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Cathodic protection and cathodic prevention in concrete: principles and applications*

L. BERTOLINI, F. BOLZONI, P. PEDEFERRI

Dipartimento di Chimica Fisica Applicata, Politecnico di Milano, Milan, Italy

L. LAZZARI

Cescor srl, Milan, Italy

T. PASTORE

Università degli Studi di Bergamo, Italy

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The paper deals with the principles of cathodic protection for atmospherically exposed concrete structures, the various protecting effects induced by the cathodic polarization and tests and field experience results. The differences between the cathodic protection applied for controlling the corrosion rate of chloride contaminated co nstructions and that applied to improve the corrosion resistance of the reinforcement of new structures expected to become contaminated are then underlined and discussed. The more recent applications of cathodic protection on carbonated concrete are also illustrated. The operating conditions (voltage and current applied), the throwing power, the protection conditions which avoid the risk of hydrogen embrittlement in prestressed structures are also discussed. Examples of cathodic protection and of cathodic prevention are also presented.

Keywords: *cathodic protection*, *cathodic prevention*, *concrete*, *throwing power*

1. Introduction

Cathodic protection (CP) of steel reinforcement in atmospherically exposed concrete structures is achieved by means of an anode system usually laid on the concrete surface (Fig. 1). This has proved to be an effective method of stopping or preventing localized pitting corrosion of reinforcement caused by the presence of chloride [1, 2].

The first mention of cathodic protection applied to structures heavily contaminated with chlorides dates back to the late 1950s [3]. The application of the technique to protect bridge decks contaminated by deicing salts began in 1973 in North America [4]. Soon, suitable hardware (anodes, overlays, reference electrodes etc.) had been set up, as well as specific protection and design criteria. In the 1980s, the development of new meshed anodes based, at first, on conductive polymeric materials and then on much more reliable mixed metal oxide activated titanium and the development of carbon containing paints, led to further applications such as bridge decks, slabs, piles, marine constructions, industrial plants and garages.

The technique has also been applied to new structures exposed to chlorides to prevent corrosion. This type of CP was named 'cathodic prevention' [5]. It can be applied to prestressed structures without risk of embrittlement of the high strength steel of tendons. Recently this technique has been proposed in conjunction with conventional patch repair of chloride contaminated structures in order to avoid the initiation of incipient pitting around the repaired zones, by utilizing sacrificial anodes embedded near the periphery of the repair patches [2]. CP also proved to be effective in repassivating steel in carbonated concrete [6, 7]. This type of CP was called 'continuous realkalization' [8], since the continuous application of low currents leads to protection effects similar to those achieved by the technique of electrochemical realkalization.

CP has been applied to more than 600 000 m^2 of corroding reinforced concrete structures in North America, where CP has been installed on more than 500 bridges, in Europe (mainly in UK, Norway and Italy), in Asia (Middle East, Korea and Japan) and Australia. About 150 000 m^2 of new and almost all prestressed concrete structures have been protected in Italy in the early 1990s.

This paper highlights some results achieved in the field of the CP of steel reinforcements embedded in concrete through the research activities and field

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* This paper is dedicated to the memory of Professor Giuseppe Bianchi.

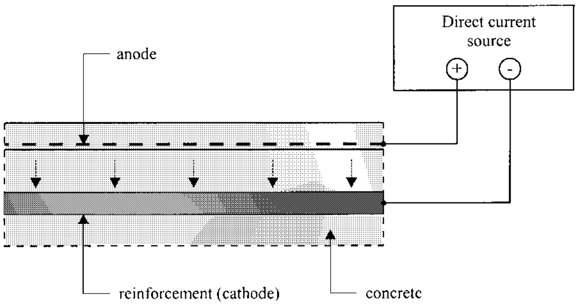

Fig. 1. Schematic representation of the cathodic protection system for concrete structures.

application assistance carried out at the Department of Applied Physical Chemistry of the Politecnico di Milano [9–26]. This paper illustrates only the principles and operating conditions of CP.

Most of the authors' work on CP in concrete, started in the early 1980s, was stimulated by Professor Giuseppe Bianchi. For this reason we dedicate the paper to the memory of the 'patriarca' of Italian corrosion scientists, as Professor Bianchi liked to be called.

2. Behaviour of steel in chloride containing concrete

Steel reinforcements embedded in 'sound' concrete (that is alkaline, with pH usually higher than 13, and chloride free) are in passive conditions. Passivity breaks down when the chloride content on the steel surface exceeds a critical threshold and pitting attack can initiate. Chloride content also affects the range of potentials in which the reinforcing steel is passive. The upper potential of this range, called the pitting potential (E_{pit}), diminishes typically from +500 to −400 mV passing from sound to very heavily chloride contaminated concrete (Fig. 2). The pitting potential is characterized by a great variability, since, beyond the chloride content, it depends on many other parameters such as pH near the steel surface, temperature, cement and type and content and concrete porosity. The highest chloride content compatible with passive conditions for a given potential is the critical chloride content, which decreases with the potential. In correspondence to the usual corrosion potentials observed on a structure exposed to the atmosphere (around 0 V vs SCE) the critical content is in the range 0.4–1% of cement weight.

The conditions for pitting initiation and propagation were pointed out by Pourbaix [27] who, during the 1970s, introduced the concepts of 'imperfect passivity' and 'perfect passivity' intervals. Besides the pitting potential, E_{pit}, he defined the repassivation potential or protection potential, E_{pro}, below which the pitting corrosion stops. At potentials in the range from E_{pit} to E_{pro} corrosion will not initiate but can propagate. In Fig. 3 the ranges of values of pitting and protection potentials (E_{pit} and E_{pro}) measured on steel immersed in $Ca(OH)_2$ saturated solution with different chloride contents, or buried in sand soaked by the same solution, are reported. E_{pro} remains about 300 mV lower than E_{pit} in all cases.

The different domains of potentials and chloride contents are plotted in Fig. 4. The extension of these domains depends on pH, temperature and other parameters mentioned above. The domain A (corrosion zone) indicates the conditions which cause initiation and stable propagation of pits; the domain B ('imperfect' passivity zone) the conditions which do not allow the initiation of new pits but the propagation of preexisting ones; the domain C ('perfect' passivity zone) the conditions which do not allow either the initiation or the propagation of pits; the domain D (immunity and also hydrogen evolution zone) where corrosion cannot take place for thermodynamic reasons and where hydrogen evolution and consequently hydrogen embrittlement of high strength steel can take place.

3. Beneficial effects of CP

To achieve the CP of steel reinforcement embedded in chloride contaminated concrete it is not necessary, as

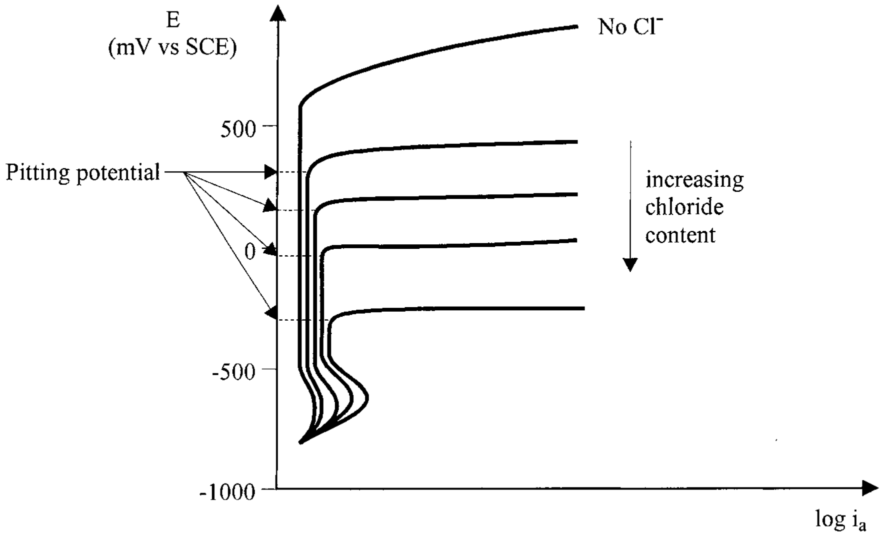

Fig. 2. Schematic illustration of the anodic behaviour of steel in the presence of chlorides.

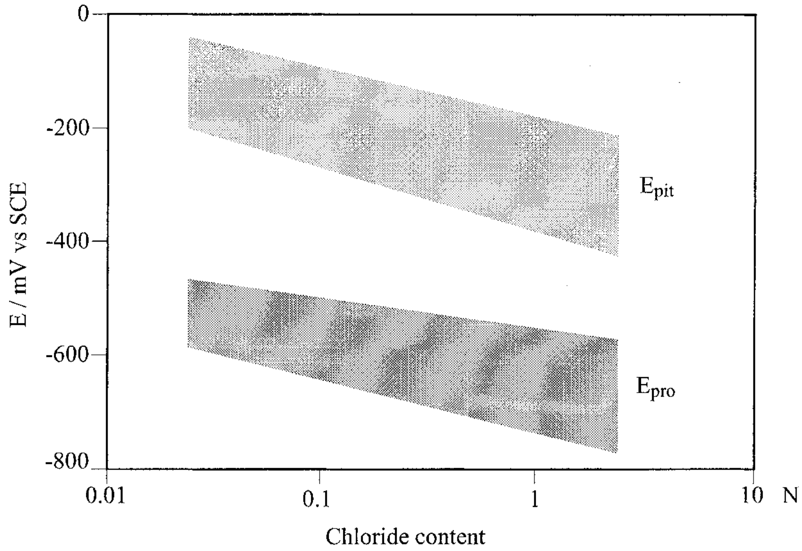

Fig. 3. Ranges of values of pitting and protection potentials (E_{pit} and E_{pro}) measured on steel immersed in a solution of saturated $Ca(OH)_2$ with different chloride content or buried in sand covered by the same solution [19, 30].

some people claim, to establish 'immunity' conditions, that is lowering the potential below the equilibrium potential E_{eq} given by Nernst's law. These immunity conditions are normally required on steel in active condition such as on structures in soil or immersed in sea water, where potentials more negative than −850 mV vs $Cu/CuSO_4$ or than −950 mV in the presence of sulphate reducing bacteria are imposed. Conversely, the target of CP in concrete structures is to reduce the corrosion rate by taking the steel into the passivity range or by reducing the macrocouple activity on its surface, and this can be done with a small reduction in potential and a smaller current.

If the potential is taken into the range from E_{pit} to E_{pro} the initiation of new pits is prevented and the corrosion rate of the existing ones is reduced, the driving voltage of the functioning of active–passive macrocells being decreased. The possibility of achieving protection or negligible corrosion rate at potentials more noble than those for immunity are also connected to a significant increase in the $[OH^-]/[Cl^-]$ ratio on the steel surface produced by the cathodic reactions and by the migration of ionic species inside the concrete. This increase favours the development of passivation and/or the onset of passivity conditions. These beneficial effects do not cease if the current is interrupted but can last for months and, under some situations, give rise to the possibility of intermittent application of CP, as well as the application of initial prepolarization at high currents in order to achieve passivity or a more persistent protection condition [2].

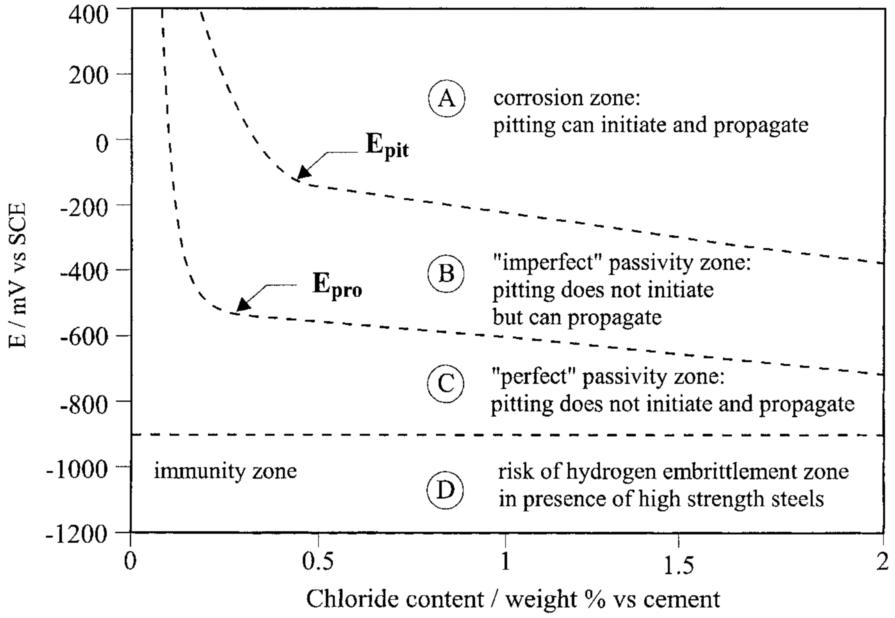

Fig. 4. Schematic illustration of steel behaviour in concrete as a function of the chloride content [6].

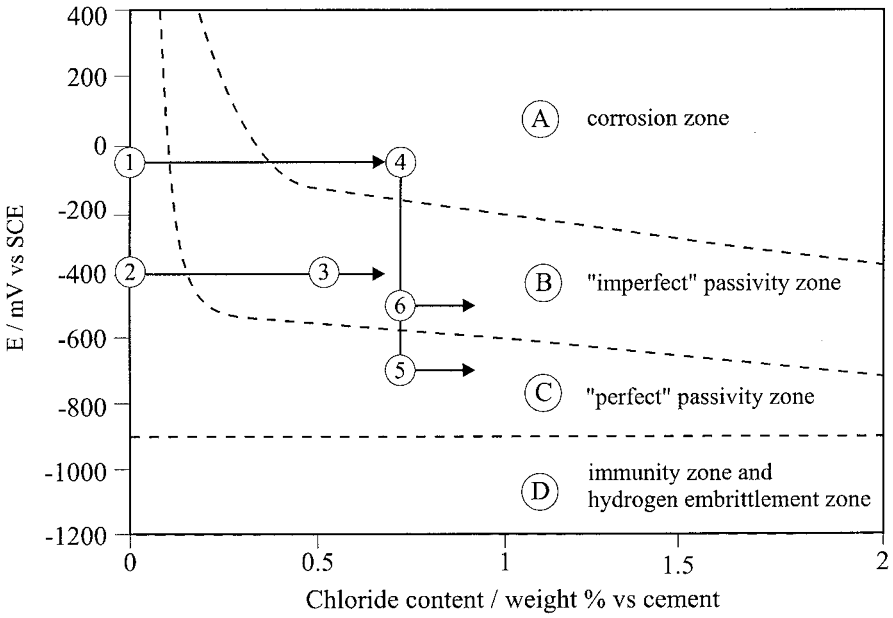

Fig. 5. Schematic illustration of steel behaviour in concrete for different potentials and chloride contents. Evolution paths of potential and chloride content on the rebar surface of an aerial construction during its service life for: cathodic prevention (①→②→③→); CP restoring passivity (④→⑤→); CP reducing corrosion rate (④→⑥→). Cathodic prevention is applied from the beginning, CP only after corrosion has initiated [6].

4. Cathodic protection

To follow the variation in the potential of steel reinforcement of a concrete structure damaged by chlorides and then protected by a CP system it is helpful to refer to the map of Fig. 5. The initial condition is represented by the dot ① where the chloride content is nil and the steel is passive. By increasing the chloride content, the working point shifts to dot ④ within the corrosion region. Corrosion of the steel occurs rapidly by macrocell mechanism. The CP leads to ⑤ so that the passivity is restored or to ⑥ without restoring passivity. In all cases the corrosion rate is reduced.

Initial current densities in the range 5–15 mA m^{-2} are generally needed for protecting constructions exposed to the atmosphere. Much lower current densities are required under conditions which reduce the access of oxygen towards the surface of the steel such as in water saturated concrete. For components operating underwater, the oxygen diffusion limiting current is very low, typically in the range 0.2 to 2 mA m^{-2} of reinforcing steel surface area.

The experience on bridge decks shows that the current required to maintain protection conditions (verified by the so called 4 h 100 mV potential decay empirical criterion[1]) decreases even after months or years from start up. This happens because the cathodic current can bring about repassivation of steel in active zones, by improving the ratio $[OH^-]/[Cl^-]$ which increases E_{pro} and/or also because the reduction of the current exchanged by the macrocell leads to the inhibition of the macrocell itself.

In the cases in which the CP path runs according to ④→⑤→ of Fig. 5, and thus passivity is established on the entire surface of the steel, the current required to maintain passivity is reduced to a few mA m^{-2} (e.g. 2–5 mA m^{-2}). If the CP path runs according to ④→⑥→, the current density to fulfill the protection criterion remains high and does not decrease with time, since passivity is not obtained. For the interpretation of the behaviour in the case of the restoration of passivity, results obtained from a laboratory test carried out on concrete slabs exposed to a ponding with sodium chloride solutions can be considered (Fig. 6) [24, 25]. The instant-off potentials of protected reinforcement, under current densities varying from 4.2 to 16.8 mA m^{-2}, were measured as shown in Fig. 6. From the same test, it should be noted that the polarization of the steel takes place mainly in the first year of CP. A further decrease in potential (of about 100 mV) is recorded in the long run at the highest current densities applied. One hypothesis is that the cathodic functioning increases the water content around the steel, thus reducing the oxygen availability on the rebar.

Another result, shown in Fig. 6, is that higher cathodic polarization occurred during wintertime than in summertime. Feeding voltage also changed during the year. Figure 7 shows that the anode potential is rather constant and the ohmic drop is negligible; hence the cathodic polarization is the main contribution of the increase in the feeding voltage in the cold season.

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[1] The '100 mV decay' criterion, used for verifying the protection conditions in reinforced concrete structures, is based on the measurement of potential decay after switching off the current. The structure is considered protected if the difference between the instant-off potential and the potential measured after 4 h (or 24 h) is higher that 100 mV. This criterion is adopted by NACE Standard [28] and CEN Draft Standard [29].

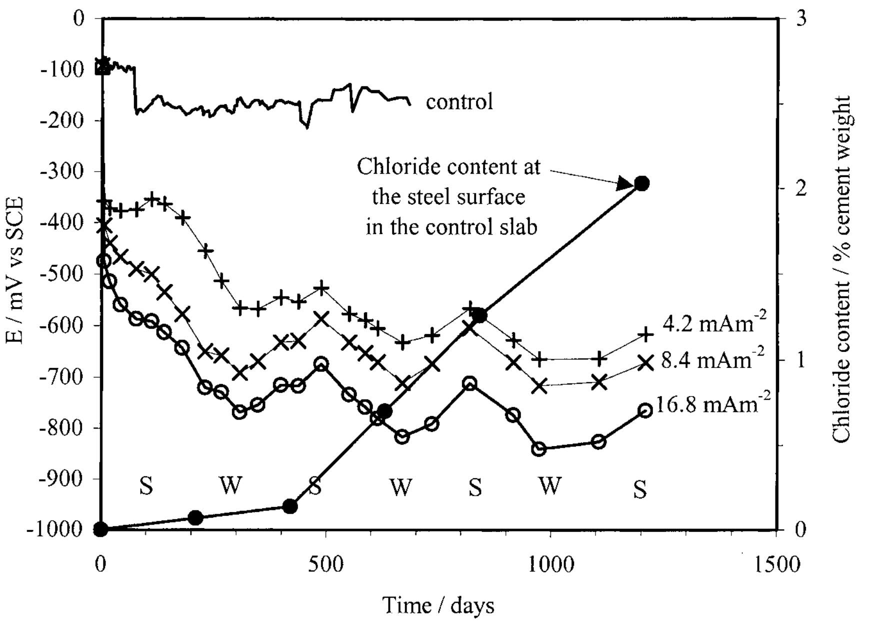

Fig. 6. Instant off potential of noncorroding steel cathodically polarized with different current densities and chloride content in the control slab. Specimens exposed to NaCl alternating ponding (3% NaCl in the first two years and a saturated solution thereafter), consisting of wetting for one week followed by drying for two weeks. Control slab started corroding after about 700 days (S = summer, W = winter) [25].

An important effect is the chloride migration, which opposes the penetration of chloride ions by diffusion. Figure 8 shows the chloride content in the concrete near the rebars during the test on the same slabs illustrated above, as a function of time and current density. A general trend can be observed: by increasing the current density from 0.5 to 20 mA m^{-2} of concrete surface, the chloride content tends to be lower. This effect was much more evident at 28 months when the chloride content was higher and for current densities greater than 10 mA m^{-2}.

4.1. *Example of CP with restoration of passivity*

A CP system was installed in 1987 on 3700 m^2 bridge deck [13] on the Appennine mountains (Italy), after severe chloride induced corrosion occurred. The CP system utilized a titanium activated mesh anode. The start up protection current was 10 mA m^{-2} of concrete surface (i.e., 10 mA m^{-2} of rebars of the first row surface corresponding to about 5 mA m^{-2} of the whole rebar surface) with a feeding voltage between 1.8–2.5 V. The protection condition (checked with 100 mV decay criterion) was achieved after five

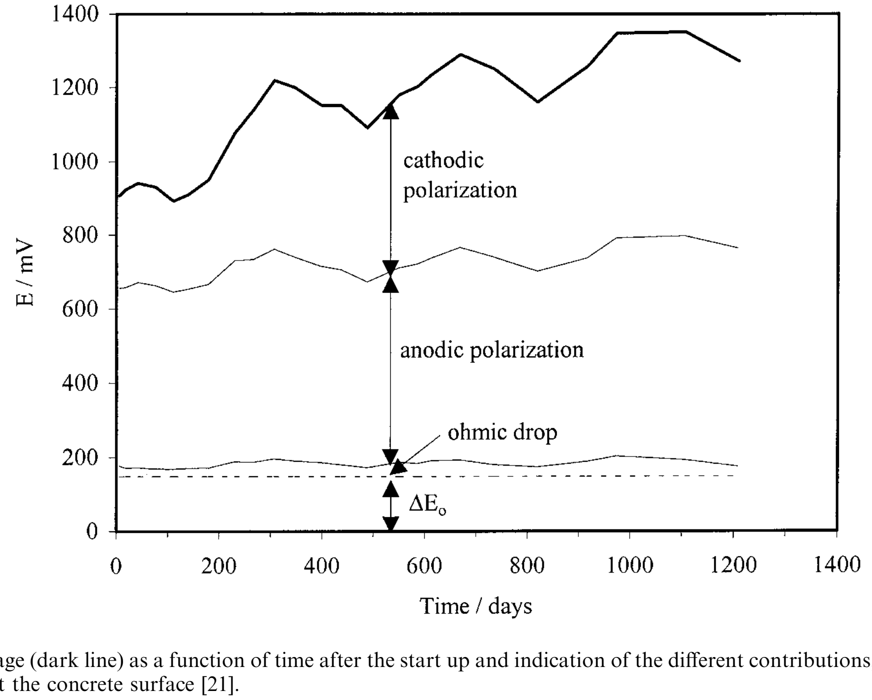

Fig. 7. Feeding voltage (dark line) as a function of time after the start up and indication of the different contributions, in the slab polarized at 10 mA m^{-2} against the concrete surface [21].

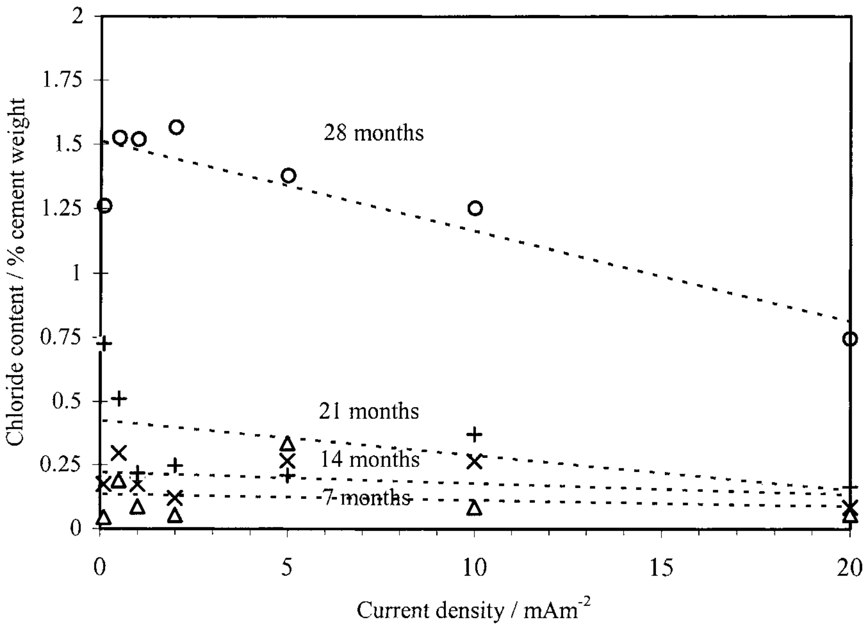

Fig. 8. Total chloride content in the concrete near the steel surface (measured on 7.5 mm thick samples) in the concrete of the reinforced slabs as a function of time (Δ 7, × 14, + 21 and o 24 months) and current density referred to concrete surface [25].

months. In the following year the protection current density decreased by approximately 30–50% due to the passivation of the steel although the subsequent increase in throwing power had also polarized the inner rebar. The current density on rebars of the first row surface was reduced to values typically in the range from 2.5 to 5 mA m^{-2}. Seasonal changes of the feeding voltage have been observed according to external temperature variations (Fig. 9). After more than nine years, the system is working satisfactorily.

4.2. *Example of CP without restoration of passivity*

A viaduct of Turin–Bardonecchia highway in Northen Italy consisting of reinforced concrete slabs supported by five prestressed concrete beams, showed corrosion degradation after five years from commissioning. After the repair of damaged concrete, a CP system was applied, utilizing a conductive overlay anode system [18]. The average current density necessary to maintain the 4 h depolarization higher than 100 mV resulted in 6 mA m^{-2} of concrete surface (i.e., 12 mA m^{-2} on first row rebars surface or about 6 mA m^{-2} on the whole rebar surface). In Fig. 10 instant-off potentials, potentials after 4 h and after 24 h depolarization are reported. The rest potentials after 24 h depolarization, ranging below −350 mV vs SCE, show that CP has not been able, after more than two years, to restore passivity. Accordingly, the current density remained at relatively

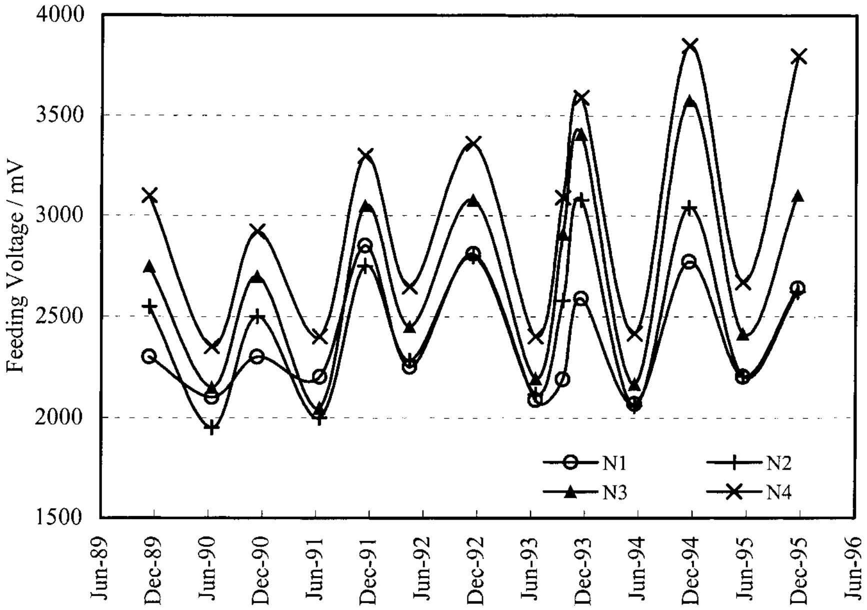

Fig. 9. Feeding voltage variations with time showing the effect of external temperature.

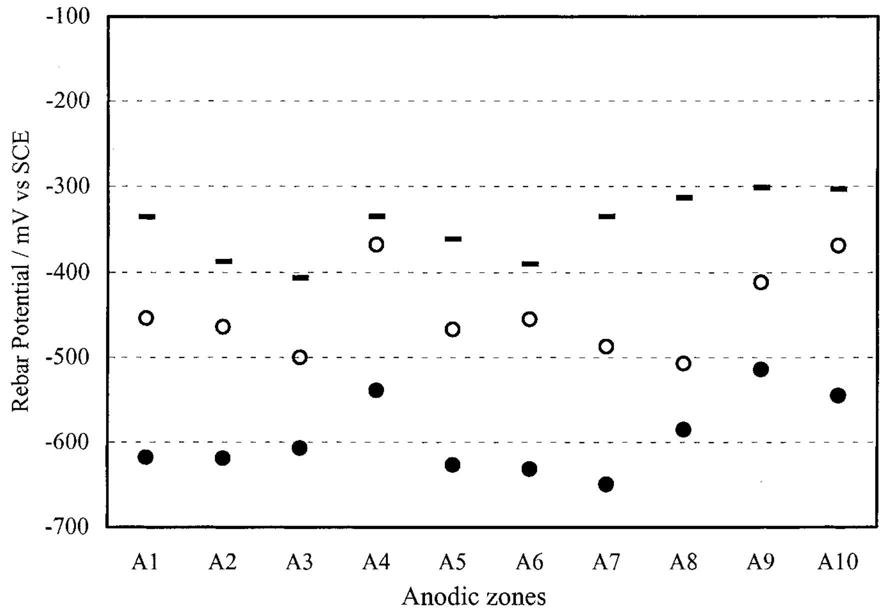

Fig. 10. Rebar potential measured at instant-off (●) and after a depolarization of 4 (○) and 24 h (▬) in cathodic protection applications on chloride contaminated viaducts (Average values of three reference electrodes in each independent anodic zone of a viaduct) [22].

high values, with only negligible reduction with time.

5. Cathodic prevention

CP is also applied to non corroding structures in order to prevent corrosion otherwise expected during the service life. This technique, called 'cathodic prevention', is based on the strong influence of the potential on the critical chloride content. In Fig. 5 a typical evolution path (①→②→③→) (in terms of potential and chloride content) of cathodic prevention is shown. At usual current densities in the range 1 to 2 mA m^{-2}, a decrease in potential of at least 100–200 mV is produced, leading to an increase in the critical chloride content higher than one order of magnitude.

Figure 11 shows the results of application of cathodic prevention to the slabs subjected to a ponding with NaCl solution. [24, 25]. After about 700 days when the chloride content at the steel surface had reached more than about 1%, the initiation of rebar corrosion was detected on the control slab (in free corrosion conditions). On the other hand a very low current density of 0.4 mA m^{-2} on the reinforcement was enough to lower the potential by about 150–200 mV so that after more than three years the initi-

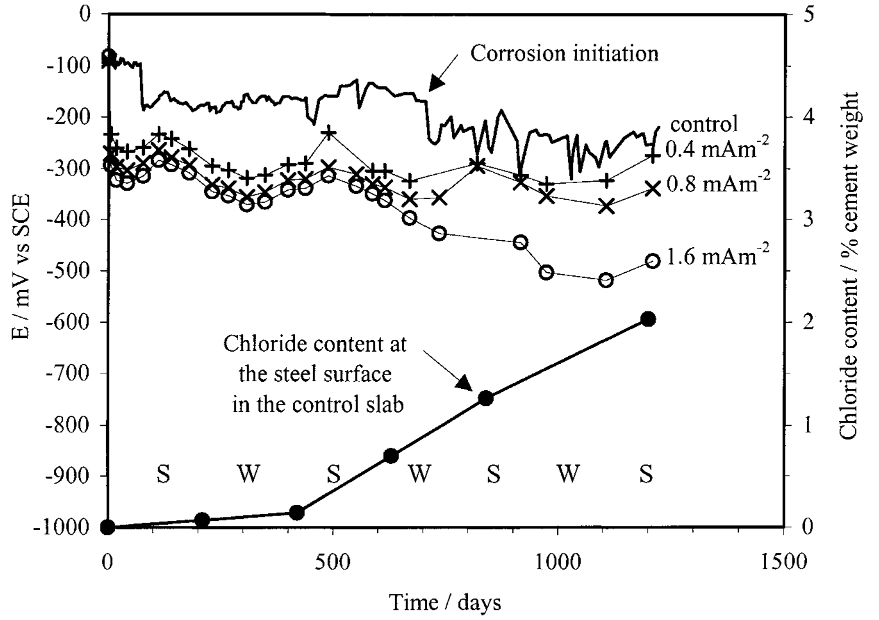

Fig. 11. Instant off potential of noncorroding steel cathodically polarized with current densities typical of cathodic prevention and chloride content in the control slab. Specimens exposed to NaCl alternating ponding (3% NaCl in the first two years and a saturated solution thereafter), consisting of wetting for one week followed by drying for two weeks. Control slab started corroding after about 700 days (S = summer, W = winter) [25].

ation of corrosion has not yet taken place, although the chloride content on the steel surface has reached values higher than 2% with respect to cement weight. On the basis of these results, the increase in the chloride threshold brought about by cathodic prevention in practical applications is expected to be sufficient to avoid corrosion initiation throughout the entire service life.

5.1. *Example of cathodic prevention*

In Northen Italy, since 1990, cathodic prevention has been applied on 140 000 m^2 of new highway bridge decks including sixteen prestressed viaducts for a total area of 104 000 m^2. Titanium activated mesh and ribbons were used for the anode system. The monitoring system was designed with the primary purpose of avoiding any risk of overprotection of steel tendons and, in the meantime, to verify the effectiveness of the cathodic prevention system through a monitoring approach based on anode and feeding voltage measurement [15]. Ag/AgCl and activated titanium reference electrodes were used. The cathodic prevention system was installed during the construction and in part also during the prefabrication of the different segments which constitute the bridge. Protection current densities in the range 1 to 2 mA m^{-2} with respect to steel surface are sufficient to maintain the 4 hour-depolarization decay in the range 100–250 mV (Fig. 12). Prevention requirements are fulfilled with a rebar potential more than 500 mV above the threshold for hydrogen embrittlement of high strength steels.

6. CP in carbonated concrete

The carbonation process reduces the pH of concrete from values higher than 13 to values lower than 9. Consequently, steel passes from passive to active conditions, and can thus corrode provided oxygen and water are available. Figure 13 shows the effect of application of CP on carbonated structures. Even a modest lowering of steel potential can produce enough alkalinity to restore the pH to values higher than 12 on the reinforcement surface thus prompting passivation [6]. Recent trials [7] have shown the effectiveness of CP in carbonated concrete with or without small quantities of chlorides. Specimens with alkaline concrete, carbonated concrete and corbonated concrete with 0.4% chloride by cement weight were all tested at current densities of 10, 5, and 2 mA m^{-2} (of steel surface). Carbonated concrete specimens polarised at 10 mA m^{-2} showed that: during the first four months of testing, the protection was not achieved (the 4 h decay was slightly lower than 100 mV); afterwards, the protection was fulfilled and higher values, in the range 200–300 mV, of the four hour potential decay were measured (Fig. 14). The same results were obtained on carbonated and chloride contaminated concrete.

Figure 15 shows the steel potential of all specimens measured 4 h after switching the current off, as a function of the exposure time. It can be observed that potential values in carbonated concrete approached those measured on passive steel in the specimen with alkaline concrete, showing that passivation occurred. The variations in the pH of the concrete around the cathode were monitored by means of the two pH sensitive probes (activated titanium wires) placed, respectively, 1 mm and 3 mm far from the steel surface. During the first four months, the potential difference the two electrodes for all specimens was negligible (Fig. 16). After five months, in the carbonated specimens protected at 10 mA m^{-2}, the potential difference between the two

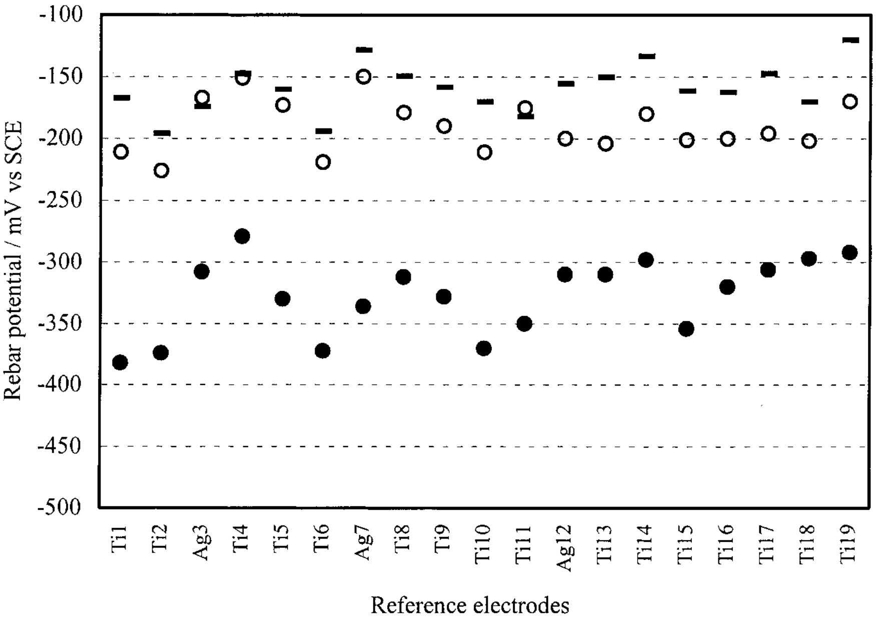

Fig. 12. Example of potential measurements versus different embedded reference electrodes in a viaduct with cathodic prevention: instant-off potential (●) four hour depolarization potential (○) and start-up potential (▬) [22].

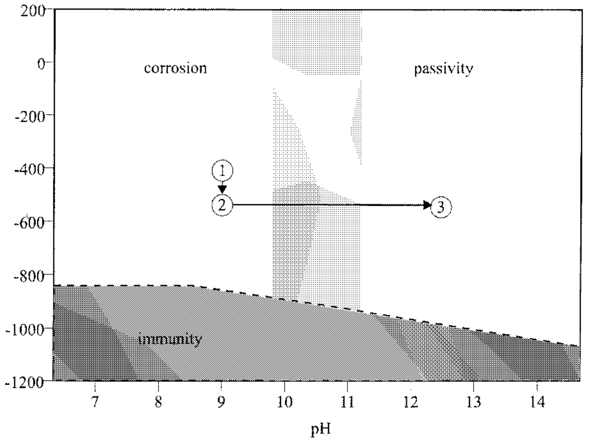

Fig. 13. Schematic illustration of evolution paths of potential and pH when CP is applied to rebar in contact with carbonated concrete [6].

activated titanium electrodes increased significantly and reached a value up to 200 mV, suggesting that the alkalinity produced by the cathodic reaction at the steel surface induced a localized realkalization of the concrete in the vicinity of the rebar (for a thickness between 1 and 3 mm).

For the other specimens (i.e., in alkaline concrete, and in carbonated concrete at 2 and 5 mA m^{-2}) realkalization of concrete and repassivation of steel did not occur (Fig. 14).

In 1997, CP was applied to some carbonated structures to stop corrosion in the case of the presence of small amounts of chloride [26].

7. Hydrogen embrittlement

High strength steels utilized in prestressed constructions (but not the ordinary steel utilized for reinforced concrete constructions) can be subjected to hydrogen embrittlement if their potential is brought to values at which hydrogen evolution can take place. However, with the exception of chromium containing steel, the risk of hydrogen embrittlement of prestressing steels is low, provided the potential is more positive than −900 mV [31, 32].

CP applied on corroding steel works mainly in the dot ⑤ of Fig. 5, that is very close to the hydrogen evolution zone. The throwing power plays an important role, as discussed in the next paragraph, in order to operate CP properly.

8. Throwing power

The throwing power depends on the steel condition. In CP of corroding reinforcement, a uniform current is difficult to achieve because of the high electrical resistivity of concrete, the small distance between anode and reinforcement, the low polarizability of corroding steel and the complex geometry of the reinforcement. The use of distributed anodes mitigates the problem only for the first reinforcing mat. To achieve a protection condition on inner active reinforcements, higher current densities are required on the top mat, with the risk of overprotection (the accepted threshold for overprotection are −0.9 V vs SCE for high strength steel and −1.1 V vs SCE for ordinary steel). The highest throwing power is achieved when the potential threshold is obtained on the first mat. In the case of active steel, the protection is obtained (by operating in zone C or in the lower part of zone B of Fig. 4) at 25 cm from the first mat for ordinary steel and 15 cm in the case of high strength steel [17].

The throwing power is much higher in the case of passive steel, where protection is achieved (by operating in zone B of Fig. 4) even at a depth of 80 cm from the first mat for ordinary steel and 60 cm in the

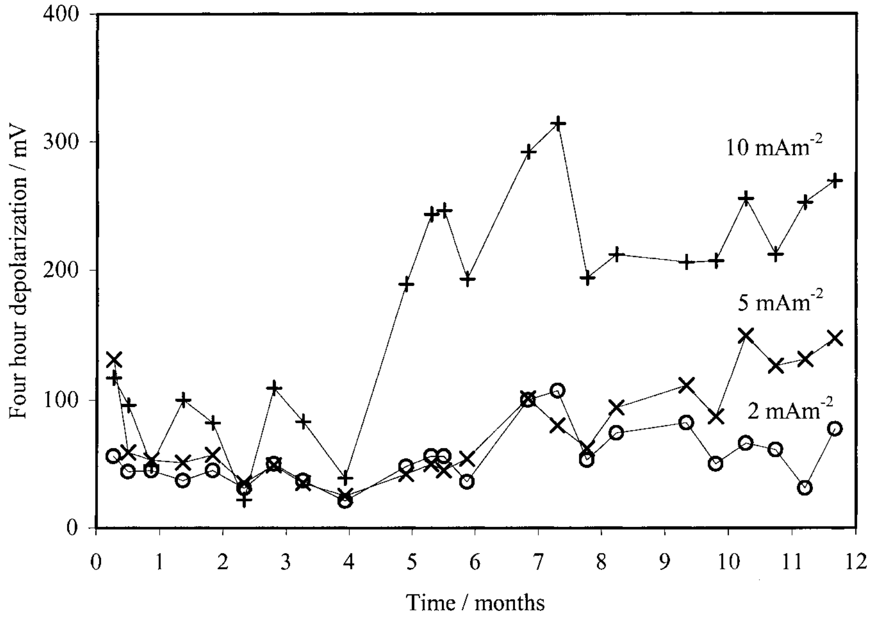

Fig. 14. Four hour depolarization of steel in carbonated concrete, against time and cathodic current density [7].

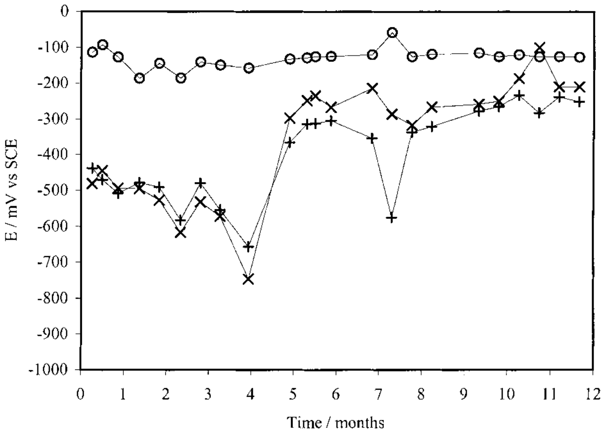

Fig. 15. Potential values of steel in alkaline (○) and carbonated concrete without chloride (×) and with 0.4% chloride by cement weight (+), protected with 10 mA m^{-2} measured four hours after switching the current off as a function of time [7].

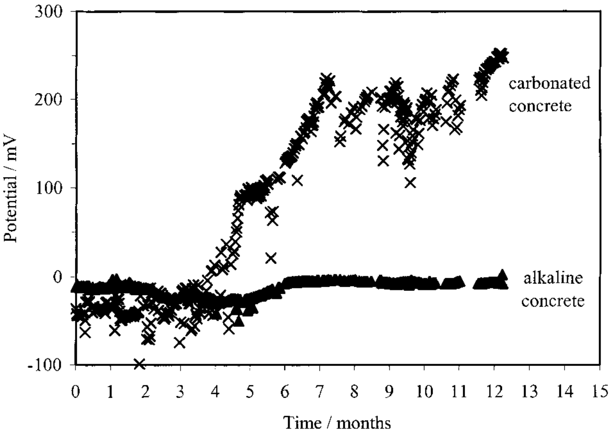

Fig. 16. Variation with the time of the potential difference between the activated titanium wires placed at 1 and 3 mm from the surface of a bar in carbonated concrete protected with 10 mA m^{-2} cathodic current density.

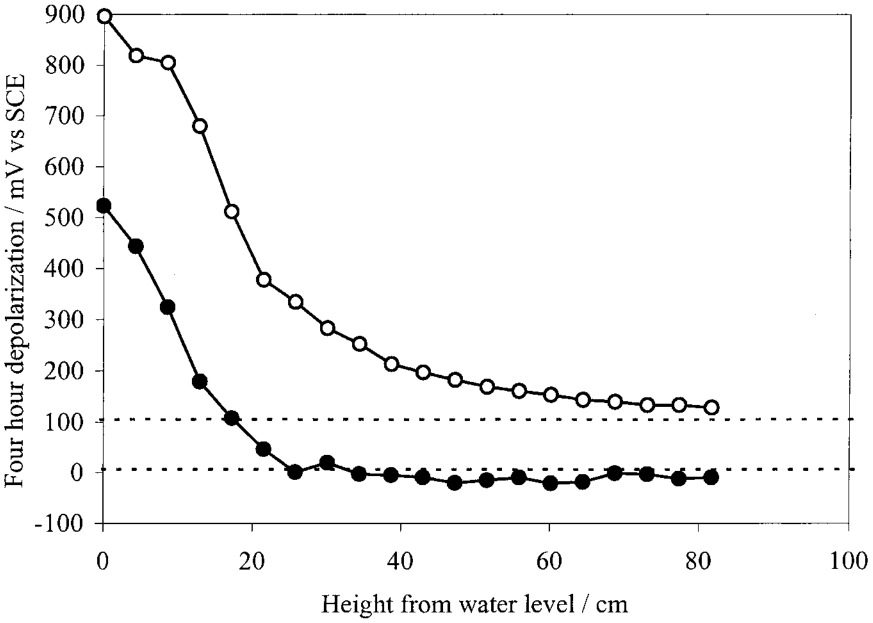

Fig. 17. Four hour depolarization as a function of height from the water level in reinforced concrete pillars (20 cm × 20 cm × 100 cm) partially immersed in artificial sea water and cathodically protected with sacrificial aluminium-indium anodes immersed in the water (● corroding steel in concrete with 3% chloride by cement weight; ○ passive steel in chloride free concrete).

case of high strength steel. The higher throwing power and the less negative potentials needed for cathodic prevention allow operation avoiding the risk of hydrogen embrittlement on prestressed construction [17].

The big difference between the throwing power of cathodic protection and that of cathodic prevention can be shown in structures partially immersed in sea water and protected with sacrificial anodes placed in the water. Figure 17 illustrates the behaviour of corroding and non corroding reinforced concrete pillars (20 cm × 20 cm × 100 cm) partially immersed in artificial sea water and cathodically protected with sacrificial aluminium–indium anodes. The results of the 4 h depolarization tests show that the 100 mV decay criterion is fulfilled up to 20 cm above the water level in the case of corroding steel and for the entire height of the pillar in the case of non corroding steel.

9. Conclusions

CP has proved to be an effective method to control chloride induced corrosion of atmospherically exposed reinforced concrete structures even in the presence of high chloride levels. The risk of hydrogen embrittlement makes its application to prestressed concrete structures possible only in cases of simple geometry and under strict monitoring control.

Cathodic prevention has proved to be a viable and safe technique to increase the corrosion resistance of reinforcement in reinforced or prestressed structures.

CP in carbonated concrete can take the pH on the rebar surface from values lower than 9 to values higher than 12 and thus transform the state of the reinforcement from corroding to passive conditions.

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