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Remote Monitoring Technique for Evaluation of Corrosion on Reinforced Concrete Structures

Guillermo Roa Rodríguez and Willian Aperador

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Abstract

This chapter presents the development of a new remote monitoring technique for the evaluation of corrosion on reinforced concrete structures, which uses embeddable variations of known ASTM standards and telecommunication technologies as a new way to estimate the rate of loss of the steel used as a component of rebar, since such phenomenon is the main cause of deterioration and degradation of the civil infrastructure. The adaptation of the technique was carried out to obtain an electrochemical half-cell that can be embedded indefinitely into the concrete, which provides the measurements corresponding to the corrosive state and allows calculating indirectly the rate of corrosion through the linear polarization resistance. The adaptation is based on a reference electrode of copper/copper sulphate, a segment of the same steel of the studied structure as working electrode and an auxiliary electrode made from pure graphite, all covered by mortar.

Keywords: Corrosion monitoring, Non-destructive testing on reinforced concrete, Corrosion Rate, Corrosion potential, reinforced concrete, Monitoring technique

1. Introduction

The reinforced concrete structures have a limited service life; such durability depends on the concrete resistance to various physical and chemical factors and its ability to protect the embedded steel against the corrosion processes. The referred processes create products of steel corrosion, which generate a volumetric expansion on the embedded reinforcements, causing extremely high stresses inside the concrete, transforming it into a medium susceptible to the generation of cracks from the position of the reinforcement to the surface or between the rebar. Once the cracks have appeared, the oxygen and moisture diffuse directly up to the reinforce-

ment at a greater rate that increments the rate of corrosion [1–3]. Like any natural disaster, earthquakes or severe weather disturbances, corrosion can generate highly risky and costly damage to multiple areas, starting from the automotive, fluid transport systems to the area of infrastructure (bridges, ports, public buildings). As a reference, from 1980 to 2002, the United States suffered 52 major disasters related to climate, which included hurricanes, tornadoes, tropical storms, floods, fires, drought and frost, incurring on losses estimated at US\$ 380 billion (US\$ 17 billion annually). According to the latest study, the direct cost carried by corrosion of metal structures is US\$ 276 billion annually, representing 3.1% of gross domestic product [3,4]. Unlike natural disasters, the phenomenon of corrosion can be monitored and controlled [3,4].

The detection of such corrosive phenomenon is usually performed when the structure clearly shows damage signals which are directly reflected in a rise in cost of corrective maintenance. From the perspective of project managers, there is a marked interest in obtaining information about the states of initiation of degradation processes, to avoid incurring the referred costs. A considerable number of articles and techniques have been published and implemented to perform the monitoring of the corrosive state on reinforced concrete, where some of them not only use a single technique but also use a combination of several evaluation methods that allow to gather information about the condition of the concrete and/or the actual situation of rebar [5,6]. Within those techniques, the standard ASTM C876-91 determines the reinforcement state in terms of probability accordingly to the corrosion potential of rebar (10% of probability of occurrence of the phenomenon, region of uncertainty, 90% of probability of occurrence of the phenomenon) [5,7]. Also a complementary technique could estimate the corrosion rate makes to consider a set of measurements as a more specific evaluation of the corrosion process; according to the aforementioned, the linear polarization resistance method (LPR) rises as the most common procedure, given its ease of interpretation of the results and its high reproducibility [5,8]. Although the mentioned techniques are widely applied, its major constraint relies on their flexibility, since they depend at all times on a hardware operated at the site of study (conducted by a user), which increases the costs due to equipment and travel expenses for the specialized personnel [9].

The purpose of this work is to introduce the design of a new remote monitoring technique for the evaluation of corrosion on reinforced concrete structures, which uses embeddable variations of known ASTM standards and telecommunication technologies as a new way to estimate the rate of loss of the steel used as a component of rebar which also allows to avoid cost overruns related with specialized technicians.

2. Introduction to the electrochemical techniques to assess the corrosive state on reinforced concrete

The corrosion of steel implies a separation of the anodic and cathodic processes that occur simultaneously on the surface; therefore, corrosion of carbon steel inside the concrete acts as a combined electrode over which the anodic and cathodic reactions take part; at the anode (where the corrosion process is carried out) steel is dissolved and oxidized into steel ions. Due

to the electronic balance condition, the ions, which have left the steel, are consumed by the cathodic reaction on the steel surface, where the oxygen is reduced and the hydroxide ions are produced. Depending on the spatial distribution of these reactions and the conductivity of the medium, it can be generated into two kinds of corrosion, uniform corrosion and macrocell corrosion. Uniform corrosion occurs when the anodic and cathodic reactions on the same area are coupled to form microcells. The electrode potential of such coupling is called corrosion potential E_{corr} . In the case of macrocell corrosion, the anodic and cathodic areas are separated; according to the circumstances of the case, it is presented as a considerable drop of the Ohmic potential that permits to separate the potentials of the cathodic and anodic area. In this process, the corrosion potential varies depending on the evaluated position within the limits of the anodic and cathodic corrosion potential [3].

2.1. Half-cell potential measuring on embedded reinforcements on concrete (open circuit)

The corrosion potential is measured as the potential difference according to a reference electrode or half-cell. This measuring is based on the electric and electrolytic continuity between the rebar, the reference electrode and the measuring element (voltmeter), which needs a high input impedance in such a way that the current which flows through the reference electrode does not disrupt the stability of the potential (it is acceptable as an input impedance of 10 M Ω). The connections must to be made such that the reference electrode is over the negative terminal and the reinforcing steel is brought to the positive port of the voltmeter; in this way the readings of the potential will be generally negatives, where the positive measurements are possibly due to passivated steels on dry concrete [3,10].

As previously mentioned, the half-cell potentials correspond to the corrosive level of steel, influenced by the surrounding environment, which is composed by variables such as the type of concrete cover, concrete resistivity, moisture content, oxygen availability and aggressive agents such as chloride ions and carbon dioxide. In corroded steels at contaminated environments, chloride ions can be obtained with potentials within a range between -400 and -600 mV versus an electrode of copper/copper sulphate; furthermore, the passive steel reacts as an oxygen electrode subject to pH variations in the pores of the concrete; hence, potentials on carbonated concrete are less negative. The corrosion potential for passive steels also depends on the oxygen availability and it varies over a great range of voltages [3,10].

The measurement technique is normalized in the standard ASTM C876-91, applicable to the evaluation in situ and is independent of the size of the reinforcement and depth at which it is located inside the concrete paste. This standard allows relating the corrosion potential measured with the probability of corrosion [3,11].

2.2. Calculation of the corrosion rate using the linear polarization resistance method (LPR)

Linear polarization resistance (LPR) is a non-destructive method designed to measure directly the polarization resistance (R_p) and indirectly the corrosion rate around the corrosion potential [3].

In order to implement the LPR measurement method, a small disturbance of polarization is applied to the reinforcement steel in the concrete surface, where its response is measured after a proper time delay. Using a potentiostatic method, an overpotential ΔE , between 10 and 30 mV, is supplied on the corrosion potential and after a typical time delay of 30 seconds, the response in current ΔI , is recorded [3,12]. Although the corrosion of steel is an electrochemical process and does not obey the Ohm's law, it has been demonstrated that if the applied polarization does not exceed ± 30 mV, the R_p value can be determined from the relation between the potential variation and the current variation and, if the polarization can be confined either to a known area A or to a small section isolated from the steel, the corrosion current density (i_{corr}) also can be calculated [3,12]. As ASTM G102 indicates, using Eq. 1, the corrosion rate can be directly determined [3,13].

$$\text{Corrosion rate} = (B \cdot K \cdot W_e) \cdot (d \cdot A \cdot R_p)^{-1} \quad (1)$$

where the value of B corresponds to the slopes of Tafel curves, where typically for the steel embedded in concrete they are assumed with values of 25 mV for steel under active conditions of corrosion and 50 mV for passive conditions, W_e is the equivalent weight in equivalent grams units and d is the density of the working electrode (rebar). K is the constant that defines the units of the corrosion rate, taking values either of 3272 to configure the units in millimeters per year *mmpy* (its units are) or a value of 1.288×10^5 for mils penetration per year *mpy* (its units are *mils* · (*ampere* · *centimeter* · *year*)) [3,13].

3. Remote monitoring technique for the evaluation of corrosion on reinforced concrete structures

The technique allows to adapt the ASTM standards into a remote mode with embeddable instrumentation with which it is possible to avoid movement of personnel to the measuring zone. The overall design allows both half-cell voltages (open circuit potential) and linear polarization resistance values become available and visualizable to the user through a web server.

3.1. Design of the embeddable cell

The reinforcement steels are typically protected by the alkaline nature of concrete. If that alkalinity is compromised at some point, the corrosion in the steel will initiate if oxygen and moisture combine. The corrosion reaction will promote the anodic and cathodic activity across the rebar, thus generating a corrosion cell by the electric difference between the two mentioned regions [14]. The design of the embeddable cell was made with a configuration of three electrodes (reference electrode, Re , working electrode, Wee , and auxiliary electrode, Ae), framed within the norms ASTM C876 and ASTM G-102.

The embeddable cell was designed with a diameter of 15 and 30 cm height. At its center, it was positioned as a segment of structural steel of 0.5 inches diameter and 15 cm height as the

working electrode. It was set as the embeddable reference electrode of copper/copper sulphate (Cu/CuSO_4) 45 mm next to the segment of steel, and finally at 42 mm of distance from the working electrode and 50 mm from the reference electrode it was embed as a pure graphite electrode (10 cm height), acting as an auxiliary electrode. The electrodes were covered by mortar with a water/binder relation for mortar as 0.65, which produces a porous mix that allows the surrounding medium to penetrate through the mortar up to the three-electrode system. This phenomenon assures that the medium inside the embeddable cell is equal to the medium of the whole structure, thus the measurements provided by the cell are reliable and equivalents. Such configuration allows to obtain an electrochemical half-cell that can be embedded indefinitely into the concrete (**Figure 1**).

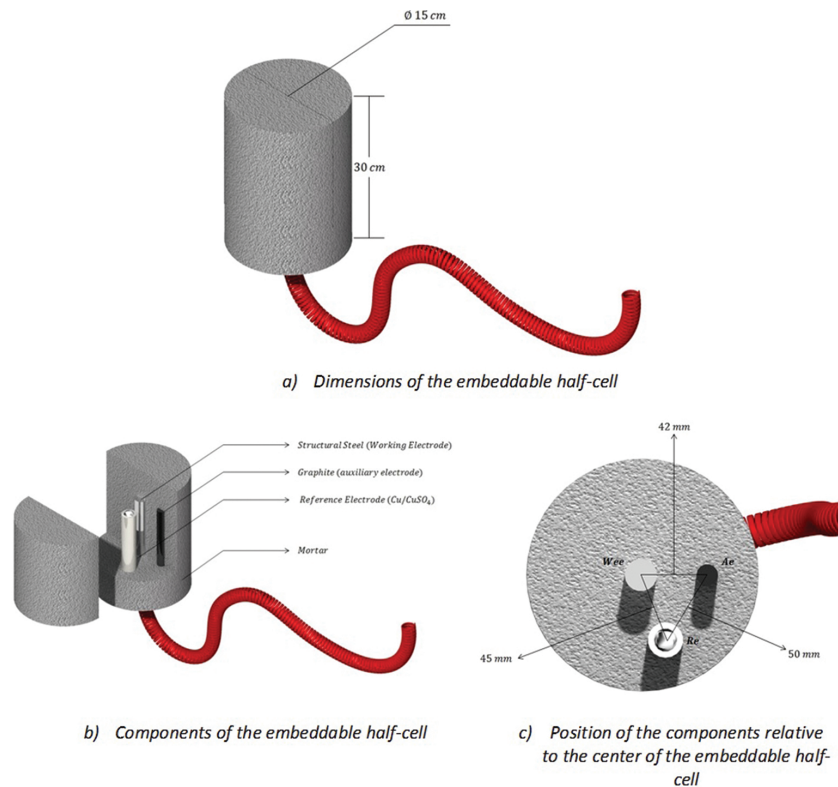


Figure 1. Design of embeddable half-cell.

3.2. Design of the control system

The design of the control system allows the equipment to prepare itself to perform the measurements after receiving a start command (the order is sent via a text message, at the discretion of the user). Once the command is received, the system determines the open circuit potential (half-cell potential) between the working electrode (rebar) and the reference electrode, subsequently, through an integrated circuit for analog to digital conversion (DAC), which guarantees accurate voltage increments up to 75 mV; owing to its resolution of 16 bits, it is supplied as a potential difference between the auxiliary electrode and the working electrode that is varied until it equals the open circuit potential minus 20 mV. To proceed to

the start of the voltage sweep, the test is done by varying the half-cell potential 1 mV per second, from -20 mV of the open circuit potential to 20 mV above it [3,14].

With each increase, the half-cell potential and the voltage are measured with a shunt resistance arrangement of $10\ \Omega$, $50\ \Omega$, $100\ \Omega$, $1\ \text{K}\Omega$, $5\ \text{K}\Omega$ and $10\ \text{k}\Omega$, which are selected according to the algorithm implemented. The mentioned selection is done to obtain the best measured resolution and also to perform de calculus of the current by Ohm's law. At the end of the voltages sweep, the measured values are used to calculate the polarization resistance and the corrosion rate using Eq. 1. Finally, the system sends the stored information in a format of a *.txt* archive to the GSM/GPRS module, which allows the transmission of information to a web server, where the variables are stored in a proprietary database, which gives the user the ability to view the information through a web application (Figure 2) [3,14].

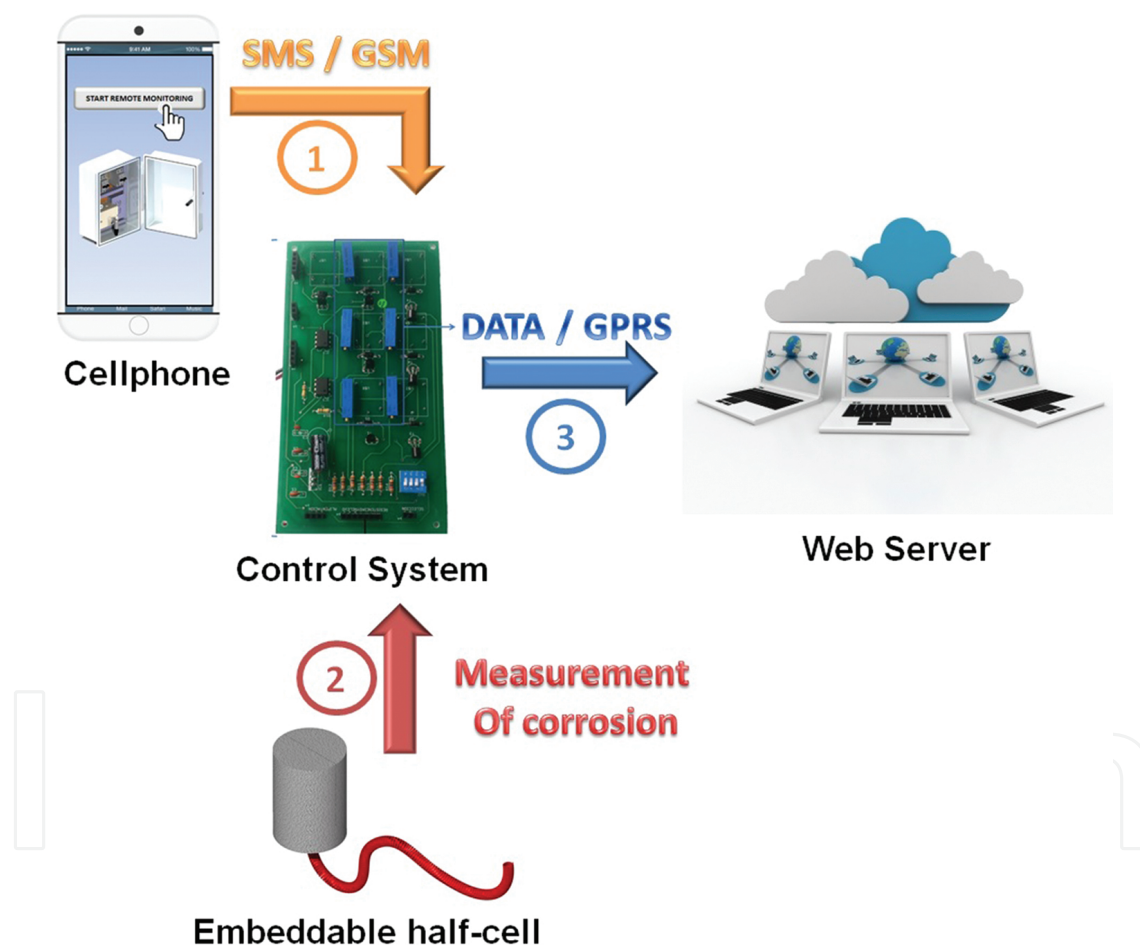


Figure 2. Design of the control system.

Once the test finishes, it is necessary to provide the information available to the user regardless of the place where comes from; for that reason, the design uses a GSM/GPRS board (Global Systems for Mobile Communications/General Packet Radio Service) which provides the ability to use the mobile network inserting a subscriber identity module for a mobile phone (SIM card), allowing to send and receive text messages, with which the remote command of the

equipment is done. The configuration of the module and the control board allows using the file transfer protocol FTP with which it is possible to send the *.txt* file to a web server to query the data generated on the tests.

3.3. Method to assess remotely the corrosive state of rebar

The method to assess remotely the corrosive state of rebar begins with the preparation of the structure to set the embeddable half-cell. First, it is necessary to identify the zone where the structural steel has the major risk of suffering the corrosive phenomenon as a critic representation of the whole structure. Once the position is known, and if it is a new construction in progress, it is elemental to locate the embeddable half-cell parallel to the reinforcement. In contrast, if the place to be measured is an existing construction, after identifying the critic zone, it is mandatory to locate the rebar and next to it bore a hole of 22 cm diameter and 40 cm depth, at which the embeddable half-cell can be placed, parallel to the structural steel. Finally, the hole needs to be backfilled with mortar where its water/binder relation is 0.65 (**Figure 3**).

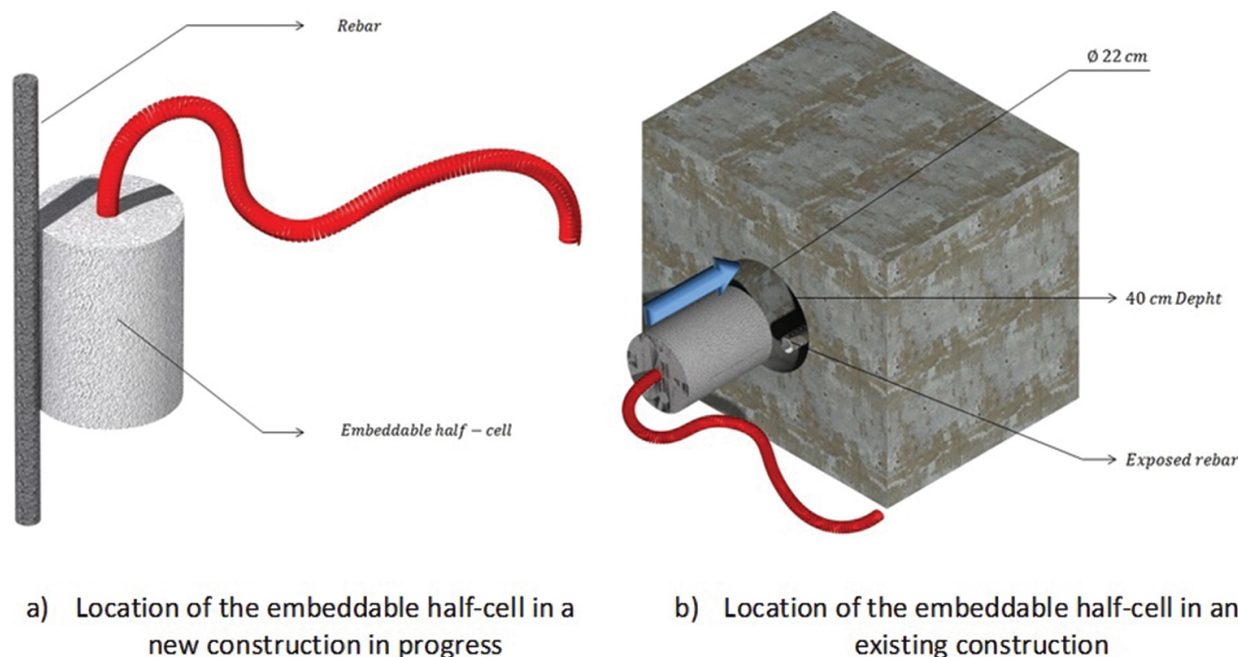


Figure 3. Location of the embeddable half-cell.

After placing the half-cell, we proceed to install the control system to perform the measurements. Once the system receives a text message with the start command, the data acquisition begins where the acquired information corresponds to the half-cell potential and the polarization potential. Then the system sends the data package to a web server through which a developed web supervisory allows consulting the information of the corrosive state (probability of corrosion and corrosion rate) (**Figure 4**).

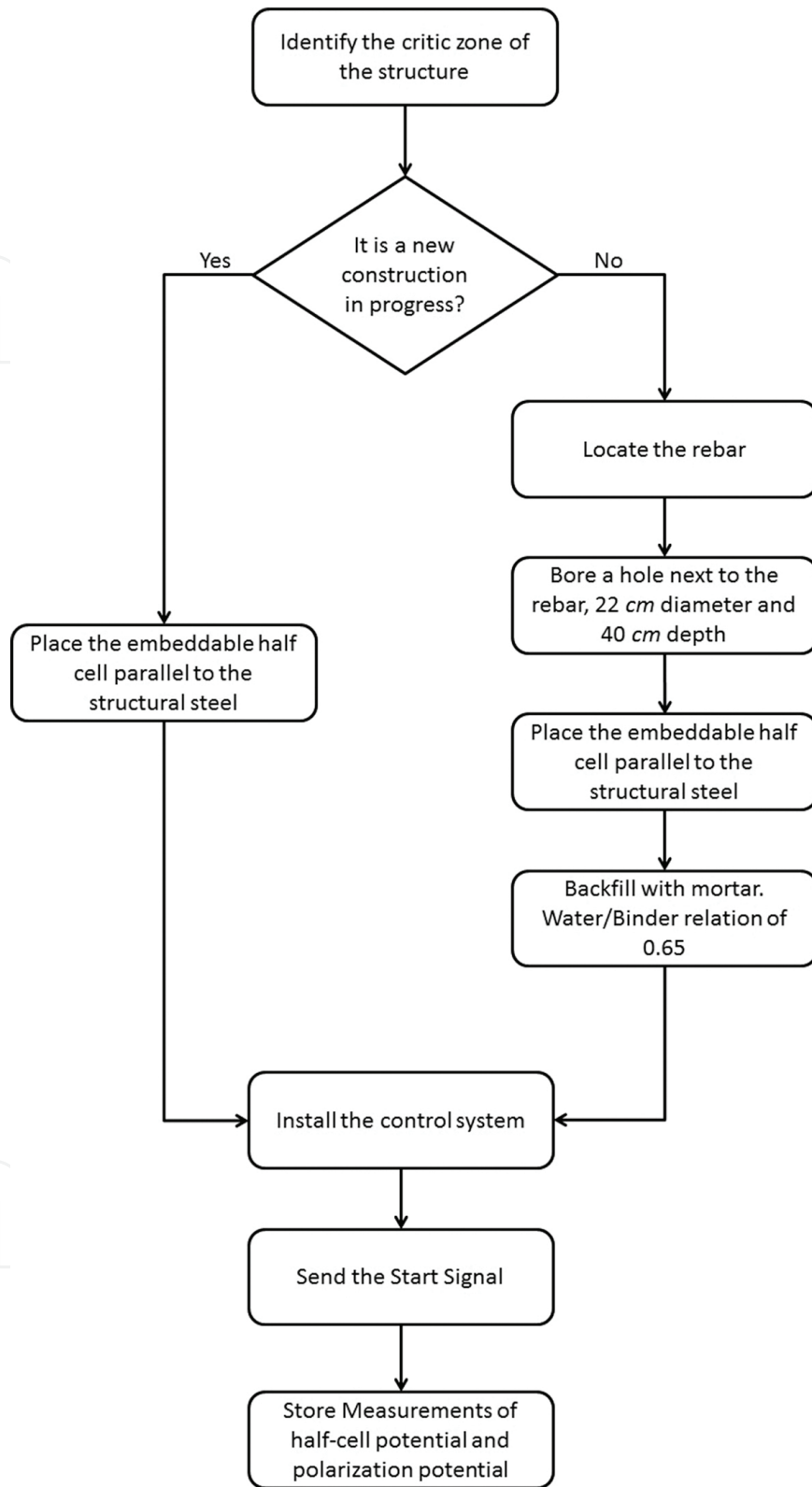


Figure 4. Flowchart for the designed method.

3.4. Corrosion monitoring test on concrete specimen

An embeddable half-cell with the specifications mentioned above was prepared. The probe was allowed to cure for 28 days at a temperature of 25°C at constant moisture (**Figure 5**).



Figure 5. Preparation of the embeddable half-cell.

After the curing period, the designed system and a commercial potentiostat (Gamry PCI4) were used in parallel in order to establish a parameter measurement for error values on the measures. Constant monitoring for 192 hours was conducted in an environment free of aggressive agents. These measurements allowed determining the state of the embeddable half-cell prior to set it into the structure object of study [3].

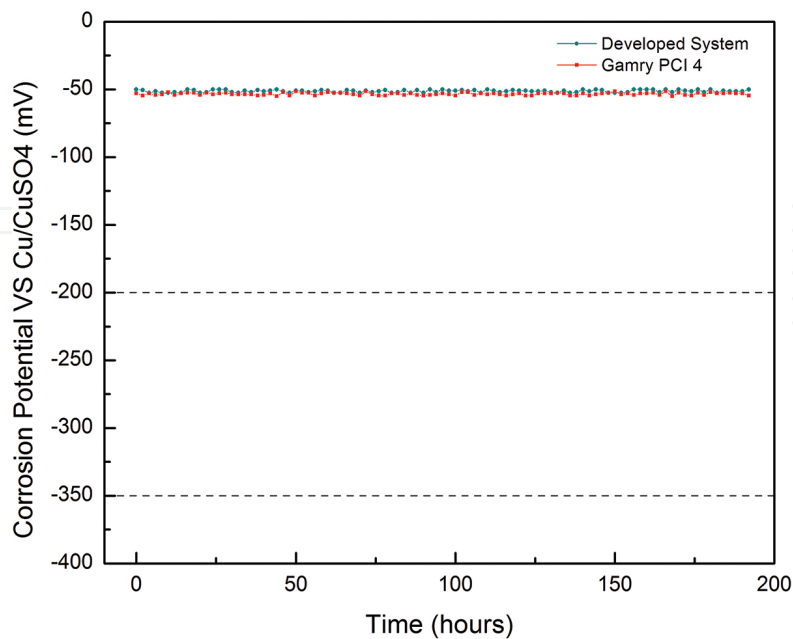


Figure 6. Corrosion potential of embeddable half-cell prior to set it into the structure [3].

As shown on **Figure 6**, the corrosion potentials are constants, allowing to calculate an open circuit potential of -52 mV, which corresponds to a 10% or minor probability of corrosion. Also, the data comparison between the proposed design and the commercial equipment over the total time of the test gives a maximum error of 8.4 and 0.03% as minimum where the average error is 3.62% [3].

The linear polarization resistance value for the test was 13 k Ω which when used in Eq. 1 with the values of the steel segment area, K , We , density and B yields a corrosion density of 0.0045 and a corrosion rate of 526.11×10^{-6} *mmpy*, which corresponds to a classification of corrosion as very low, concordant with the obtained corrosion probability, where B was assumed as 50 mV because the passive corrosion conditions, We takes a value of 27.92 equivalent grams, the density of steel is considered as 7.87 and K was assumed as 3272 to establish the units of corrosion rate as millimetre per year *mmpy* [3]. The error values of the linear polarization resistance were found, wherein the maximum gives 6.58%, the minimum error gives 0.019% where the average error is 3.46% (**Figure 7**) [3].

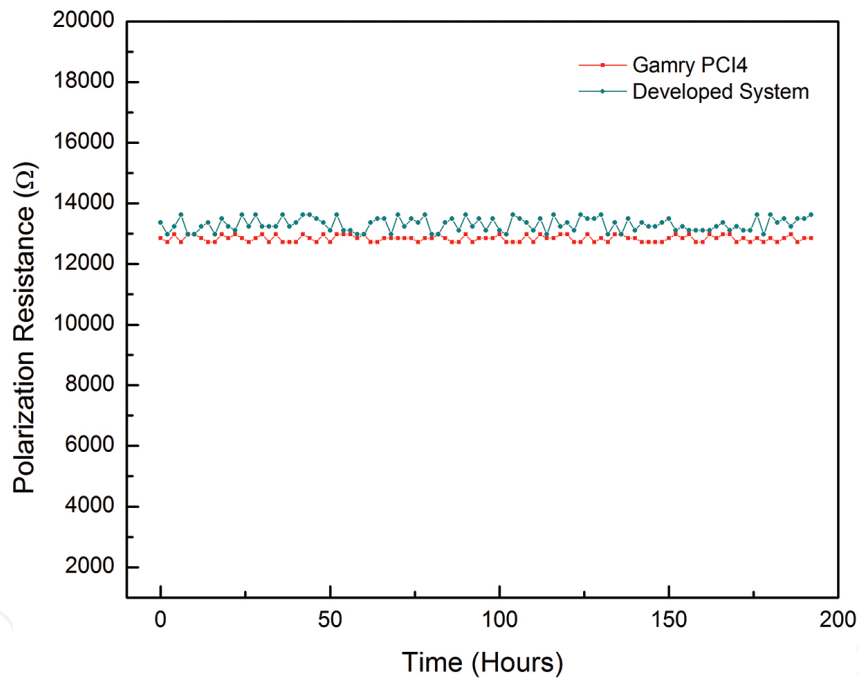


Figure 7. Polarization resistance of embeddable half-cell prior to set it into the structure [3].

After determining the error of the half-cell, it was taken to the measuring site, located in the city of Cajicá in the Department of Cundinamarca in Colombia, specifically at the Acoustical Shell of the Universidad Militar Nueva Granada.

As the place of measuring was a new construction in progress, first it was identified as the zone where the structural steel has a major risk of suffering corrosion, the embeddable half-cell was set parallel to the reinforcement as shown in **Figures 8** and **9** and where the place has a high concentration of chloride ions, as the acoustical shell is located 14 km from a mining area of extraction and refining of salt. Finally, the control system was installed.



Figure 8. Acoustical Shell of the Universidad Militar Nueva Granada.



Figure 9. Installation of the embeddable half-cell.

As shown in **Figure 10**, monitoring was carried out each 2 hours during 10 days, reaching a maximum potential of -386mV corresponding to a probability of corrosion just over the limit of 90%. Once the pores of the concrete are saturated owing to the high concentration of CO_2 and chloride ions, the corrosion potential stabilizes over -305mV on the uncertainty region.

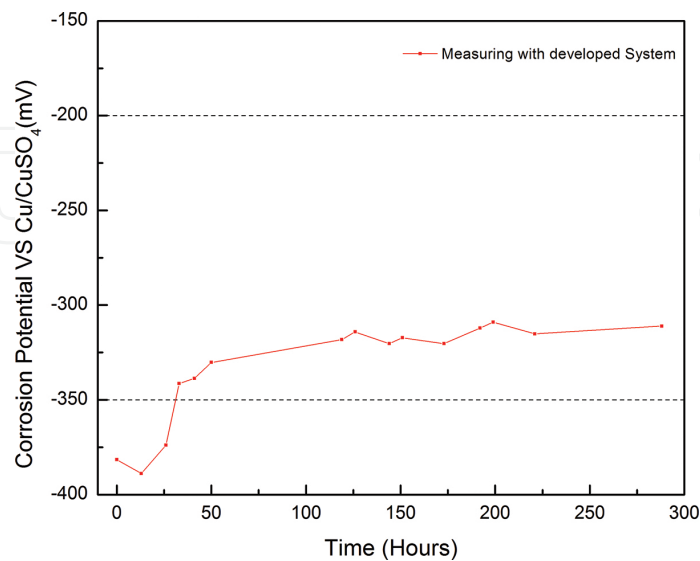


Figure 10. Remote monitoring of corrosion potential [3].

The test of linear polarization resistance was carried out after 10 days as shown in **Figure 11** wherein the average value of the linear polarization resistance was $1.98 \text{ k}\Omega$ when used in Eq. 1. Together with the values of the steel segment area, K , We , density and B (B is assumed to be 26 mV , since the corrosion conditions are active) yield a corrosion density of 0.309 and a corrosion rate of $3.592 \times 10^{-3} \text{ mmpy}$, which corresponds to a classification of corrosion as low/moderated, concordant with the obtained corrosion probability, We takes a value of 27.92 equivalent grams, the density of steel is considered as 7.87 and K was assumed as 3272 to establish the units of corrosion rate as millimetre per year *mmpy*.

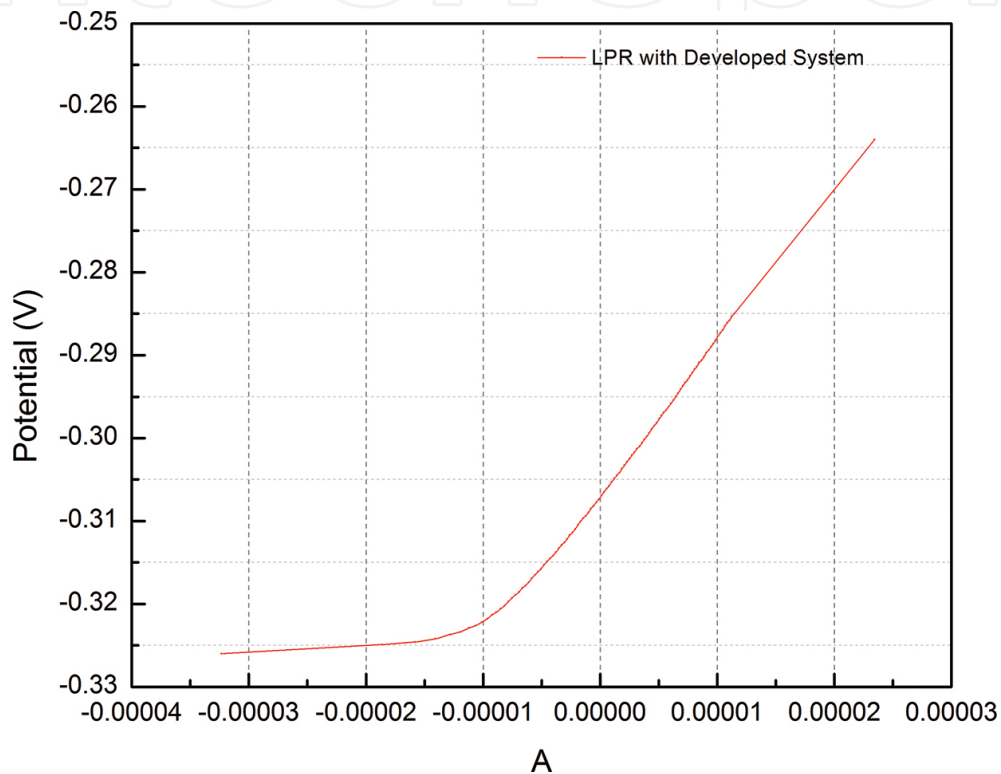


Figure 11. Remote monitoring of linear polarization resistance [3].

4. Conclusions

Through this study, the feasibility of implementing an embeddable remote monitoring technology for determining the corrosive state of reinforced concrete structures subjected to the carbonation phenomenon following the regulations present in the standards ASTM C876 and ASTM G-102 was verified. Such viability was determined from the given performance of the developed system versus commercial equipment used as a pattern, where the mean error on open circuit potential was 3.62% while the mean error on the test for resistance to linear polarization with respect to the calculations from the polarization resistance was 3.46% . Use of the remote measuring technique and the information provided by the developed system

allow diagnosing a reinforced concrete structure identifying the corrosive state of the reinforcing steel structure by determining the corrosion probability and the corrosion rate of the material, avoiding any movement of personnel to the measuring site and any destruction of the structure.

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Author details

Guillermo Roa Rodríguez and Willian Aperador

*Address all correspondence to: guillermoroa.rrg@gmail.com

School of Engineering, Universidad Militar Nueva Granada, Bogotá, Colombia

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