrosion conditions of steel in the reference specimens will be considered first. Then the effects of *CP* will be analysed.

3.1 Corrosion conditions in carbonated concrete

The free corrosion tests in reference carbonated specimens were carried out to characterise the propagation of corrosion in the different materials and exposure conditions. Figure 2 compares the average values of the corrosion rate for the different materials and environments, calculated from the values obtained in the last year of tests, i.e. after stable moisture conditions of concrete and corrosion rate of steel were obtained. In all specimens, as expected, a lower corrosion rate was observed in the dry environment with respect to the wet environment: for instance for concrete *A*, made with CEM II/A-LL and *w*/*c* of 0.55, the corrosion rate decreased from 5.7 to 1.3 mA m^{-2} passing from the wet to the dry environment. Comparing different materials in the same environment, it can be seen that in the wet environment high corrosion rates were measured in specimens *B* and *D*, made with CEM II/A-LL and containing 0.4% chlorides by mass of cement, and in specimens *E* and *F*, made with CEM III/B: all these values ranged between 7.8 and 8.7 mA m^{-2}. Concrete mixes *E* and *F* were not added with chlorides; however, analyses showed a chloride content around 0.03% with respect to concrete mass (i.e. about 0.2% by mass of cement). In specimens *A* and *C* the corrosion rate was 5.7–5.8 mA m^{-2} in the wet environment. In the dry environment, only in specimen *A* the corrosion rate of steel was lower than 2 mA m^{-2}, while in specimens *B*, *C* and *F* it was around 2.5 mA m^{-2} and in specimens *D* and *E* it was relatively high, 4.8 and 3.8 mA m^{-2}, respectively.

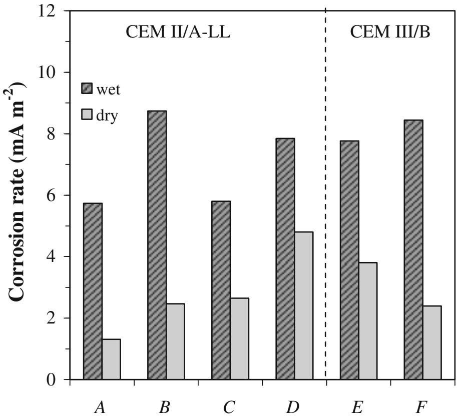

Fig. 2 Average corrosion rate of steel in carbonated concrete in wet and dry environment, for different concrete mixes

The water/cement ratio did not show any systematic effect on the propagation of corrosion in carbonated concrete. The corrosion rate passed from 1.3 to 2.6 mA m^{-2} in chloride-free concrete and from 2.5 to 4.8 mA m^{-2} in concrete with 0.4% chlorides, in dry environment, after increasing the *w*/*c* from a value of 0.55 to a value of 0.70. However, in wet environment, the corrosion rate either remained the same or decreased when *w*/*c* was increased. In specimens made with CEM III/B, the corrosion rate increased in the wet environment and decreased in the dry environment after increasing *w*/*c*.

Figure 3 shows the relationship between corrosion potential and corrosion rate, by plotting each single measure. In spite of the great variability of these data, an approximately linear correlation emerges, regardless of the environment or concrete composition. It can be observed that measurements carried out in wet conditions gave low values of steel potential and high values of corrosion rate, while the opposite applies in the dry environment. This graph confirms the well known correlation between steel potential and corrosion rate due to their dependence on concrete humidity [24].

It should be noted that the free corrosion rates measured on reference specimens (Fig. 2) are lower than those

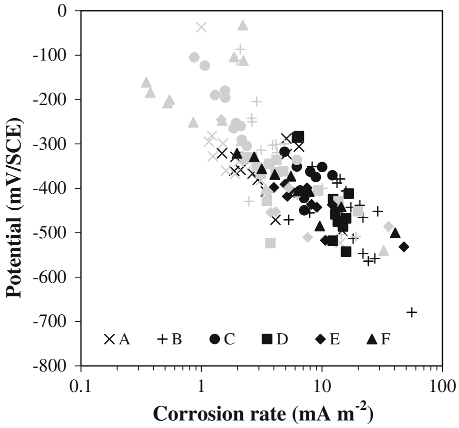

Fig. 3 Values of corrosion potential and corrosion rate of steel bars in the wet (*black symbols*) and dry (*grey symbols*) environments, for different concrete mixes after carbonation

measured in the same concrete mixes on the specimens used for *ER* tests (compare with Fig. 8 in Part I), but the correlation between potential and corrosion rate is the same (Fig. 9 in Part I). The observed difference can therefore be attributed to different moisture conditions, probably due to a barrier effect of the outer layer of mortar embedding the anode mesh.

Corrosion rate values reported in Fig. 3 also show that the propagation of steel corrosion in carbonated concrete may lead to concrete damage in a relatively short time, even in dry conditions. Corrosion rates ranging from few mA m^{-2} to several tens of mA m^{-2} were measured in the wet environment, while in the dry environment they ranged from values lower than 1 mA m^{-2} to values around 10 mA m^{-2}. Values of corrosion rate around 10 mA m^{-2} will lead to propagation times as low as 10–20 years or even less [2].

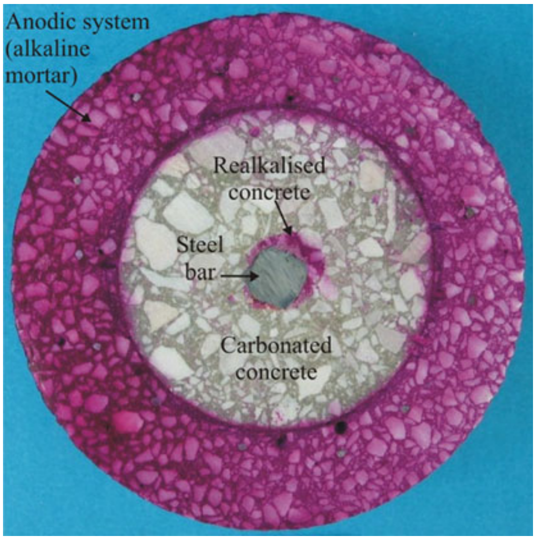

Fig. 4 Phenolphthalein test after the start-up at 100 mA m^{-2} for 3 weeks on the *pre-corroded* specimen made with concrete *C* (CEM II/A-LL and *w/c* 0.7) in the dry environment. The external *dark ring* is the alkaline mortar of the anodic system, while the *dark area* around steel bar is realkalised concrete

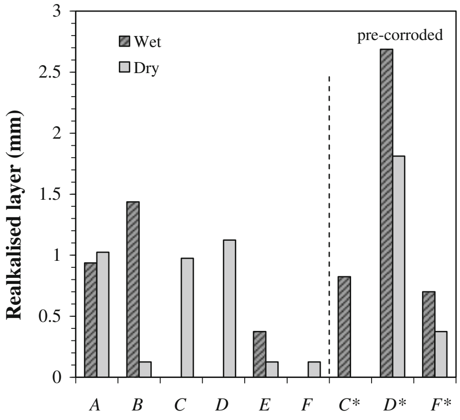

Fig. 5 Average value of thickness of realkalised concrete around steel bar at the end of the start-up period at 100 mA m^{-2} for 3 weeks (circulated charge of 50 A h m^{-2})

3.2 Effects of cathodic protection

The effects of cathodic protection were evaluated on the specimens subjected to the application of a current density of 10 mA m^{-2} with a start-up period of 3 weeks at 100 mA m^{-2}. At the end of the start-up period, when the circulated charge was around 50 A h m^{-2}, the realkalisation of concrete was checked with phenolphthalein test. An example is shown in Fig. 4. A thin layer of alkaline concrete was detected around the steel, while the rest of the specimen was carbonated. Figure 5 reports the average value of the realkalised thickness of concrete that was relatively small, around 0.5–2.5 mm, for all the specimens. In this case, unlike in the case of *ER* treatment [1], there seems to be no correlation between concrete composition and thickness of realkalised concrete. Nevertheless these values, being very small, are characterised by a high uncertainty. It should be noted that a low thickness of realkalised concrete may simply indicate that the amount of alkalinity produced by the current is more localised around the steel, and does not necessarily indicate a lower effectiveness of *CP*.

Afterwards, during the application of 10 mA m^{-2}, concrete realkalisation was monitored indirectly by measuring the potential values of the MMO internal electrode embedded in each specimen close to the rebar, during depolarisation tests. As discussed in Part I, the potential of MMO electrodes depends, among other factors, on the pH of the concrete pore solution with which they are in contact [25]. This has been used, for instance, to detect the realkalisation of initially carbonated concrete due to cathodic protection [13] that brings about a decrease in the potential of MMO electrode of 200–300 mV. Figure 6 shows that in the reference specimens, where concrete was completely carbonated, the potential of MMO electrodes had an average value around 200 mV/SCE in the wet environment (single values ranged from 0 to 400 mV/SCE) and slightly higher, around 250 mV/SCE in the dry environment (single values from 0 to 450 mV/SCE). The potential distribution of MMO electrodes in the specimens subjected to cathodic protection clearly shows a shift towards more negative values, both in wet and dry environment, although the distribution partially overlaps with that of reference specimens. The average values of the distribution are 160 mV/SCE in wet environment and 240 mV/SCE in dry environment, and the minimum values are around −200 mV/SCE (typical of alkaline concrete) in both environments. This indicates that the concrete in contact with the MMO reference electrode (that was placed at few millimetres away from the steel surface) had undergone realkalisation due to the applied cathodic current that produced alkalinity and made it spread around the steel bar. Unlike in the case of *ER*, the thickness of realkalised concrete was approximately the same as the distance of the MMO electrode from the steel surface, and moreover, also initial data were considered in the statistical analysis (the concrete was initially carbonated). This explains the partial overlapping of the distribution curves.

Regarding the electrochemical conditions of steel, the effectiveness of *CP* was assessed by means of the 100-mV decay criterion: it was assumed that a rebar could be considered protected (i.e. repassivated) when its 4-h decay was higher than 100 mV. Figure 7 shows, as an example, the result obtained from 4-h depolarisation tests on specimens made with concrete *A* (CEM II/A-LL and *w*/*c* of 0.55) and concrete *B* (the same with addition of chlorides), both exposed to the wet environment: trends of instant-off values of potential ($E_{\mathrm{off,0}}$), potential after 4 h from switching off the current ($E_{\mathrm{off,4h}}$) and 4-h depolarisation (i.e. $E_{\mathrm{off,4h}}$–$E_{\mathrm{off,0}}$) are shown. In concrete *A* (Fig. 7a), at the end of the start-up period the 4-h decay was around 165 mV, indicating that steel protection was fully achieved during start-up, and then slightly increased in time, indicating a strengthening of protection conditions as a consequence of the continuous cathodic current applied. After about a year of tests the 4-h decay was 250 mV and $E_{\mathrm{off,4h}}$ was around −300 mV/MMO and that for this specimen corresponds to a value of about −360 mV/SCE. In concrete *B* (Fig. 7b) the steel showed 4-h decay values as low as 30 mV after the start-up period, and then a progressive increase, however, even after a year the threshold of 100 mV was not reached. $E_{\mathrm{off,4h}}$ was around −800 mV/MMO, which corresponds to a value of about −600 mV/SCE, considering that the potential of MMO internal electrode was 160 mV/SCE for this specimen. Comparison of Fig. 7a and b suggests that in the presence of chlorides, even in small amount, the protection conditions are more difficult to achieve.

Figure 8 compares the trends of 4-h decay for all the specimens. Also *pre-corroded* specimens, which had been exposed to a wet environment to promote reinforcement corrosion before the application of CP, are shown in Fig. 8 and are indicated with a star on the corresponding concrete (for example, *C** is the specimen made with concrete *C* that has undergone pre-corrosion of steel bar). Considerable differences emerged between different materials and exposure conditions, as well as between *pre-corroded* and non *pre-corroded* specimens. In the wet condition (Fig. 8a) only in specimen *A*, the steel bar showed clear conditions of protection, as it was commented for Fig. 7a. In the other specimens, the steel showed much lower values of 4-h decay, as well as much longer times necessary to reach the threshold value of 100 mV. In particular, the *pre-corroded* specimens (*C** , *D** and *F**) showed 4-h decay values of

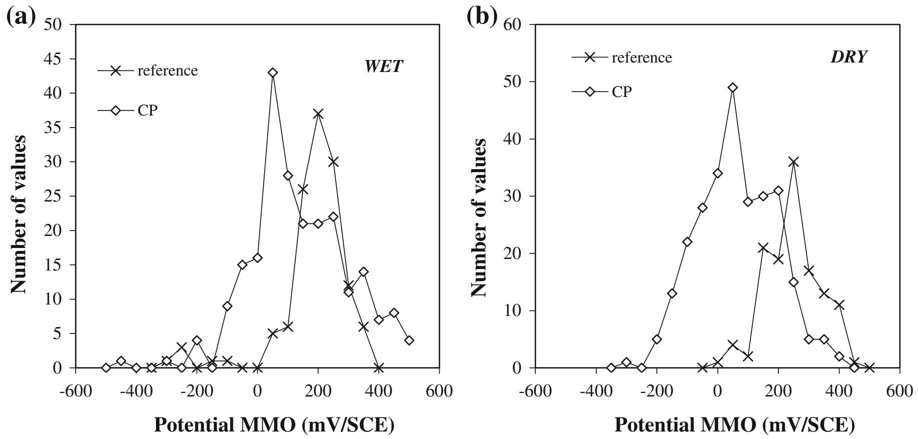

Fig. 6 Frequency distribution of potential of MMO electrodes measured in all the different concretes in wet (**a**) and dry (**b**) environment

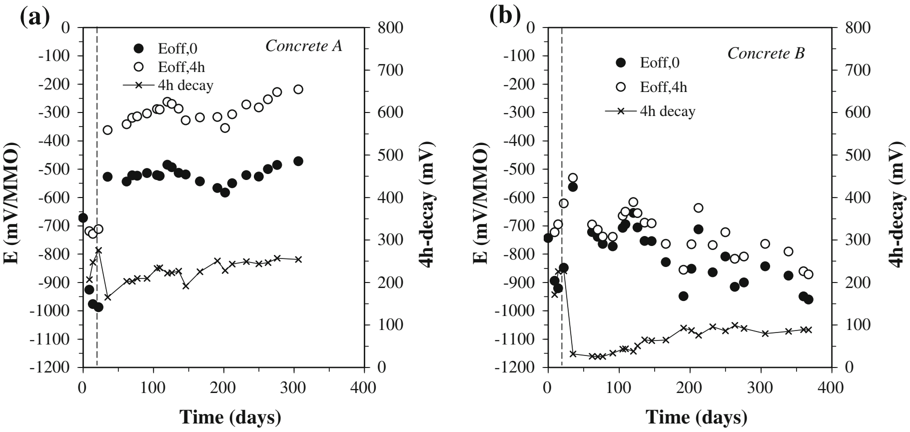

Fig. 7 Example of trend of instant-off value of potential ($E_{\mathrm{off},0}$), potential after 4 h from switching the current off ($E_{\mathrm{off},4\mathrm{h}}$), measured versus MMO internal electrode, and 4-h decay for steel bars in concrete *A* (**a**) and concrete *B* (**b**), in wet environment. The *vertical dotted line* indicates the end of the start-up period at 100 mA m^{-2} and subsequent decrease of the current density to 10 mA m^{-2}

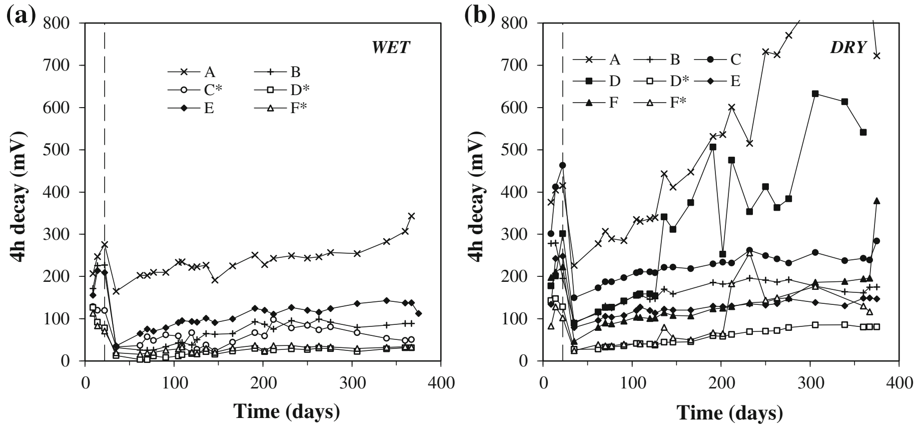

Fig. 8 Four-hour decay of steel bars as a function of time measured in the different concretes in wet (**a**) and dry (**b**) environment (* indicates pre-corrosion of the rebar in the specimen). The *vertical dotted line* indicates the end of the start-up period

only few tens of mV, even after a year. In the dry environment (Fig. 8b) higher values of 4-h decay were measured compared to the wet environment. Again, steel in chloride-free concrete showed the highest values of decay, always higher than 100 mV, although in this case a considerable difference arose between low *w/c* ratio (concrete *A*) and high *w/c* ratio (concrete *C*), compared to free corrosion conditions where the behaviour of specimens *A* and *C* was almost the same.

All the results are summarised in Fig. 9, where for each specimen the values of 4-h decay immediately after the start-up period (35 days) and at the end of tests (1 year) are reported. In all cases, the increase of the 4-h decay in time indicates the progressive benefits achieved by the continuous application of the current. In the wet environment (Fig. 9a), where the corrosion rate of steel in carbonated concrete is high, full protection after the start-up period was achieved only on concrete *A*, which was chloride-free and with low *w/c* ratio. In chloride-bearing concrete (for instance, specimens *B* and *E*) the protection was achieved with more difficulties, i.e. lower values of 4-h decay both after start-up and after a year compared to specimen *A*. The very low values of 4-h decay measured after a year in the *pre-corroded* specimens (*C**, *D** and *F**) indicated that if the rebars had undergone considerable corrosion before the application of cathodic protection, the protection was strongly hindered in spite of the start-up period at 100 mA m^{-2}. In the dry environment (Fig. 9b) conditions of protection or close to protection were reached in most of the specimens at the end of the start-up period (*A*, *B*, *C*, *D* and *E*); in concrete *F* the threshold of 100 mV was reached after about 100 days from the beginning of tests (Fig. 8b). In concrete *D**, where the rebar was *pre-corroded* and chlorides were added to the concrete, the 4-h decay was negligible at the end of the start-up period, then it increased but remained lower than 100 mV during the year of tests while in concrete F^* the protection could be achieved at the end of the tests. A comparison between Figs. 5 and 9 shows that the phenolphthalein test only gives an indication on the alkalinity of concrete, and cannot be directly correlated to the corrosion conditions of steel, in particular in the presence of chlorides. The two *pre-corroded* specimens in dry environment showed values of 4-h decay always higher than in the wet environment, in spite of the presence of chlorides: this suggests that if, together with the application of cathodic protection, also conditions of low water content in the concrete are achieved, this will mitigate the effects of the presence of corrosion products

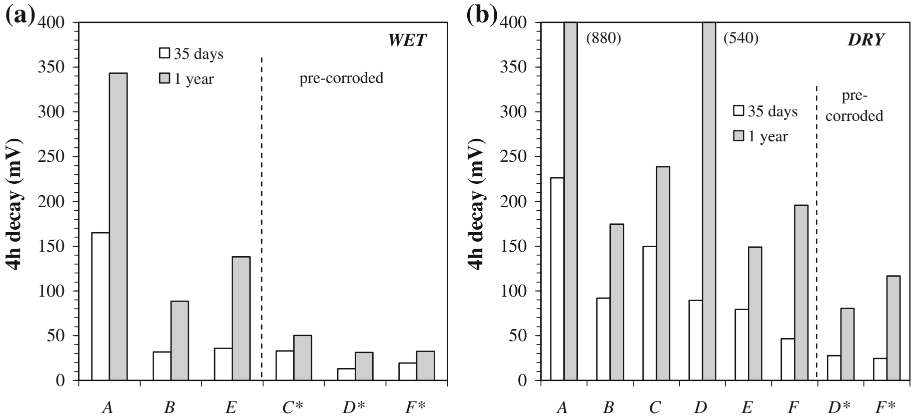

Fig. 9 Four-hour decay with an applied current of 10 mA m^{-2}, measured after 35 days from beginning of tests (i.e. after start-up period) and after 1 year (i.e. at the end of tests), in wet (**a**) and dry (**b**) environment

on the reinforcement surface. However, the dissipation of energy due to ohmic contributions in the concrete, and therefore the feeding voltage, will be higher. Typical values of feeding voltage during the application of 10 mA m^{-2} were 1 V in the wet environment and 2 V in the dry environment (the rest potential difference between anode and cathode in the reference specimens was around 0.5 V); in real cases, if the relative humidity is lower than 85%, a further increase of feeding voltage would be expected.

In practical applications of *CP* with impressed current, a lack of protection indicated by a potential decay lower than 100 mV is usually overcome by a proper increase of the applied current; however, attention should be paid to avoid overprotection of the steel, as well as to avoid unnecessary high values of applied current. To this regard, the steel potential values reached under the different cathodic currents were analysed. It was assumed that potential values could be described with a normal distribution, and the average and standard deviation were calculated from experimental results (since no substantial effect of concrete composition was observed, all the specimens were considered together in the analysis). The results of this analysis are reported in Fig. 10, plotting the potential distributions on a Pourbaix diagram, and assuming that when the applied current was 10 mA m^{-2} the pH of concrete in contact with steel was 13 (this is consistent with results in Fig. 5), while when the applied current was 100 mA m^{-2} the pH was that of carbonated concrete, i.e. around 8 [9]. For comparison, also potential values measured in the reference specimens are reported on the diagram, as well as potential values measured on specimens subjected to *ER* treatment, after the application of the treatment itself [1]. Finally, the shadowed area indicates conditions below the equilibrium potential for the cathodic reaction of hydrogen evolution. It can be seen that in carbonated concrete the steel potential threshold under which hydrogen develops is around −700 mV/SCE. In free corrosion conditions, steel potential is always above this threshold, both in the wet and in the dry environment. During the start-up, when the applied current is 100 mA m^{-2}, as well as during the ER treatment with an applied current of 1 A m^{-2}, potential distribution lies below, indicating that not only reduction of oxygen, but also evolution of hydrogen may take place. In alkaline concrete the threshold for hydrogen evolution is lower, i.e. about −1 V/SCE. Assuming that the pH of realkalised concrete, similarly to that of original alkaline concrete, is around 13, it can be observed that an applied current of 10 mA m^{-2} leads to potential values of the steel always

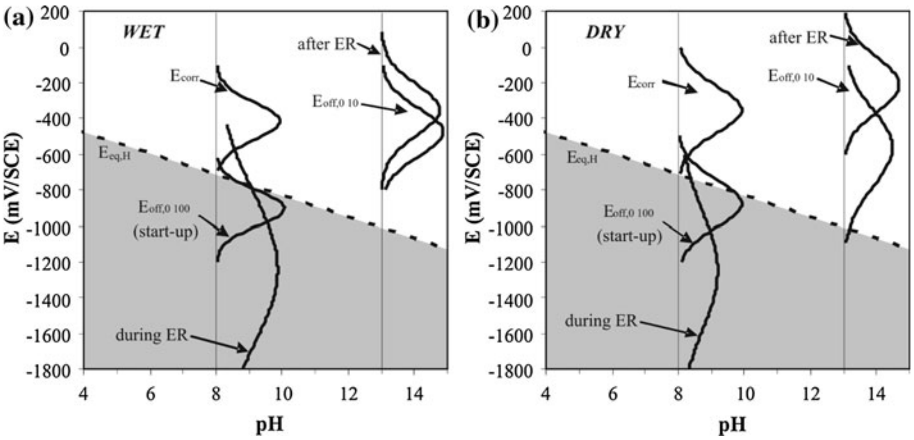

Fig. 10 Normal distribution of steel potential in the reference specimens, during the application of 10 and 100 mA m^{-2}, and after *ER* treatment [1], in wet (**a**) and dry (**b**) environment

higher than this threshold [26]. Of course, also the potential of steel at the end of the *ER* treatment is far above the values that may promote hydrogen evolution.

The results of the previous analysis show that when *CP* is applied in the presence of steel reinforcement that may suffer hydrogen embrittlement, care has to be taken to avoid conditions of overprotection due to a local increase of the cathodic current applied. A current density of 10 mA m^{-2} can be safely applied without risk of hydrogen evolution, while a current density of 100 mA m^{-2} should be avoided, as well as higher current densities as those applied during *ER* treatment (around 1 A m^{-2}). A properly designed cathodic protection system could then be considered also in the presence of prestressing steel, while *ER* treatment is not a feasible solution. Care should be taken in the selection of the start-up current, in order to prevent overprotection conditions. The start-up current could even be avoided and a current density of the order of 10 mA m^{-2} could be applied from the beginning. Although this could delay the time when realkalisation of concrete and repassivation of steel take place, the results show that if this current is applied in the early stage of the corrosion of steel (i.e. when the corrosion of steel has not led to significant amount of corrosion products yet) and in chloride-free concrete, protection of steel may be achieved in relatively short times (i.e. few months [13]). Furthermore, the mechanism of continuous realkalisation provided by *CP*, although localised in a small layer of concrete around the steel bar, is beneficial, since it lowers the potential threshold under which hydrogen evolution can take place, and so, on the long term, it mitigates the risk of hydrogen evolution even if low values of potential were reached during the application of the current.

4 Conclusions

In free corrosion conditions, the corrosion rate of steel was mainly determined by the exposure conditions and the presence of chlorides, even in small amount, while the water/cement ratio did not play any significant role. In the presence of chlorides the corrosion rate of steel was not negligible (average values around 5 mA m^{-2}) even in the dry environment, while in the wet environment it was high for all the concrete mixes considered (average values always higher than 5 mA m^{-2}).

CP tests confirmed the role of local realkalisation of concrete in contact with the steel. Phenolphthalein tests that were carried out on all the specimens at the end of the start-up period showed a layer of few millimetres of alkaline concrete around the rebar. However, the evaluation of the corrosion conditions of steel, carried out with depolarisation tests, indicated that immediately after the start-up period, when the current was reduced to 10 mA m^{-2}, the 4-h decay was above the threshold of 100 mV only on specimens without chlorides (*A* in the wet environment and *A* and *C* in the dry environment).

Afterwards, during the continuous application of 10 mA m^{-2}, the 4-h decay progressively increased for all specimens, however, for *pre-corroded* specimens it was always lower compared to other specimens, in particular in the wet environment where it did not exceed few tens of millivolts even after a year, showing lack of protection. The results obtained on *pre-corroded* specimens show that, although *CP* is a repair technique, and as such is usually applied after corrosion initiation, its effectiveness is influenced by the presence of corrosion products on the steel surface, and therefore, the sooner it is applied, the more effective it will be.

Increasing the applied current, in order to reach more stable conditions of protection or reducing the time necessary to protect the steel, should be carefully considered if hydrogen evolution has to be avoided. To this regard, the analysis of potential values indicated that if concrete in contact with the reinforcement has undergone realkalisation, a current density of 10 mA m^{-2} can be safely applied. This current does not allow hydrogen evolution and is effective in protecting steel even in the wet environment, provided concrete is chloride-free and steel bar is not heavily pre-corroded. Unlike the temporary technique of *ER*, *CP* can be designed to avoid the risk of hydrogen evolution and to obtain a long-term protection to steel in carbonated concrete.

Acknowledgments The authors are thankful to COST (European Cooperation in the Field of Scientific and Technical Research) Action 534 “New Materials and Systems for Prestressed Concrete Structures” for fruitful discussion within the activities of Working Group 4 “Electrochemical Maintenance Methods”.

References

1. Bertolini L, Redaelli E (2011) J Appl Electrochem. doi: 10.1007/s10800-011-0301-4
2. Bertolini L, Elsener B, Pedeferri P et al (2004) Corrosion of steel in concrete. Prevention, diagnosis, repair. Wiley-VCH, Weinheim
3. Broomfield JP (1997) Corrosion of steel in concrete. Understanding, investigation and repair. E & FN Spon, London
4. Lazzari L, Pedeferri P (2006) Cathodic protection. Polipress, Milan
5. Mudd CJ, Mussinelli GL, Tettamanti M et al (1988) Mater Perform 27:18
6. Wyatt BS (1993) Corros Sci 35:1601
7. Polder RB, Peelen WHA, Lollini F et al (2009) Mater Corros 60:130
8. Page CL, Sergi G (2000) J Mater Civ Eng 12:8
9. Pedeferri P (1993) L’Edilizia 10:69 (in Italian)
10. Bertolini L, Bolzoni F, Lazzari L et al (1998) J Appl Electrochem 28:1321
11. Bertolini L, Bolzoni F, Pedeferri P et al (1998) In: Corrosion/98, Nace, Houston (TX), paper 98639

12. Bertolini L, Bolzoni F, Pastore T et al (1997) In: Understanding corrosion mechanism of metals in concrete—a key to improving infrastructure durability, Cambridge, 27–31 July
13. Bertolini L, Pastore T, Pedeferri P et al (2003) Mater Corros 54:163
14. Cigna R, Andrade C, Nürnberger U et al (2003) COST Action 521, Corrosion of steel in reinforced concrete structures, Final report. European Communities, Luxembourg
15. Rizzo FE (1988) Mater Perform 27:17
16. Glass GK, Hassanein AM, Buenfeld NR (1997) Corros Sci 39:1451
17. Bennet J, Broomfield JP (1997) Mater Perform 36:16
18. Glass GK (1999) Corrosion 55:286
19. EN 12696 (2000) Cathodic protection of steel in concrete—part I: atmospherically exposed concrete
20. Glass GK, Chadwick JR (1994) Corros Sci 36:2193
21. Pedeferri P (1996) Constr Build Mater 10:391
22. Glass G, Taylor J, Roberts A et al. (2003) In: Corrosion/03, Nace, Houston (TX), paper 03291
23. Page CL (2007) In: Page CL, Page MM (eds) Durability of concrete and cement composites. Woodhead Publishing Limited, Cambridge
24. Glass GK, Page CL, Short NR (1991) Corros Sci 32:1283
25. Myrdal R (2007) The electrochemistry and characteristics of embeddable reference electrodes for concrete, European Federation of Corrosion Publication no. 43. Woodhead Publishing Limited, Cambridge
26. Polder RB, Alonso MC, Cleland DJ et al (2009) COST Action 534, New materials, systems, methods and concepts for prestressed concrete structures, Final report. COST Office, Brussels