

# Cathodic protection for concrete structures

## *Proteção catódica de estruturas de concreto*



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### Abstract

Protection techniques against corrosion for concrete structures are required when there is concern about the possibility of corrosion of steel reinforcement. Among the techniques available as corrosion protection techniques, cathodic protection is outstanding for both preventing premature corrosion as well as reducing an ongoing corrosion process. Abroad, the cathodic protection technique has been applied to several types of concrete structures, especially those subject to corrosion attack by chloride ions. In Brazil, this technique is hardly used regarding concrete structures which is partially due to the lack of knowledge of cathodic protection techniques and the lack of commercially available systems for application for concrete structures (reinforced or prestressed). The objective of this paper is to present the principle of cathodic protection both for new concrete structures as well as for those in the process of steel reinforcement corrosion. Cathodic protection methods with impressed current and with sacrificial anodes are discussed. A case study with the use of impressed current cathodic protection is also presented.

**Keywords:** concrete, cathodic protection, impressed current, galvanic protection.

### Resumo

A adoção de técnicas de proteção às estruturas do concreto é recomendada quando há preocupação com a corrosão das armaduras de aço-carbono. Dentre as principais técnicas, destaque-se a proteção catódica que pode tanto evitar a corrosão prematura como diminuir um processo corrosivo em curso. No exterior, a técnica de proteção catódica tem sido aplicada em vários tipos de estruturas de concreto, especialmente nas sujeitas à corrosão pelo ataque de íons cloreto. No Brasil, essa técnica é pouco usada em estruturas de concreto, o que decorre, em parte, do desconhecimento sobre o seu princípio de funcionamento e da ausência de sistemas disponíveis para aplicação ao concreto (armado ou protendido). O objetivo deste trabalho é apresentar o princípio da proteção catódica para estruturas com armaduras de aço-carbono novas ou já em processo de corrosão. Os métodos de proteção catódica por corrente impressa e por anodo de sacrifício são discutidos. Um caso prático com uso de proteção catódica por corrente impressa, também, é apresentado.

**Palavras-chave:** concreto, proteção catódica, corrente impressa, proteção galvânica.

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## 1. Introduction

Traditionally, cathodic protection is used as a method of combating corrosion of submerged or buried metal structures, being widely used for protection for ships' external bodies and for buried pipes. In recent decades, this protection technique has been used for the rehabilitation of deteriorated concrete structures (Chess [1]; NACE RP0209 [2]) and was adopted for the first time in 1973 for a bridge in California (United States) which presented severe corrosion of the reinforcement (Beamish and Belbol [3]). Besides the use of degraded structures, the cathodic protection technique has been used in new structures as a corrosion prevention technique. Such usages may occur in partially or completely buried or submerged structures or in atmospheric structures, both for reinforced concrete or prestressed concrete.

According to Broomfield [4], until 1994, there were more than one million square meters of cathodic protection applied in concrete structures in the United States and Canada and, probably, another million or more in the rest of the world. According to Pedferri [5], until 1996, the cathodic protection technique had already been applied in about 500,000 m<sup>2</sup> of concrete structures presenting chloride-induced corrosion and 140,000 m<sup>2</sup> of new structures, the latter mostly prestressed concrete structures.

The general concept of cathodic protection in concrete structures is defined according to the steel state (passive state or active state) and according to the corrosion induced agent, namely:

- repassivation of nucleated pits: such as concrete structures presenting chloride-induced corrosion;
- reduction of generalized corrosion rates: such as structures presenting carbonation-induced generalized corrosion or chloride-induced advanced corrosion in which the pits have been coalesced giving rise to generalized corrosion;
- cathodic prevention: such as new structures (passive state) prone to chloride contamination or chloride-contaminated structures at levels below the critical threshold.

Despite the application of cathodic protection being suited to structures exposed to different conditions and states of preservation, it is more widely used in atmospheric structures subjected to chloride contamination, such as those located in marine environments, industrial environments with chloride sources and, in some countries, in environments that use de-icing salts. The chloride contamination associated with high humidity determines the decrease of electrical resistivity of concrete. Thus, smaller electrical current densities to achieve the desired level of protection are required which is not the case for concrete structures without a chloride contamination. Carbonated-concrete structures require higher current densities because the carbonation increases the concrete resistivity.

The application of cathodic protection in concrete structures can be done by means of two methods: impressed current and sacrificial anodes. Normally, the impressed current cathodic protection is used in most atmospheric structures. However, in high humidity environment, such as splash or tidal zones, sacrificial anode cathodic protection is also used successfully. The sacrificial anode technique is used for submerged or buried structures as well.

Both the impressed current and the sacrificial anodes are dependent mainly on the characteristics of the structure to be protected as well as the characteristics of the environment to which the structure will be exposed. In addition to these factors, the ease of anode installation, the cost, the aesthetic, the required lifetime and the maintenance are

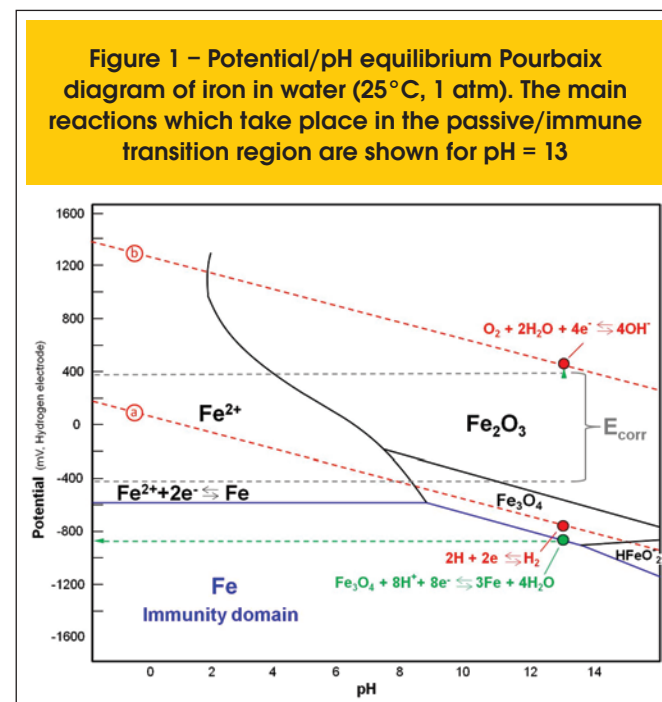
factors to be considered for an effective cathodic protection design.

In Brazil, the application of cathodic protection technique in concrete structures exposed to high aggressive environments is unusual. Typically, stringent project criteria are adopted. These include a high covering thickness and a high quality concrete. In the case of deteriorated structures, traditional techniques for recovery and concrete surface treatments are usually adopted. In practice, these criteria are not always a guarantee for concrete structure durability. Additionally, the effectiveness of the traditional techniques regarding the lifetime extension of structures exposed to very high environments is questionable. Thus, the importance of the topic addressed in this work is justified. It is expected that a better knowledge of the cathodic protection principles will encourage Brazilian engineers to consider its application in both new structures as well as for the recovery of deteriorated concrete structures.

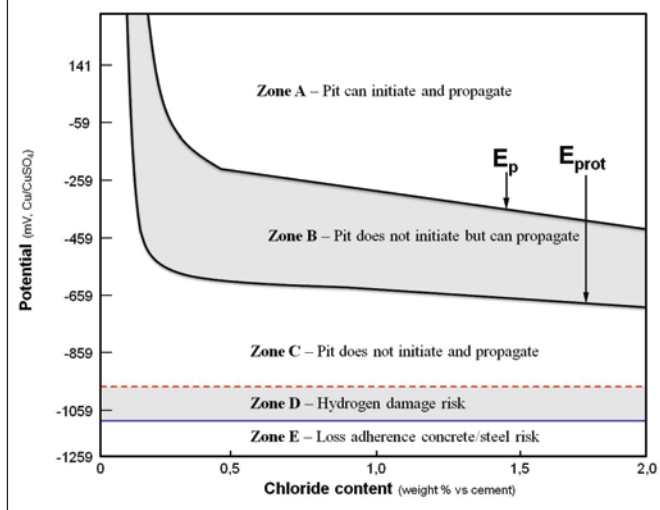
## 2. Cathodic protection principle

The principle of cathodic protection technique is to reduce the steel/concrete potential to more negative values than its natural corrosion potential ( $E_{corr}$ ). This is obtained by applying, to the steel reinforcement, a direct current which may be provided by an external electric power supply (impressed current protection) or by an electrical connection of the steel reinforcement to a more active metal (sacrificial anode protection). In either method, the supply current must be suitable to negatively polarize the steel/concrete interface.

Classically, the cathodic protection brings the steel/environment potential to very close or into the immunity domain of the iron/water Pourbaix diagram. In concrete structures, this concept can be applied only to submerged or buried structure. For atmospheric structures, the concept is different. To better understand this, consider Figure 1 which shows the Pourbaix diagram.



**Figure 2 – Schematic illustration of steel behaviour in concrete for different potentials and chloride contents at 20 °C (Pedefferri (5))**



From Figure 1, it is observed that, at high potential values, the steel/concrete interface potential remains in the passive domain at pH about 13 which is the usual pH of a sound concrete. The passive state is due to the presence, on the steel surface, of a film composed of  $\text{Fe}_3\text{O}_4$  or  $\text{Fe}_2\text{O}_3$  oxides. Steel becomes immune to corrosion when the potential of steel/concrete interface is brought to values below the equilibrium potential value of the reaction  $\text{Fe}_3\text{O}_4 + 8\text{H}^+ + 8\text{e}^- \rightarrow 3\text{Fe} + 4\text{H}_2\text{O}$  (point 1 of Figure 1). The immunity domain starts at the potential around -900 mV (EH, hydrogen electrode). At this potential, the reduction of hydrogen ( $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ ; Point 2 in Figure 1) and the reduction of oxygen ( $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$ ; point 3 in Figure 1) also take place. The reduction of oxygen also occurs at a potential in the passivation domain, i.e., when steel is embedded in a sound concrete (the range named  $E_{\text{corr}}$  shown in Figure 1).

When steel/concrete interface potential is maintained in the immunity domain, both above mentioned reduction reactions determine a progressive increase of the concrete alkalinity which may result in concrete degradation if it contains reactive aggregates (alkali/aggregate reactions). In addition, the increased volume of hydrogen due to the  $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$  reaction may hinder the steel/concrete adherence. In the case of prestressed concrete, this condition can cause hydrogen induced fracture of high strength steels due to the penetration of atomic hydrogen in the metal. Due to these possible consequences, the traditional application of very negative potentials in cathodic protection systems is not applied in atmospheric concrete structures, especially in prestressed concrete.

The principle of cathodic protection applied in concrete structures can be clarified by understanding the mechanism of occurrence of pitting corrosion of steel reinforcement due to chloride ions. In this case, the corrosion control through cathodic protection is done by the pit repassivation principle or by the delay of pit nucleation.

Pitting corrosion occurs at potential values higher than a characteristic potential known as pit potential ( $E_p$ ). Once pit is initiated, it can propagate at a potential more negative than  $E_p$ . To stop pit propagation, it is necessary to reach a lower potential, known as repassivation potential or protection potential ( $E_{\text{prot}}$ ) below which active

pits repassivate. The  $E_p$  and  $E_{\text{prot}}$  values depend on several factors, including chloride content, pH at the vicinity of corroding surface, temperature and type of cement. Among these factors, the chloride content and the pH of the concrete are the most important, namely:

- the higher the chloride content, the higher  $E_p$  and  $E_{\text{prot}}$  values;
- the lower the pH, the lower  $E_p$  and  $E_{\text{prot}}$  values.

According to Bertolini et al. [6],  $E_p$  values of the steel in concrete vary from -259 mV (CCSE – copper/sulfate electrode) to -459 mV (CCSE) and  $E_{\text{prot}}$  values from -559 mV (CCSE) to -809 mV (CCSE). In general,  $E_p$  values are 300 mV more positive than  $E_{\text{prot}}$  values. Figure 2, drawn by Pedefferri [5], shows the behavior of steel for different potentials and chloride contents at 20 °C. Different zones are shown in Figure 2: **zone A** where pit can initiate and propagate; **zone B** where pit does not initiate but can propagate; **zone C** where pit does not initiate or propagate; **zone D and E** where hydrogen evolution occurs. Based on Figure 2 and on known protection criteria (EN 12696 [7]; Pedefferri [5]), it can be concluded that:

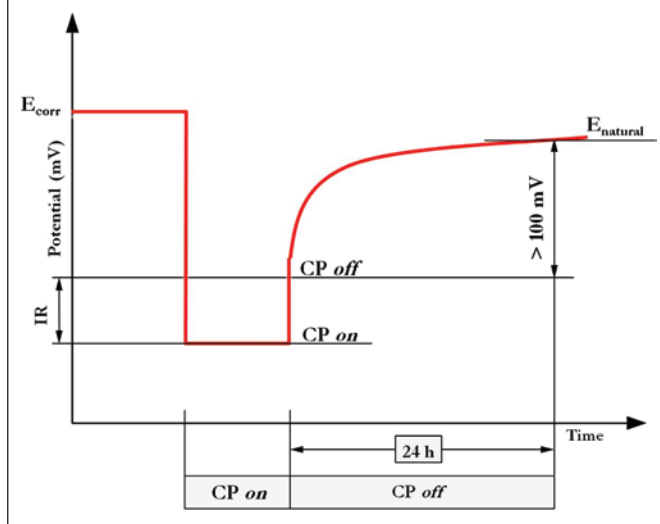
- **new sound structures or chloride contaminated corrosion-free structures:** the concrete is alkaline and the steel reinforcement is in a passive state without pits. Under these conditions, the cathodic protection aims at keeping the potential below the  $E_p$  potential (**zone B** in Figure 2). Thus, when the chloride contamination reaches critical levels, the steel will remain passive without nucleation of pits. The goal in this case is to prevent corrosion. The typical current density for this case is between 0.2 mA/m<sup>2</sup> and 2 mA/m<sup>2</sup> (regarding the reinforcement area). The variation of the current density is due to several factors, such as the concrete electrical resistivity and the chloride contamination level;
- **structures presenting chloride induced corrosion:** the concrete is alkaline and the steel reinforcement presents pitting corrosion. Under these conditions, the cathodic protection aims at decreasing the potential to values below the  $E_{\text{prot}}$  potential. Thus, the formed pits will be repassivated and there will be no formation of new pits. In prestressed concrete, the steel should necessarily be maintained in **zone C** of Figure 2. In reinforced concrete, the potential can be maintained in **zones C or D**. When only the decrease in corrosion rate is desired, the potential value can be kept at the lower part of **zone B**. The typical protection current density for this case remains between 2 mA/m<sup>2</sup> and 20 mA/m<sup>2</sup> (regarding the reinforcement area). This variation is due to several factors, such as those above mentioned and the degree of corrosion already present on the steel reinforcement surface;
- **structures presenting carbonation induced corrosion:** the pH of the concrete assumes lower values and the reinforcement presents generalized corrosion. Under these conditions, the cathodic protection is normally applied by decreasing the potential to values between the reinforcement corrosion potential and the iron equilibrium potential. As a result, a decrease in the corrosion rate is obtained.

In practice, for the application of the cathodic protection technique, the knowledge of  $E_p$  and  $E_{\text{prot}}$  values is not necessary. Empirical criteria are widely accepted, including the 100-mV depolarization criterion (NACE RP0209 [2]).

In corroded atmospheric structures in which the reinforcement potential value is more negative than -200 mV (CCSE), the adopted protection current must be such that, at the most anodic location in each 50-m<sup>2</sup> area, a minimum of 100 mV of “real” cathodic po-



**Figure 3 – Typical potential decay measurement after disconnecting the cathodic protection system (Raupach and Bruns (8))**



larization should be achieved. In a sound concrete or in a slightly chloride-contaminated concrete in which the reinforcement potential value is more positive than  $-200$  mV (CCSE), which indicates that the steel is passivated, there is no need for adoption of this minimum threshold of cathodic polarization (NACE RP0209 [2]). Figure 3, proposed by Raupach and Bruns [8], illustrates the application of the “real” 100-mV polarization criterion. In Figure 3, it is observed that, when the reinforcement is not protected, it assumes its natural corrosion potential ( $E_{corr}$  in Figure 3). When cathodic protection is applied, the steel potential is shifted into cathodic direction, assuming the value **CP on** of Figure 3. After switching off the protection current or, in the case of sacrificial protection, after disconnecting the anode, the steel potential presents a sudden in-

crease up to the value named instant off potential (**CP off** in Figure 3) also known as “real” IR-free potential because the sudden increase is a consequence of the potential decay due to soil resistivity. Then, an asymptotic increase of the steel potential is observed reaching a steady state value named  $E_{natural}$  (Figure 3).

The absolute value of the difference between the natural potential and the instant off potential ( $E_{natural} - E_{CP\ off}$ ) is the “real” depolarization value of the steel/soil interface which is the value that should be equal or above 100 mV to achieve the above mentioned 100-mV depolarization criterion. If in a given cathodic protection system, the “real” depolarization value is lower than 100 mV, higher cathodic protection current should be applied.

According to Bennet and Turk [9] and Pedferri [5], a period of 4 h is required for the  $E_{natural}$  stabilization. However, in some cases, this time may be insufficient to achieve the stabilization. In these cases, larger periods may be adopted which may reach 24 h (Pedferri [5]). It is worth mentioning that the potential stabilization depends on the oxygen availability and not of the cathodic protection efficiency. In water saturated structures, where the availability of oxygen is lower, the stabilization time is greater (Glass, Hassanein, Buenfeld [10]; NACE RP0209 [2]). The cathodic protection effectiveness is ensured by continuously measuring the steel potential in concrete with respect to reference electrodes. This may be done by burying sensors (permanent electrodes) in the concrete in most critical areas aiming at representing different corrosion conditions of the entire structure to be protected or in places where the potential control is of the most importance. Mostly used reference electrodes are: Ag/AgCl/KCl-0.5 mol/L; Mn/MnO<sub>2</sub>/NaOH-0.5 mol/L and activated titanium with or without mortar backfill. For monitoring buried or submerged concrete structures, external (immersed or buried) zinc electrodes or copper/copper sulfate electrodes may be used (Lourenço [11]).

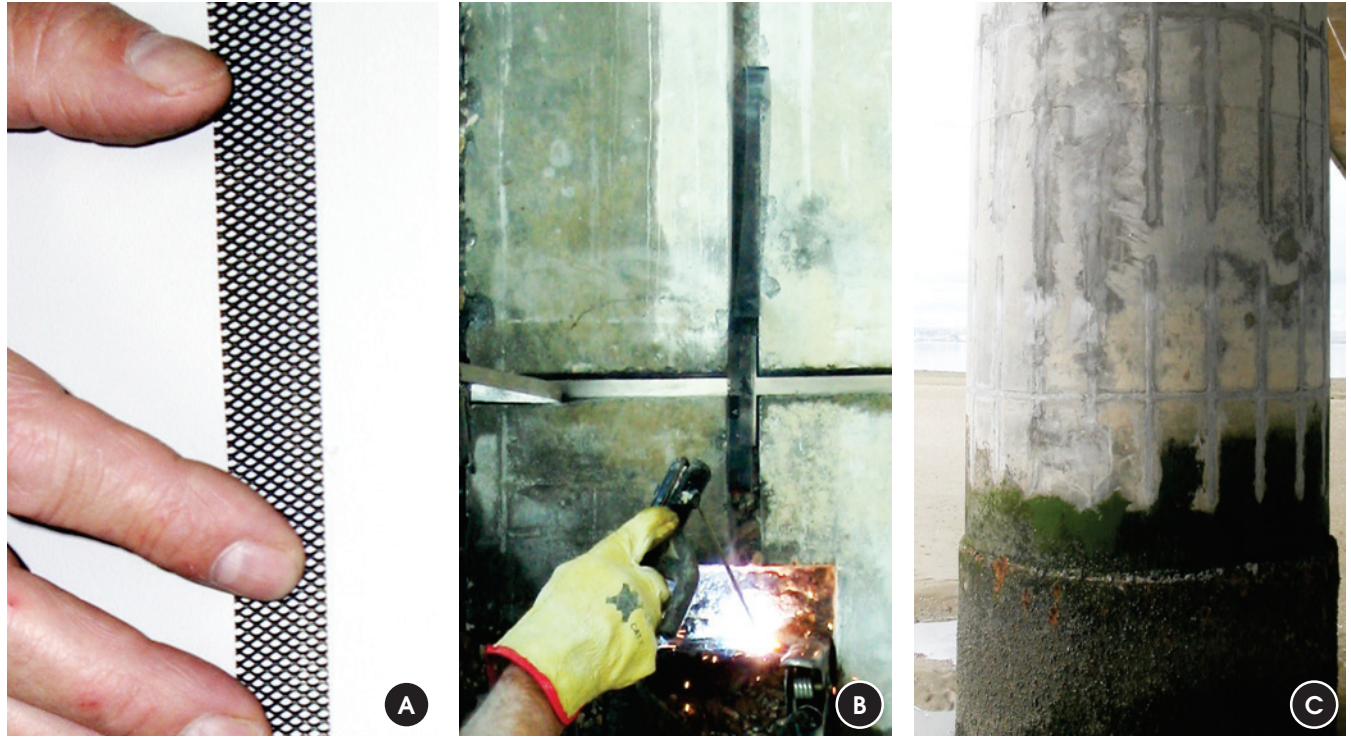
### 3. Impressed current cathodic protection

In the impressed current cathodic protection method, the electric current is provided by applying an electrical potential using an external electric power source. Typically, an alternating current rectifier is used with its positive pole connected to the anodes and

**Figure 4 – Activated titanium mesh application. Mesh fixation on the concrete surface (a). Cover mortar applied by projection (b)**



Figure 5 – Mesh type Ti/MMO tape (a). Titanium tapes installation and welding (b). Final visual aspect (c)



its negative pole to the steel reinforcement to be protected. The anode system, whose function is to supply a uniform current distribution to the steel reinforcement, is made of a high lifetime conductive material plus an overlay, embedded in the concrete or applied on the concrete surface. With such a system, the current can easily be adjusted in order to maintain the steel/concrete potential at a desired level. This is done by setting the rectifier output potential. For atmospheric structure, the most used anode systems are:

- activated titanium mesh coated with noble metal oxides (Ti/MMO) with a low resistivity mortar overlay. The Ti/MMO mesh is fixed to the surface of the concrete structure and is encapsulated with mortar that usually is applied by projection (see Figure 4);
- conductive coatings or organic paints applied directly on the concrete surface;
- probe shape anodes with different lengths and diameters, depending on the concrete structure to be protected. The anode material can be titanium covered by electroplated platinum; Ti/MMO or conductive ceramics in tubular, tape or rod form. The anodes are inserted in holes made in the concrete containing conductive fillers such as a graphite gel or a low resistivity mortar;
- mesh type Ti/MMO tapes with different thicknesses. The tapes are installed in shallow grooves made on the concrete surface and then covered by low resistivity mortar applied by spraying (see Figure 5);
- conductive coatings sprayed on the concrete surface. These are essentially cementitious material containing nickel coated carbon fibers;
- thermal sprayed metallic coatings (mainly pure zinc). This type

of anodes are also used in the galvanic cathodic protection method (see item 6).

Figure 6 shows the possible electrochemical reactions that can occur on an anode surface and on a cathode (steel reinforcement) surface. If the anode material does not oxidize, which is the case

Figure 6 – Schematic representation of impressed current cathodic protection

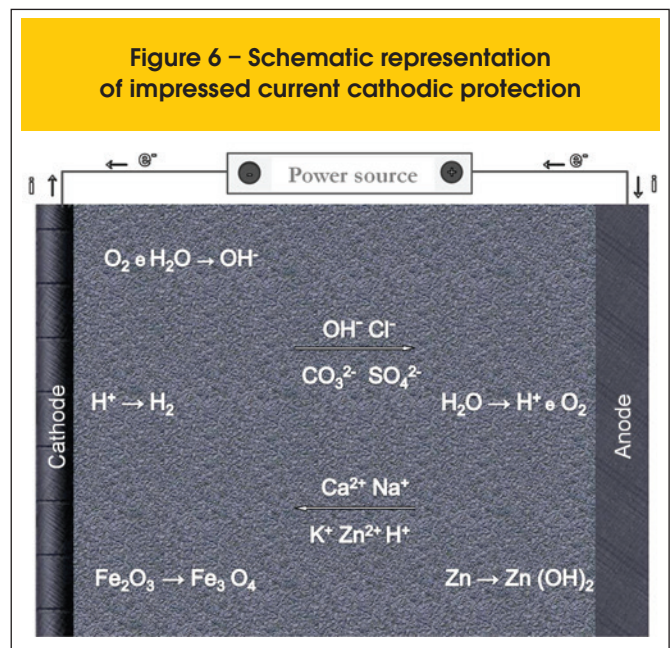




Figure 7 – Tapes installation (a). Concreting (b)  
Electric power supply (c).  
General view after repairing (d)



of inert anodes such as titanium, platinum and nickel, the only possible anodic reaction is water oxidation ( $2\text{H}_2\text{O} \rightarrow 4\text{H}^+ + \text{O}_2 + 4\text{e}^-$ ). If the anode material oxidizes, which is the case of soluble anodes such as zinc, the main reaction is anode oxidation ( $\text{Zn} + 2\text{H}_2\text{O} \rightarrow \text{Zn}(\text{OH})_2 + 2\text{H}^+ + 2\text{e}^-$ ). At the cathode surface, the reduction of oxygen occurs ( $\text{O}_2 + \text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$ ). When the steel/concrete potential is sufficiently polarized up to the iron immunity domain, the reduction of iron oxides ( $\text{Fe}_3\text{O}_4 + 8\text{H}^+ + 8\text{e}^- \rightarrow 3\text{Fe} + 4\text{H}_2\text{O}$ ) and the reduction of hydrogen ( $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ ) also take place.

As can be seen in Figure 6, the cathodic protection current applied on the steel reinforcement may cause other chemical modification in the concrete. Negative ions (hydroxides, chlorides, carbonates and sulfates) are repelled by the cathode and the positive ions (calcium, sodium, potassium, zinc and hydrogen) are attracted to the cathode. Thus, the cathodic protection effect is not only the corrosion mitigation, but also the restoration of the passive film on the steel surface due to the decrease of the chloride concentration in the vicinity of the protected reinforcement (Lourenço and Costa [12]).

#### 4. Sacrificial anode cathodic protection (galvanic protection)

In the sacrificial anode galvanic protection method, the cathodic electric current is provided by means of the natural potential difference between the two distinct metals, the one of them being the steel prestressed (cathode) and the other a less noble metal (anode). The mostly used metal and alloys in this cathodic protection method are zinc, aluminum or magnesium and their alloys (13 ACI 222.3R [13]).

Beyond an adequate potential difference, this method also demands a conductive environment in order to guarantee the electric current flowing between the steel reinforcement and the anode. In concrete structures, such conditions are normally achieved when concrete is exposed to a continuous humid atmosphere or in immersion condition. When these conditions are not achieved, the concrete resistivity will change and may assume very high values causing a deep decrease of the electric current which can compromise the protection of the prestressed. It is worth emphasizing that this method is not applied for structures subjected to stray current. In Brazil, the most known galvanic protection system is the use of pure zinc tablets embedded with a conductive and alkaline mortar. They are galvanically connected to the exposed reinforcement before applying the repair mortar. According to NACE 01105 [14], this system has the objective to provide greater efficiency to the patch repair since it can delay the corrosion onset and also can avoid the appearance of incipient anodes adjacent to the repaired site.

Abroad, beside the tablets, jacketing systems are also used. This system is composed of a zinc mesh fixed to a fiberglass plate. The jacket system can be successfully used for the rehabilitation of on-shore piles. This is done by using two-piece stay-in-place fiberglass forms lined with a zinc mesh anode electrically connected to the steel reinforcement. Then, the jacket is filled with a suitable cement mortar [15].

Another system, both for new and damaged structures, is the metallization of the concrete surface which is done by spraying a thin layer of pure zinc or aluminum/indium alloy on the concrete surface. According to NACE publication 01105 [14], in some cases, it is also necessary to use a moisture retention promoter (hydrophilic product) under the film. In marine structures, in which periodic concrete humidification occurs, the system can maintain a current of  $10.8 \text{ mA/m}^2$  which satisfies the 100-mV depolarization criterion for many years.

## 5. A case study of impressed cathodic protection for a concrete structure

A cathodic prevention system was installed during the construction of the new general cargo wharf of the Aveiro Port, Portugal. The cathodic protection system was installed in the tidal and splash zones of the front beam of the wharf. This area is considered the greatest corrosion risk zone due to the proximity of the water. The wharf has a length of 250 m. The total area of reinforced concrete to be protected was 1046 m<sup>2</sup>. Mesh tapes of Ti/MMO, with 0.5 mm wide and 20 mm thick, were used as anodes. The tapes were installed with a spacing of 250 mm and connected, by welding, to another titanium tape used as a current distributor (see Figure 7). The tapes were fixed to the reinforcement before the concrete casting. Appropriate spacers were used, aiming at avoiding a short circuit

The control and monitoring of the cathodic protection system was carried out manually through a Control Central Unit. This unit was essentially composed of three power supplies, one per zone, voltmeters and ammeters to measure the intensity of the supplied voltage and current and high impedance voltmeters for the steel/concrete electrode potential measurements (see Figure 7).

Before starting the current application, tests were performed in order to verify the functionality of all system components and to ensure the correct connection of all circuits. The system was energized in the constant current mode. Initially, a low protection current was applied aiming at allowing a slow polarization of the system. In each subarea, different current values were applied in order to evaluate the influence of the protective current on the polarization and depolarization of each part of the structure.

The relationship between the depolarization values (potential CP off) and the current density obtained in each subarea is presented in Figure 8. These results indicate that the required current density for obtaining 100-mV depolarization, after 72 h of interruption of the current, is about 3.5 mA/m<sup>2</sup>. As the system was designed to provide much higher current densities than the maximum recom-

mended, the need to increase the current does not present problems of anode or other system components' durability.

## 6. Conclusions

Cathodic protection is an effective technique to avoid premature deterioration and to extend the service life of concrete structures subjected to high risk of premature degradation such as those exposed to a high aggressive environment or presenting high construction quality problems.

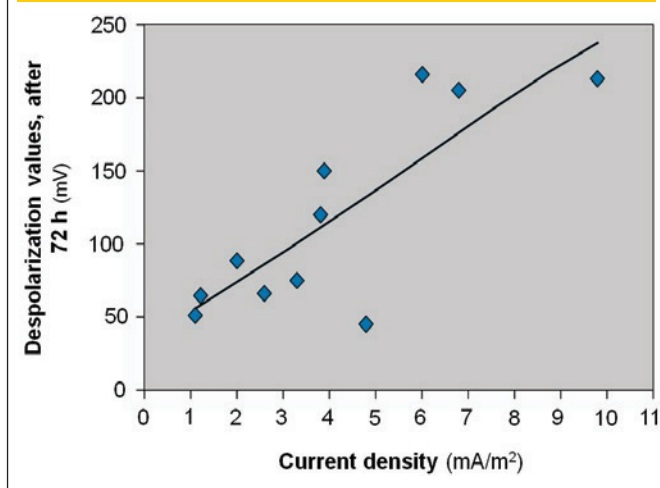
The present review showed that despite the application of cathodic protection being suited to structures exposed to different conditions and states of preservation, it has been especially applied in new atmospheric structures subjected to corrosion by chloride ions or in old structures presenting a severe ongoing corrosion process. The impressed current cathodic protection method is used more in concrete structures than the sacrificial anode method. However, the latter is prudentially used to protect elements subjected to a continuous wetting. In general, the application of the sacrificial anode method presents higher simplicity and easier monitoring.

The selection of both cathodic protection methods should be made on a detailed study of the concrete structure to be protected taking into account the environmental conditions to which the structures are exposed. In addition, the ease of anode installation, the cost, the aesthetic, the required lifetime and the maintenance are factors to be considered for an effective cathodic protection design. The application of both must be made with the assistance of qualified personnel.

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Figure 8 – Mean values of depolarization (72 h) as a function of applied current density



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