

INFLUENCE OF COATINGS ON THE BEHAVIOUR OF STEEL REINFORCED CONCRETE IN SALINE ENVIRONMENTS

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Abstract

The present work has as its purpose the comparison of the behaviour of three steel solutions against the behaviour of steel currently used in concrete structures subject to the action of chlorides. Steel coated with acrylic paint, galvanized steel and protected by imposed current steel were adopted.

Tests were performed in the laboratory with concrete specimens that were monitored with sensors installed that enabled to measure the resistance of polarization, the potential for corrosion and the ionic resistivity of concrete. During the tests, the chloride content of the concrete was determined.

The results obtained allow us, in the first place, to identify the different stages of deterioration of reinforced concrete structures subject to attack by chlorides, namely, the identification of the initiation stage of the process of steel corrosion. On the other hand, it was found that steel coating with acrylic paint slightly slows the onset of reinforcement corrosion, but does not prevent its rapid spread. That galvanized steel display a good long-term behaviour and that the cathodic protection delays chloride ion arrival to the steel surface.

Keywords and phrases: monitoring, reinforced concrete, coated steel, chlorides.

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1. Introduction

Reinforced concrete structures have a strong environmental impact which results mainly from the high amount of energy that is consumed in the production of cement. For the mitigation of this impact, there are two approaches that can be adopted, the first consists of changing the quantity and composition of the binder used in the manufacture of concrete, and the second will be through the increased durability of structures [1]. Knowing that the performance of the concrete results from a complex interaction of factors, internal and external, of which we may highlight its constitution, in particular with regard to the quantity and quality of the binder used (cement or cement and adjuvants), the w/c ratio, the thickness of the coating layer, the conditions of environmental exposure, namely, the type of degradation agents (carbon, chlorides, sulphates) and how they interact with the concrete and the susceptibility of steel to the attack of the deterioration agents.

Given the variety of processes and complexity of factors that contribute to the performance of reinforced concrete it is important to carry out its monitoring, in particular in regards to the potential and corrosion speed of the steel reinforcement and the ionic resistivity of concrete [2], [3], [4], and [5].

The durability of a structure is associated with the concept of service life, which was developed by Tuutti, and originates from the definition of the level of acceptable degradation in order to determine the acceptable limit for the life of the structure, e.g., the service life, the time from which the structure does not perform the functions for which it was designed in accordance with the security requirements defined [6].

The concept of service life of a structure of reinforced concrete involves two phases designated by period of initiation and propagation. The period of initiation corresponds to the penetration of the degradation agents of the concrete in the coating layer up to the surroundings

reinforcement, by creating the conditions necessary for its despassivation, i.e., removal of the passive film that protects the steel from corrosion. The destruction of this film can occur by effects of carbonation, which leads to the reduction of the PH of the surrounding concrete reinforcement to values below 9, or by the concentration of chlorides above a given value assigned by the critical content of chlorides. The propagation phase is the period of time that elapses between the despassivation of the reinforcement, that may be generalized or localized as a result of the degradation agent, and the durability limit established, which can be defined on the basis of loss of section of the steel, associated to a certain degree of reinforcement corrosion and deterioration of the concrete. Figure 1 shows a Tuutti model for the degradation of concrete [7], [8].

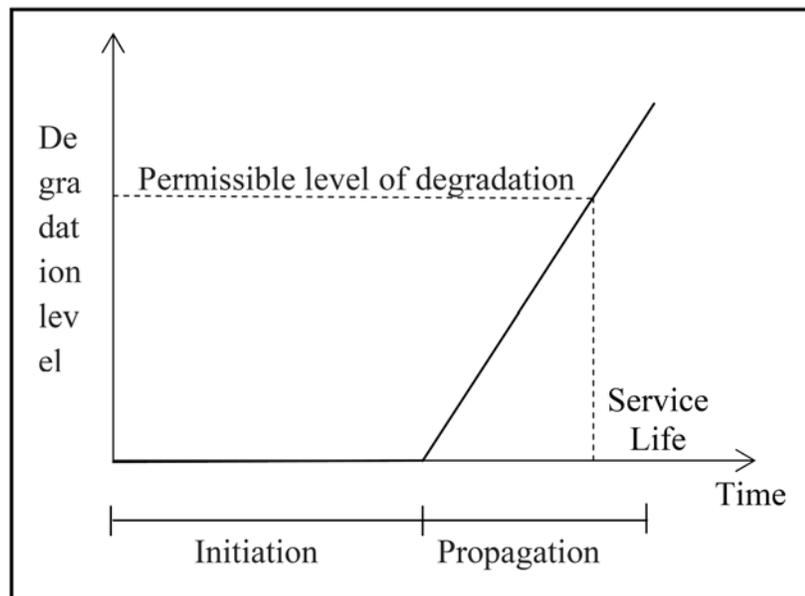


Figure 1. Tuutti model for degradation of reinforced concrete [6].

The duration of the propagation period depends on the susceptibility of the reinforcement to degradation agents varying as a result of the type of steel adopted. The use of steel protected with corrosion inhibitors will

increase the service life of the structures. Four types of reinforcement were studied: current steel, cathodic protection, galvanized steel, and coated steel.

Steel reinforcement has the greatest expression in the area of construction being the cheapest resource. They feature a stable behaviour during the initiation phase, while the pH of the concrete remains at levels greater than 9, becoming very vulnerable to aggressive agents after the loss of the passive film protection, which occurs when the pH values are lower than 9.

The cathodic protection technique has been used in the last two decades with success in reinforced concrete structures exposed to very aggressive environments. This technique is based on the imposition of an electrical field between a surface metal mesh, that functions as an anode and the reinforcement, which operates as a cathode. The electrical field installed cathodically polarizes the reinforcement and enables the reduction of the intensity of the anodic reactions on the surface of the steel and consequently the reduction of corrosion [9].

Galvanized steel have been used in some relatively recent buildings with the intention of prolonging the service life of the structures, displaying a good behaviour in situations where the steel corrodes due to chloride or carbonation attack. This reinforcement results from the superficial treatment of steel through a process of immersion in molten zinc or by electrolysis. The diagram of Pourbaix, shown in Figure 2, indicates that the zinc is susceptible to corrosion when the pH of the surrounding environment is greater than 10.5, this process results in the formation of hydrogen zincate soluble ions (HZnO_2^{2-}) and, for pH values higher than 13.1, the product of corrosion is soluble zinc peroxide (ZnO_2^{2-}). In normal conditions, the concrete has a pH in the range between 12.5-13.0 and, in spite of the water in the pores of the concrete generally having a pH above that of what zinc can tolerate, the behaviour of galvanized steel is normally good [10].

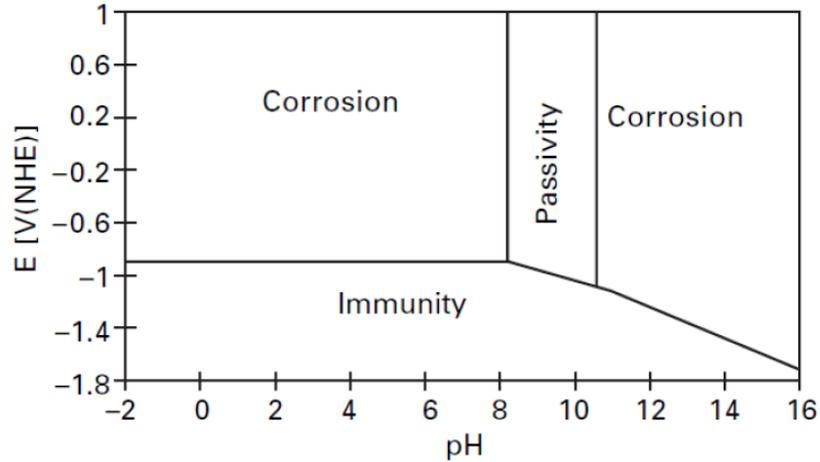


Figure 2. Pourbaix diagram for zinc [10].

Epoxy-coated reinforcement have been used over the last few years, in maritime construction, with the objective of increasing the period of initiation of the process of corrosion of steel structures exposed to these highly aggressive environments. Its use has consequences at the level of adhesion between the steel and the concrete, and there are several studies that point to the reduction of adhesion tension between 15 to 50% [11]. In this work, rods coated with acrylic paint were used, with the knowledge beforehand that its use had implications in the adhesion between the steel and the concrete, with the aim of understanding the impact of this type of coating in terms of protection against corrosion.

2. Experimental Part

The tests were performed in the laboratory using four sets of three reinforced concrete specimens with dimensions of $400 \times 300 \times 150\text{mm}^3$. For each set of test specimens, a different reinforcement steel solution was adopted, the specimens being designated by "S" current steel, the "R" specimens coated steel, the "G" specimens galvanized steel, and the "P" specimens current steel with cathodic protection. For all solutions, we

adopted an orthogonal mesh composed of 3 rods of 10mm diameter spread out approximately 100mm. In the execution of the test, specimens were used a concrete dosage prescribed in accordance with the Standard NP-EN 206-1, with incorporation of 340kg/m^3 of cement CEM II/A-L 42.5 R, 3.4kg/m^3 of plasticizer (Chrysoplast 775), 302kg/m^3 of fine sand, 506kg/m^3 of coarse sand, and 1016kg/m^3 of gravel 1. In the concrete production 170kg/m^3 of water was incorporated, corresponds to an w/c ratio of 0.5. It was obtained a concrete C30/37 D16 XC 3(P) C1 0.2 S2. For the coating layer, a thickness of 50mm was adopted.

The concrete was subject to a healing process of 28 days in a humid atmosphere at a temperature of about 25°C . Following the cure, the specimens were prepared for the immersion of one of the faces in a solution of sodium chloride 3% contained in a plastic container. The test specimens were subject to chloride action during a period of approximately 9000 hours.

The test specimens were equipped with two types of probes in order to gather information concerning the behaviour of reinforcement, potential and the speed of corrosion, and the concrete, ionic conductivity and resistivity.

To determine the corrosion speed of the reinforcement, the *MonIcorr^{Pat}* [12] corrosion monitoring system was used. These electrodes have a nucleus with the form of a parallelepiped of a square basis with a 2.5cm side and a height of 8cm, where two pairs of electrodes or metal rods protrude (a pair made of current steel similar to the reinforcement and the other stainless steel AISI 304), in addition to a reference electrode (pseudo-reference of graphite) and an electrical cable that directly connects to the reinforcement. This set will determine the speed of corrosion of the steel, through the technique of linear polarization resistance (LPR), the galvanic current between the electrodes of steel and stainless steel and the conductivity of the concrete around the reinforcement [13].

Through the technique of the two electrodes the resistivity of the concrete was determined, with resource to cylindrical electrodes with 3cm diameter and 4cm in height, placed at a distance of 5cm from one another that enabled to measure the concrete resistivity at a depth of 1.5cm of the exposed surface. These electrodes created an alternate electrical field (172Hz) between the stainless steel rings located at the same depth, establishing a current and measuring the difference of alternate potential response [14].

The collection of information was processed by data acquisition systems, which allowed the control and collection of the data from periodic readings made by installed sensors.

3. Results and Discussion

(a) Process of reinforcement steel corrosion

Figure 3 shows the variation of potential corrosion (E_{corr}) and the polarization resistance (R_p) of the steel cage throughout the test period, where the steel did not have any superficial treatment. The progress of the various magnitudes clearly identifies three phases. An initial phase, up to about 200 days, where there is a decrease in the potential for corrosion and an increase of the polarization resistance of steel, a sign of a decrease in the rate of corrosion of the same. From the 200th day onwards, there is a tendency for the decrease of the resistance of polarization, alongside the continued fall of potential corrosion. Finally, a third phase arises from the 400th day onwards when a drastic decrease of the values of both parameters are found, pointing to a despassivation of the steel. During this period, it seemed to be observed a certain tendency for the occurrence of processes of repassivation that are manifested by simultaneous increases in the polarization resistance and the potential steel corrosion.

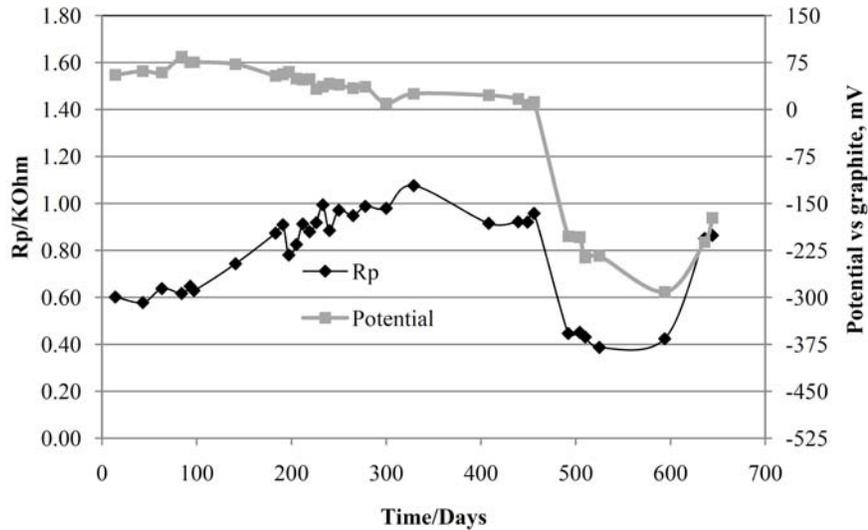


Figure 3. Variation of polarization resistance, R_p , and corrosion potential of there inforcement steel without any surface treatment during the immersion in saline solution.

Figure 4 shows the variation of the resistivity of the concrete and the concentration of total chlorides within the concrete at the level of the reinforcement, throughout the time for the reinforcement steel without any surface treatment. It was verified that the resistivity of the concrete gradually diminishes, in an almost linear fashion, as the result of a progressive increase in the concentration of chloride ions and other ions inside the concrete. Actually, considering that the moisture content is constant, given the conditions of immersion in which the specimen is found during the test, the decrease of the resistivity of the concrete should be attributed to the increase of ionic concentration, firstly by incorporation of chloride ions and sodium, in order to ensure the electro-neutrality within the pores of the material.

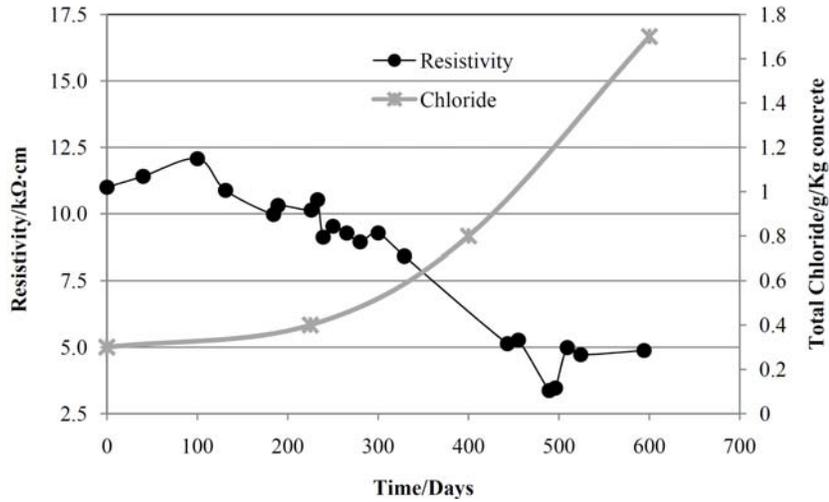


Figure 4. Change of the concrete resistivity and chloride concentration near there inforcement steel installed in specimen S1.

The relationship between the two figures enabled to check that the phases of the degradation process previously identified, namely, initiation of the corrosive process by stinging and generalized propagation, coincide largely with the ranges of resistivity, normally accepted. In other words, when the conductivity of the concrete becomes high (resistivity values lower than 10kΩ.cm), the initiation phase of corrosion sets in and when the conductivity becomes very high (resistivity values lower than 5kΩ.cm), the steel enters a stage of widespread corrosion. Thus, the results obtained clearly validate the use of values of the resistivity of the concrete for monitoring the corrosive process of submerged structures or structures where it might be considered that the moisture content of the concrete within their pores remains constant over time.

(b) Effect of the application of an organic coating

Figure 5 shows the variation of potential corrosion (E_{corr}) and resistance of polarization (R_p) of the steel cage along the time of the test in which the steel has been coated with an acrylic paint. In the

first place, it appears that the curve movements follow the movements checked with the tests performed with the reinforcement steel without any coating. Indeed, it is striking the stage in which the chloride ions reach the surface of the steel, approximately after 250 days, and then the phase of considerable increase of the widespread tendency to corrosion, after 450 days. However, it is noted that the resistance of polarization is, in the whole process, approximately one order of magnitude higher, which ensures a low corrosion speed. On the other hand, the steel potential shows very similar values to the steel without any coating that leads us to conclude that the iron suffers all the same processes and ultimately also ends by despassivating.

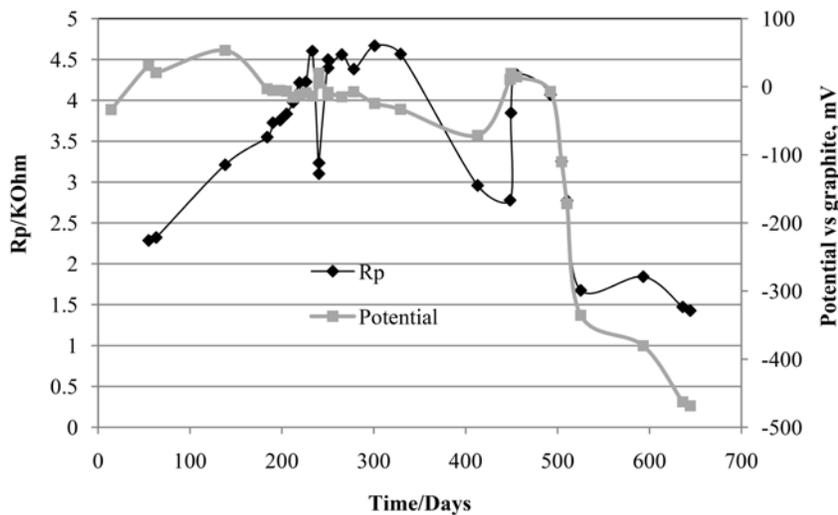


Figure 5. Variation of polarization resistance, R_p , and corrosion potential of the organic coated steel during the immersion in saline solution.

The effect of the organic coating is a barrier effect hindering the access of aggressive ions (chloride) to the surface of the metal. Actually, the results show that effect and that translates into a positive effect of ensuring the longevity of structures. The coating is one more barrier to impede the ions reaching the surface of the metal.

Another relevant aspect that can be removed from these results is that monitoring sensors with coated probes continue to allow a good monitoring of the whole degradation mechanism.

(c) Effect of cathodic protection

The cathodic protection is one of the most effective forms of protection of metallic structures submerged or buried against corrosion. From a theoretical point of view, the process is very simple to explain because it means eliminating all anode areas (where degradation processes occur by oxidation) of the structure to protect, making it operate, in its entirety, in a cathode form, as local reactions of reduction by avoiding the reactions of oxidation and degradation of the metal. To this end, it is necessary to associate the structure to an external anode which is less noble, from an electrochemical point of view, than the material of the structure- cathodic protection by sacrificial anodes - the structure operating as a cathode; or to an inert anode through which is quickly spread a cathodic current (that originates a reduction process of constituent metal structure) injected (imposed) in the structure to protect- cathodic protection by imposed current - and requires for this purpose a generator of continuous current, which is achieved in the most economic form through a transformer/rectifier system. Also from the thermodynamic/kinetic point of view, the issue is easy to understand, since it is merely the case of injecting an electric current, in order to force the balance of oxidation/reduction of steel in the direction of its reduction, e.g., making the oxidation reaction of steel little extensive.

Figures 6 and 7 show the variations of potential corrosion (E_{corr}) and resistance of polarization (R_p) of the reinforcement steel throughout the test period in which the steel was protected cathodically: In Figure 6 by galvanization and in Figure 7 by imposed current.

With regard to the results of the galvanization, it is noted that the resistance of polarization and the potential feature a behaviour relatively close to the tests where no coating was used on the reinforcement steel, not being observed, however, the rapid drop in potential. In this case, the potential and the decrease of the resistance of polarization happen gradually. On the other hand, it is also observed that the potentials are

lower, an obvious result that we are in the presence of a zinc coating, and that the polarization resistance shows values in the same order of magnitude of the reinforcement without coating. The results clearly point to a positive effect of galvanizing whereas the zinc is in fact protecting the steel. It is evident that this protection will not last forever, e.g., it will only be in effect while there is zinc, but clearly there is an increase in longevity of the structure.

In the case of cathodic protection by imposed current (see Figure 7), it is noted that the polarization resistance is low and that the potential is kept very low, by imposition of rectifier, ensuring that the metal is in a zone of immunity. The low resistance of polarization is not due to steel oxidation but to the reactions of reduction, possibly from water, that generate hydroxylic ions. It is interesting to note that there is a clear growth over time of own resistance of polarization, the sign of a major impediment in the process.

It should be noted, also, that in both cases with this monitoring strategy, real results were obtained that allow monitoring the corrosive phenomenon presenting clear potential in terms of works.

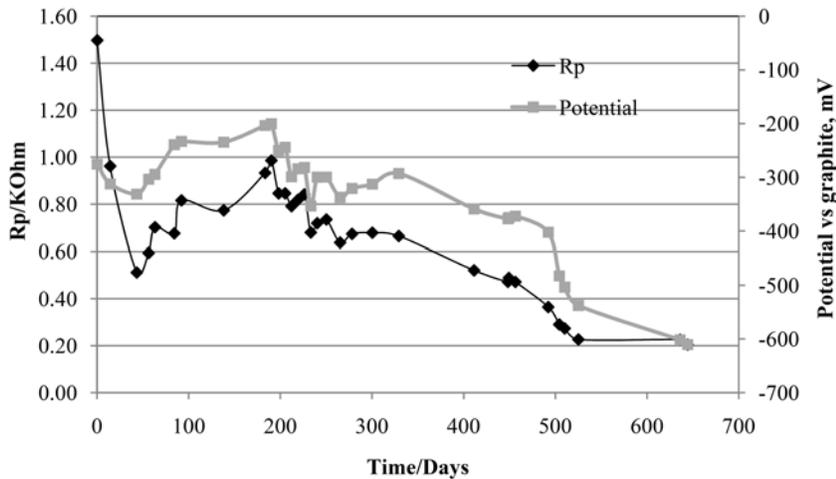


Figure 6. Variation of polarization resistance, R_p , and corrosion potential of the galvanized steel during the immersion in saline solution.

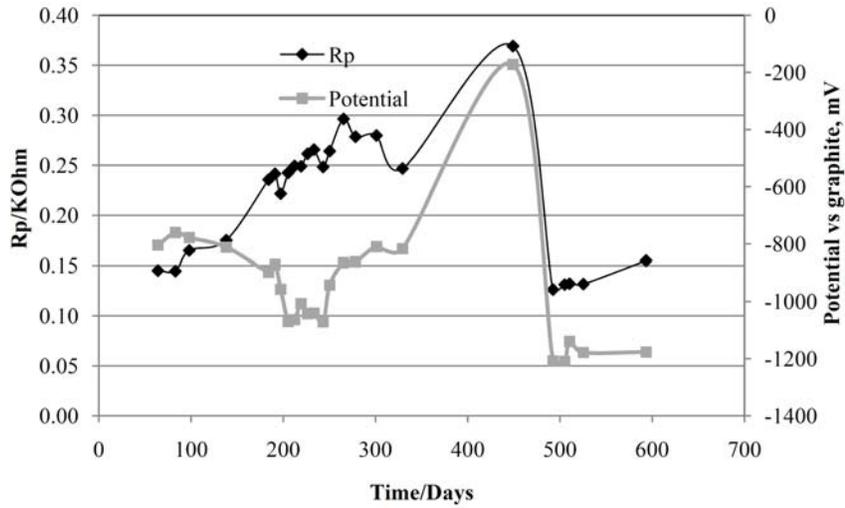


Figure 7. Variation of polarization resistance, R_p , and corrosion potential of the cathodic protection steel during the immersion in saline solution.



Figure 8. Steel at the end of the trial-reinforced steel, organic coated, galvanized steel and cathodic protection steel.

4. Conclusion

The main objective of this work was to compare the behaviour of different solutions for the protection of reinforcement steel to face the behaviour of current steel in saline environments, with recourse to monitoring systems. The main conclusions obtained in this experiment were the following:

- Coating with acrylic paint slightly slows the onset of reinforcement steel corrosion, but does not prevent its rapid generalization.
- The galvanized steel show a good long-term behaviour, presenting at the end of tests spot corrosion, while the current steel had already suffered widespread corrosion.
- The cathodic protection enables to delay the arrival of chloride ions to the surface of the steel.
- The continuous monitoring of reinforced concrete structures, with the measurement of the variation of the potential for corrosion of the steel cage, its resistance of polarization and resistivity of concrete, permits to follow the various stages of the process of degradation of reinforced concrete and to identify the beginning of the phase concerning the steel corrosion.

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