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Examples of reinforcement corrosion monitoring by embedded sensors in concrete structures

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ABSTRACT

An increasing number of concrete structures are being monitored to enhance their durability. However, the literature provides only some guidance for the interpretation of the monitoring results [Broomfield JP. Corrosion of steel in concrete, understanding investigation and repair. 2nd ed. UK: Taylor & Francis; 2006; Andrade C, Alonso C. On-site measurements of corrosion rate of reinforcements. Constr Build Mater 2001;15(2–3):141–45; EN 206 2000. Concrete—Part 1: specification, performance, production and conformity]. Past experience shows the difficulty of interpreting the data collected due to the influence of temperature and moisture, and of using these data to predict future evolution of any deterioration processes.

This paper presents several examples of recorded data for corrosion potential, electrical resistance and corrosion rates, along with a methodology to obtain a representative corrosion rate, averaged per year. The representative value can be used in corrosion predictive models to calculate the remaining service life.

1. Introduction

Corrosion of reinforcement is one of the main durability problems for concrete structures. The corrosion is induced by two main factors: carbonation of the concrete cover and penetration of chlorides contained either in the marine environment or in chemicals in contact with concrete. Corrosion of reinforcement induces structural damage that affects the serviceability and the safety of concrete structures. The structural risk associated with corrosion is promoting the use of embedded sensors, which can indicate the need for repair of the structure before reaching dangerous levels of damage [1,2,4].

In consequence, sensors have been installed in several critical structures, but difficulties arise when interpreting the results because the corrosion parameters are affected by temperature and moisture [5]. Although parameters correlated to the corrosion process (such as corrosion potential, galvanic currents, concrete resistivity or water content) can be monitored, the only parameter able to quantify the corrosion process is the corrosion rate, I_{corr}.

Very few studies have been published on the in situ monitoring of the corrosion rate and the influence of climatic changes and, in particular, of temperature, T [6,7]. All the studies conducted in the laboratory are based on controlled conditions of relative humidity, RH, and T. Only few studies have reported on the effects of the natural climatic cycles on the corrosion rate [8–12].

Apart from the monitoring of different complementary parameters, this paper presents I_{corr} results obtained from the monitoring of three concrete structures. The relationship between temperature and corrosion rate is also shown.

To account for the variation of I_{corr} due to the environment, it is necessary to establish a methodology for determining the representative value of the corrosion rate in one structure. This paper also illustrates how to calculate a representative corrosion rate using the data collected by sensors or single corrosion rate measurements when monitoring is not possible.

2. On-site electrochemical techniques for corrosion measurement

2.1. Corrosion potential and resistivity maps

Due to its simplicity, the measurement of corrosion potential, E_{corr}, is the method most frequently used in field determinations. From these measurements, potential maps are drawn revealing those zones that are most likely to undergo corrosion in the active state [13]. However, such measurements are qualitative, which makes data interpretation difficult [14]. The same argument can be extended to measurements of resistivity, ρ [15], which are used sometimes jointly with E_{corr} mapping. The ρ values indicate the moisture content of the concrete [16], which is related to the

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corrosion rate when the steel is actively corroding, but which may mislead the interpretation in passive conditions. In Fig. 1, a corrosion risk map of a slab is represented. The risk level has been calculated by a combination of these two parameters: E_{corr} and ρ. The risk level or incidence probability presented in Fig. 1 takes into account the classification made by ASTM C867 [13] for the E_{corr} results, mixed with a parallel classification of resistivity results in which lower resistivity provides higher corrosion risk.

2.2. Polarization resistance

The only electrochemical parameter which allows one to quantitatively estimate the corrosion rate is the polarization resistance, R_p [17]. The R_p measurement has been extensively used in the laboratory. It is based on the application of a small electrical perturbation to the metal by means of a counter and a reference electrode. Provided that the electrical signal is uniformly distributed throughout the reinforcement, the $\Delta E/\Delta I$ ratio defines R_p.

The corrosion current, I_{corr}, is inversely proportional to R_p, i.e.,

$$I_{corr} = B/R_p \tag{1}$$

where R_p is expressed in kΩ cm^2 and B is a constant resulting from a combination of the anodic and cathodic Tafel slopes. The standard unit of I_{corr} is μA/cm^2.

The Tafel constant, B, takes values between 12 and 52 mV in the case of reinforcement measurements. In general, higher corrosion results in lower measured values for the Tafel constant. For conditions in which it is not possible to calculate B, due to the destructive nature of the test, it is recommended a B value of 26 mV be used as an averaged value to reduce the error for estimating this parameter. This procedure can, however, be a problem if I_{corr} needs to be calculated exactly, mainly when steel is passive [18]. In general, the use of an average value for B has not been problematic for the on-site corrosion evaluation in concrete.

The relatively high resistivity of the concrete results in I_{corr} values that are too low, if compensation of the voltage drop across the electrolyte resistance is neglected or not adequately performed. This IR drop is the product of current, I, and resistance, R. This is due to the fact that the calculated R_p is the sum of the resistance related to the corrosion process and the resistance associated with the electrolyte. The potentiostats to be used for R_p measurements have to be able to calculate the ohmic drop, or to compensate for its influence during the recording of the R_p measurement. Direct estimation of true R_p values from $\Delta E/\Delta I$ measurements is usually not feasible in large concrete structures. This is because the applied electric signal tends to vanish with distance from the counter electrode, CE, rather than spread uniformly along the working electrode, WE. Therefore, the polarization by the electric signal is not uniform, and it reaches a certain distance that is named the critical length, L_{crit}. Hence, $\Delta E/\Delta I$ measurements on large structures using a small counter electrode provides an apparent polarization resistance ($R_{p\ ap}$) that differs from the true R_p value depending on the experimental conditions. Thus, if the metal is actively corroding, the current applied from a small CE located on the concrete surface is 'drained' very efficiently by the metal and it tends to confine itself to a small surface area. Conversely, if the metal is passive and R_p is high, the current applied tends to spread far away (e.g., around 50 cm) from the application point. Therefore, the apparent R_p approaches the true R_p for actively corroding reinforcement, but when the steel is passive, the large distance reached by the current needs a quantitative treatment.

2.3. Modulated confinement of the current (guard ring) method

There are several ways of accounting for a true R_p value, among which the most popular is the use of a guard ring [19], which confines the current in a particular rebar area, as Fig. 2 depicts. The equipment used is able to automatically make the IR compensation in the R_p determination. The measurement is made by applying a galvanostatic pulse, lasting from 30 s (corroding) to 100 s (passive), from the central counter electrode. Then, another counter current is applied from the external ring. This external current is modulated by means of two reference electrodes called "ring controllers", located between the central counter electrode and the external ring, in order to achieve the required counterbalancing electrical field. These twin electrodes permanently control the external ring by means of detecting the current lines coming from the central counter electrode in order to adjust them within the predetermined area, which enables a correct confinement, and therefore, calculation of R_p. This method then makes an electrical delimitation of the area instead of determining it. So, as the measurement area is delimited by the guard ring, the use of the confinement method allows the evaluation of corrosion in certain localized areas. In this way, it is possible to determine the zones in a real concrete structure in which the rebar is corroding, and quantify the velocity of this deterioration. Even when this method is not able to distinguish directly between generalized and localized corrosion, as the measurement area is reduced to a small part of the rebar, it is useful for the localization of active pitting areas in a concrete structures. The interpretation of the corrosion rate maps obtained from the measurements made in the structure can help diagnose the causes that led to corrosion.

It should be noted that not all guarded techniques are efficient. Only that using a modulated confinement controlled by the two small twin sensors for the guard ring control placed between the central auxiliary electrode and the ring (Fig. 2) is able to efficiently confine the current within a predetermined area. The use of guard rings without this control leads to high values of I_{corr} for moderate and low values. Accordingly, the error introduced in the case of very localized pits is high [20,21].

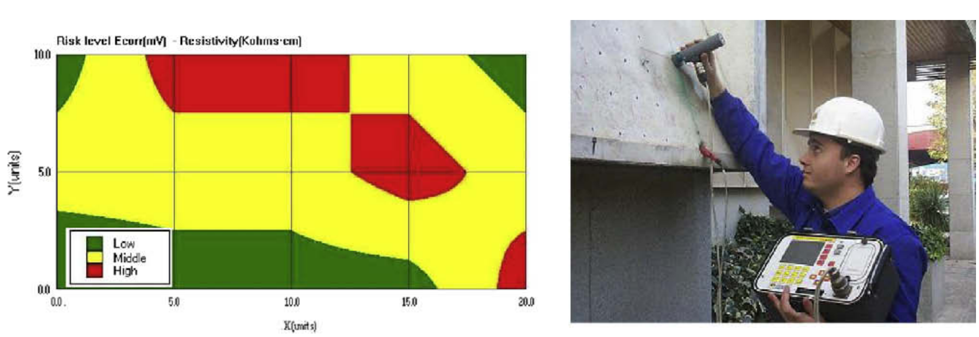

Fig. 1. (a) Corrosion risk map of a reinforcement slab calculated from the combination of E_{corr} and ρ measurements; and (b) on-site measurement with a portable corrosion rate meter (Gecor 08).

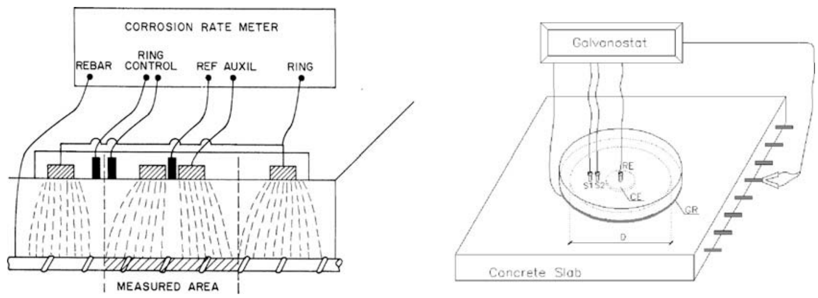

Fig. 2. Modulated confinement of the current (guard ring) method.

2.4. Potential attenuation method

As it is impractical to prepare a sensor to be installed in a concrete structure to measure the modulated confinement, another method has been developed in order to have a sensor of easier practical application for monitoring proposes. For these situations, the measurement of potential attenuation with distance [22] has been developed. This method is based on the direct measurement of the critical length. The sensor consists of a small disc acting as the only counter electrode, which has in its centre the reference electrode for the recording of E_{corr}. Three other reference electrodes are aligned with the E_{corr} sensor at fixed distances. For the measurement, a potentiostatic step, lasting between 15 and 60 s, is applied to the bar. This applied potential step attenuates with distance as observed in Fig. 3 [23]. From the distance (L_{crit}) reached by the signal and by accounting for the bar diameter, it is possible to calculate the true R_p [22].

3. Monitoring of structures

3.1. Sensors for in situ corrosion monitoring

Sensor selection depends on the type of structure to be monitored (existing structures versus structures under construction). The installation of surface sensors is appropriate in the case of existing structures; embedded sensors are suitable in the case of structures under construction in which is possible to implement the sensors before casting. The types of embedded and surface sensors are shown in Figs. 4 and 5, respectively.

For the case of embedded sensors, the first prototype was designed by the authors for in situ corrosion monitoring in 1994 and is shown in Fig. 4. For this first test, it was necessary to study the long-term behaviour of the reference electrodes in concrete. Each sensor had different reference electrodes (Ti, MnO_2, Ag and Pb). A stainless steel disc was used as counter electrode for the corrosion rate and resistivity measurements made by the galvanostatic pulse method. Apart from the electrochemical corrosion parameters, temperature was measured using a thermocouple and in some cases, strength gages were also installed.

The surface sensors, which were designed in 2002, have MnO_2 as reference electrodes. These electrodes provided the best behaviour in the previous tests carried out using the embedded sensors mentioned before. In this case, the potential attenuation method [22] was implemented for the corrosion rate measurements. The sensor, which is shown in Fig. 5, can be easily attached to the concrete surface by means of a specific conductive interface of cement mortar.

3.2. Structures monitored

The structures that are being monitored include: (1) a bridge over Gualaquivir river in the south part of Spain (the sensors installed are shown in Fig. 5); (2) a loading platform in a harbor on the south coast of Spain (the sensors are shown in Fig. 4); and (3) a pilot container for radioactive waste storage (the sensors and structure are shown in Fig. 6).

Electrochemical and non electrochemical measurements were made in the three structures by installing a Geologger measurement system. The system is a galvanostat–potentiostat capable of measuring the electrochemical parameters and recording the deformation and temperature. It has up to 50 channels and can be pre-programmed to activate an alarm system when threshold values are exceeded. The equipment includes a data-logger for storing all the information and processing the results obtained.

3.3. Bridge over the Guadalquivir river

The bridge consists of a post-tensioned deck with a metallic girder. The concrete was contaminated with chlorides during mixing due to salt in the mixing water. Because of this contamination, corrosion is believed to have started in some parts of the bridge since its casting. When the problem was detected, surface sensors measuring corrosion rate, corrosion potential, concrete resistivity and temperature, were installed to monitor thirty two locations in

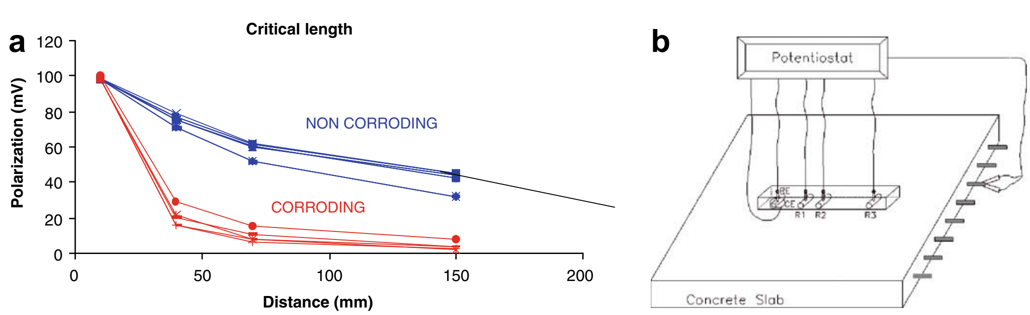

Fig. 3. Potential attenuation method: (a) example of the critical length reached by the current in corroding and non corroding structures; and (b) scheme of the electrodes disposition for the application of the method in a concrete structure.

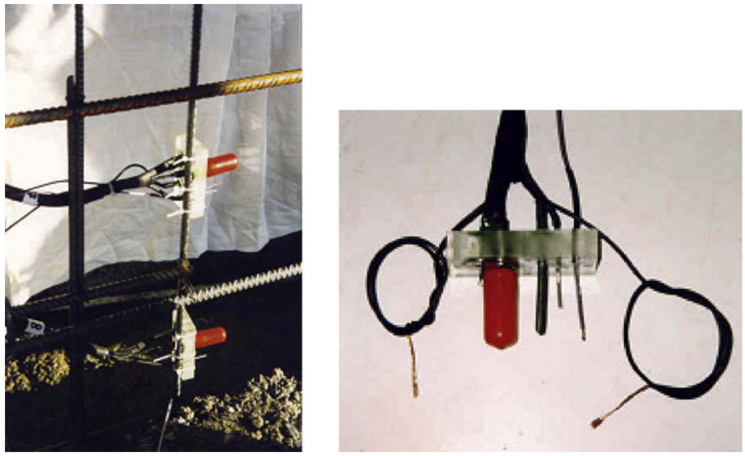

Fig. 4. Embedded sensors for electrochemical and temperature measurements installed in a dock in the south of Spain.

Fig. 5. Surface sensors installed underneath a bridge.

Fig. 6. Various stages during the embedment of sensors inside the pilot container in El Cabril, Córdoba.

the deck near the four pillars of the bridge (Fig. 7). Average values of the corrosion parameters are given in Fig. 8. From these average results, it can be concluded that the area near pillar 2 is the most affected by the corrosion problem. The average corrosion rate value registered in this area is higher than 0.1 $\mu A/cm^2$, while the rest of the areas evaluated near pillars 1, 3 and 4 provided corrosion rate values under 0.1 $\mu A/cm^2$, which can be interpreted as absence of corrosion. The corrosion potential results are in concordance with the quantitative corrosion rate mentioned before, as the values obtained in the area near pillar 2 indicate that the corrosion risk or

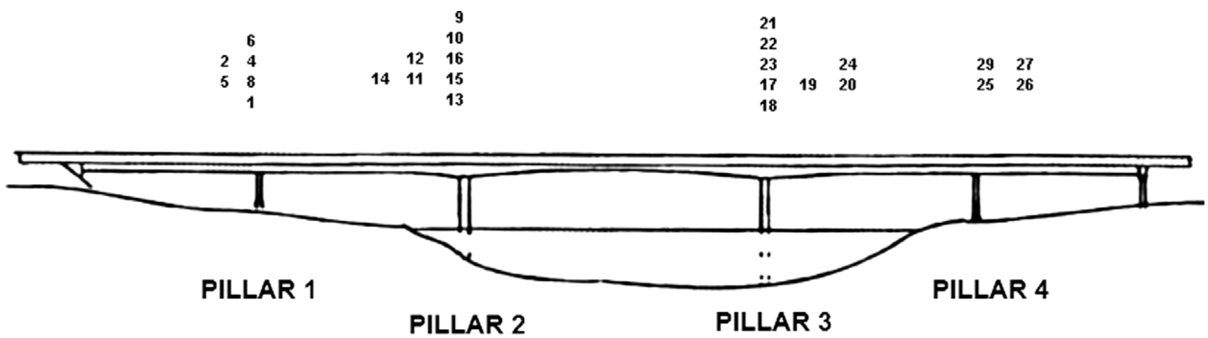

Fig. 7. Scheme of the sensors location along the bridge.

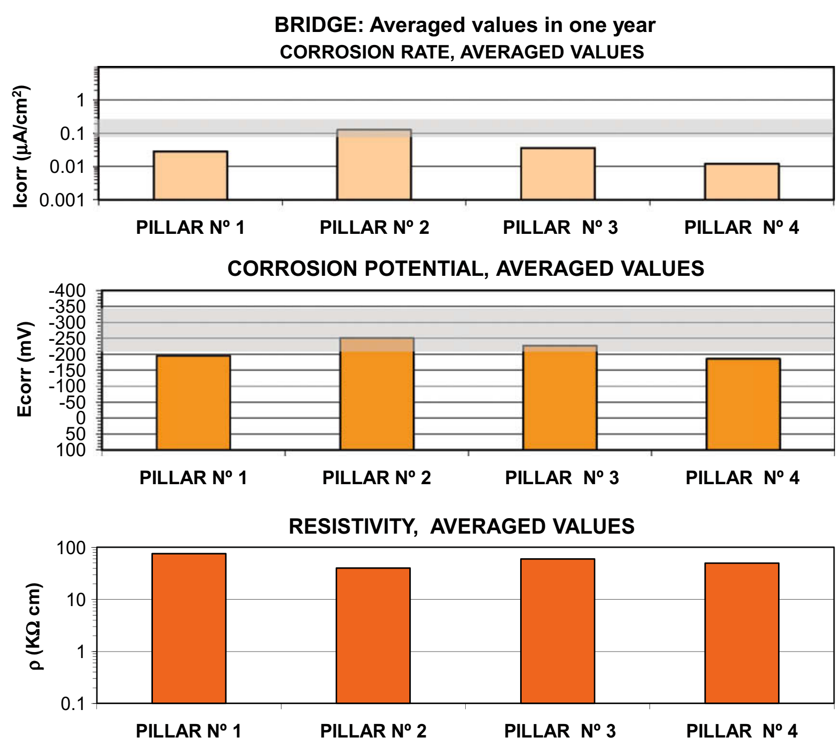

Fig. 8. Average values obtained for the different zones of the bridge deck over the Guadalquivir river.

the damage probability in this area is higher than in the other areas [13]. With respect to concrete resistivity, even when the lower resistivity values have been measured also in the area near pillar 2, the averaged values presented in the four pillars are in the same range, i.e., all the values are between 40 and 75 KΩ cm. This shows that resistivity measurements alone are not sufficient for corrosion detection. It is also necessary to monitor the corrosion rate.

An example of the results of the sensors installed in the area near pillar 2 is shown in Fig. 9. As can be observed in this figure, all the sensors situated in that area indicate more or less the same behaviour.

3.4. Harbor in the south coast of Spain

The harbor structure is a hollow cube in a dock of around 30 m wide. Fourteen groups of sensors were embedded at different depths, as shown in Fig. 10. The same figure presents an example of the results obtained in some of the sensors installed. As could be expected in an underwater structure, in which the concrete pores are almost saturated with salt water, resistivity values are lower than 10 KΩ cm. Even when the resistivity is so low, the results show that there is no corrosion. The values of E_{corr} in this structure are, however, not easy to interpret due to the saturated condition.

3.5. Radioactive waste storage

A special example of the use of embedded sensors is the case of storage facilities of low and medium radioactive wastes in El Cabril (Córdoba) [24]. A pilot reinforcement container has been monitored since 1995 by embedding 27 set of electrodes (Fig. 6). The parameters being monitored are temperature, concrete deformation, corrosion potential, resistivity, oxygen availability and corrosion rate. The impact of temperature on several of the parameters is described in more detail, and therefore, care has to be taken when interpreting in situ results.

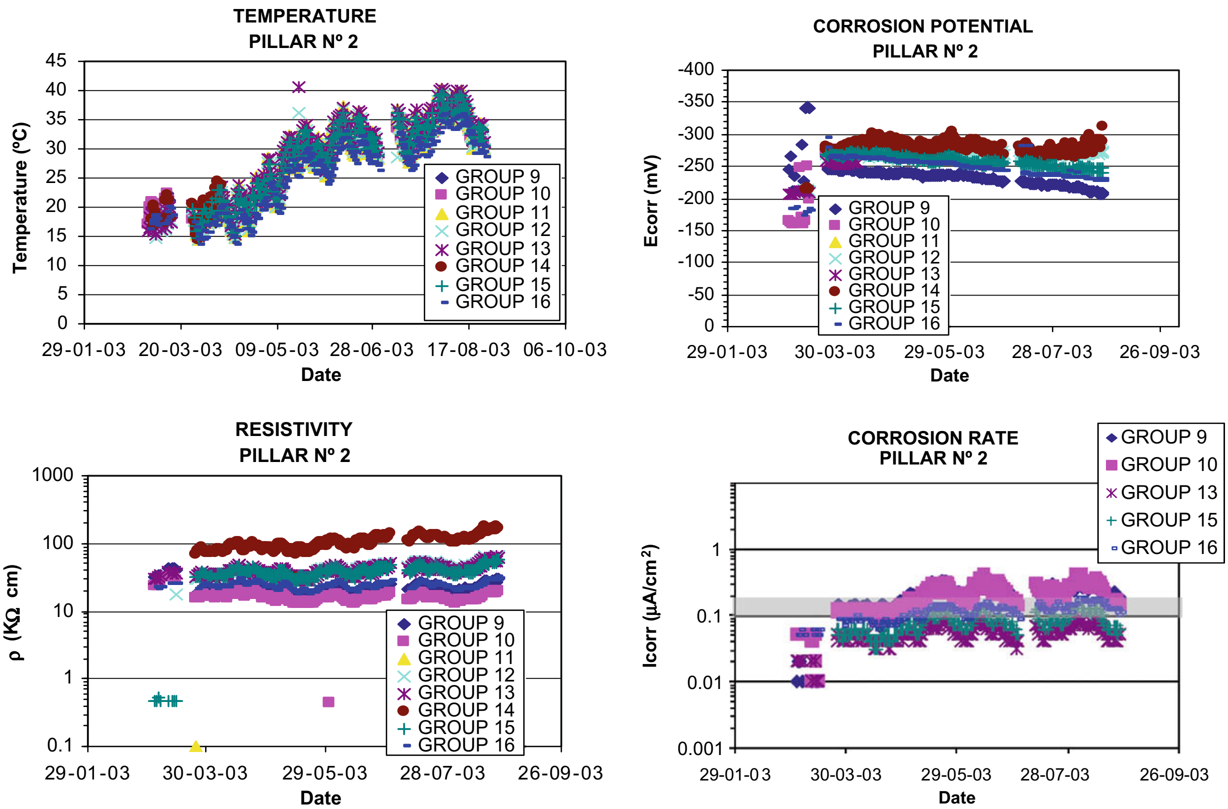

Fig. 9. Example of the results obtained near pillar no. 2 using corrosion surface sensors installed in the bridge deck.

For measuring the corrosion potential and the corrosion rate, either the main rebar of the container, or the sanded surface of the drums placed inside were used as working electrodes. The resistivity is measured by means of the current interruption method from a galvanostatic pulse. The oxygen flow at the rebar level is measured by applying a cathodic constant potential of about −750 mV (SCE) and measuring the current of reduction of oxygen [25]. From the 27 groups of sensors installed, less than 10% of them have failed. The remaining sensors show a good response even 10 years after their installation. As an example, Fig. 11 depicts the results obtained from one group of sensors placed in one wall of the concrete container (group 13).

The reinforcement remains passive as expected ($I_{corr} < 0.1$ μA/cm^2), and the corrosion potential presents values between −200 and −150 mV in comparison to MnO_2 reference electrodes. These results are related with low corrosion probability.

The annual cycles due to the environment influence are clearly detected in all the parameters monitored. The concrete resistivity increases during dry and hot periods and decreases during wet or cold seasons. Taking the annual average values, it increases with time due to the drying of the concrete during the exposition, reaching the value of 40 KΩ cm after 10 years. Even though this is not a high value, no corrosion is detected. Nevertheless, the increase of resistivity is expected to continue.

It is also observed that the oxygen reduction current measured tends to zero after about 5 years in the exposure conditions. This means that oxygen availability decreases with time, as was expected in a buried structure. Some data does not follow the same trend. This might be due to some errors in those measurements.

In summary, monitoring over 10 years has enabled several deductions. It can be stressed that the temperature significantly influences the responses of the sensors and that a progressive decrease of the amount of oxygen is detected without changing the values of the corrosion potential. The progression of hydration is well reflected by the electrical resistivity and, when the concrete is fully cured, the strains are good detectors of the presence of water in its liquid state.

As an example from among the 27 groups of sensors, Fig. 12 shows the correlation between resistivity and temperature of Group 13, and how it changes with time. It is clear that this relation is different at temperatures below and above about 22 °C.

4. Representative corrosion rate

In situ monitoring of concrete structures [26] has confirmed the ranges of values previously recorded in laboratory experiments [17]. In general, values of corrosion rates higher than 10 μA/cm^2 are seldom measured while values between 0.01 and 1 μA/cm^2 are the most frequent. When the steel is passive, very low values (smaller than 0.05–0.1 μA/cm^2) are recorded. These current density values can be translated into a loss in diameter applying the Faraday law, resulting that a corrosion rate of 1 μA/cm^2 produces a section reduction of 10 μm per year. When the corrosion rate is presented as μm/year, it is named V_{corr} instead of I_{corr}.

The accumulated corrosion is termed corrosion penetration, P_x, and can be expressed as a loss in diameter $\phi_t = (\phi_0 - 2P_x)$ with ϕ_t being the diameter after time t and ϕ_0 = the initial diameter. This reduced diameter can be due to localized (P_{pit}) or homogeneous corrosion, as Fig. 13 illustrates. It has been established that P_{pit} can be calculated from P_x [27] as there is a relation between the homogenous corrosion penetration and the maximum depth of a pit. This relation is named pit factor, α, which usually ranges between 3 and 15, with 10 being a suggested averaged value.

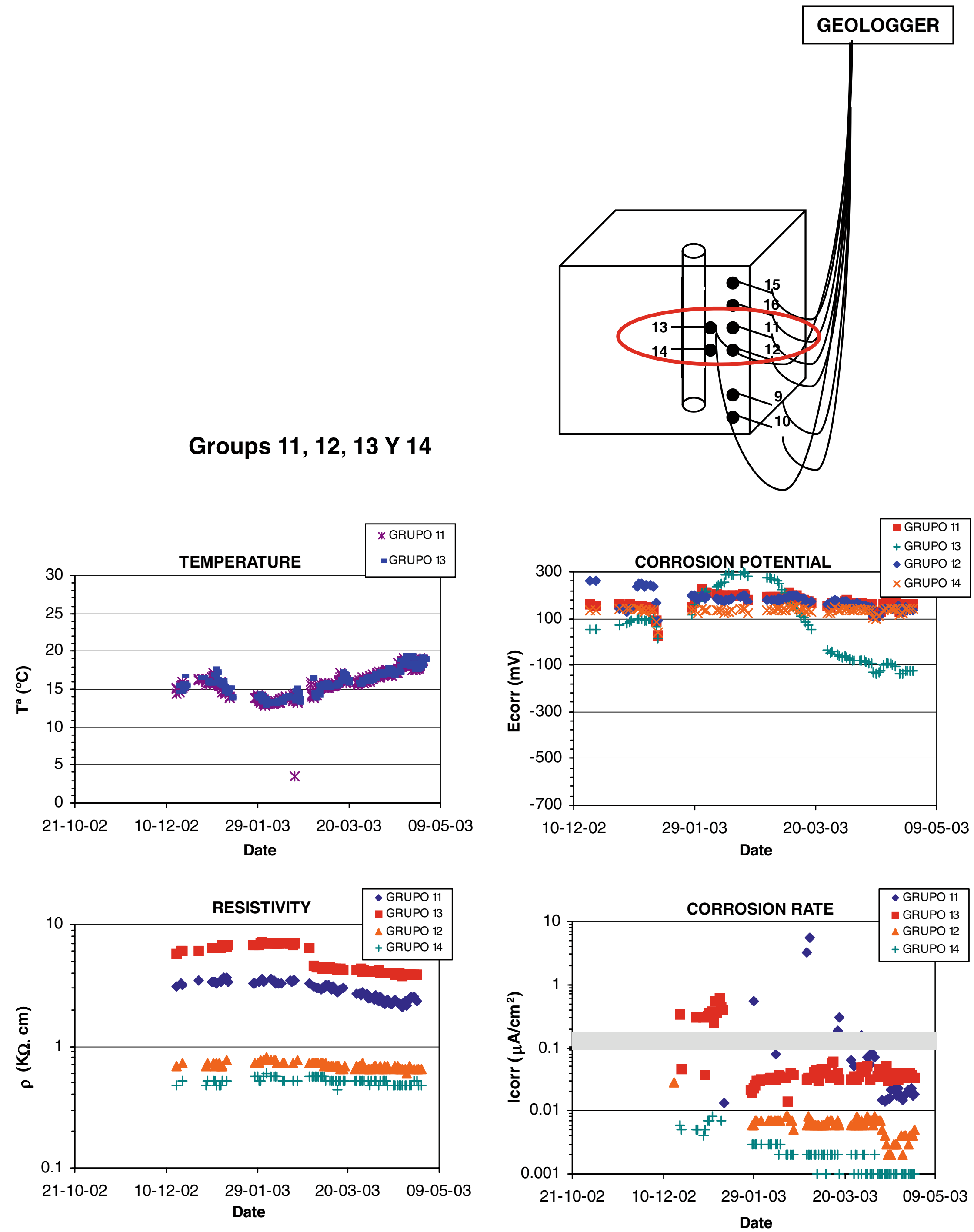

Fig. 10. Results obtained in the harbor structure situated in the south part of Spain.

As the corrosion rate does not have a constant value over time, neither in ambient conditions with constant humidity and temperature nor much less in structure is exposed to the open atmosphere, there is a need to calculate what has been termed a representative corrosion rate, $V_{corr,\ REP}$. There are several methods to obtain this averaged value which are summarized in Table 1:

1. The value of $V_{corr,\ REP}$ can be the result of the integration of the instantaneous I_{corr}–time curves presented in Figs. 9–11 over time and dividing the integral value by the years of corrosion propagation.
2. When no corrosion sensors have been installed and direct readings of the corrosion rate are not available for the particular structure, the approach to estimate an annual averaged value for $V_{corr,\ REP}$ is to assign a value as a function of the aggressivity of the particular environment. In Table 2, averaged $V_{corr,\ REP}$ values are given for the exposure classes of EN 206 [3].
3. When isolated measurements are the only possibility, obtaining a representative I_{corr} is more uncertain. In order to interpret the readings in the most accurate way, the procedure recommended is based on the relation between resistivity and I_{corr} [27]. Fig. 14 indicates that in the same structure the usual

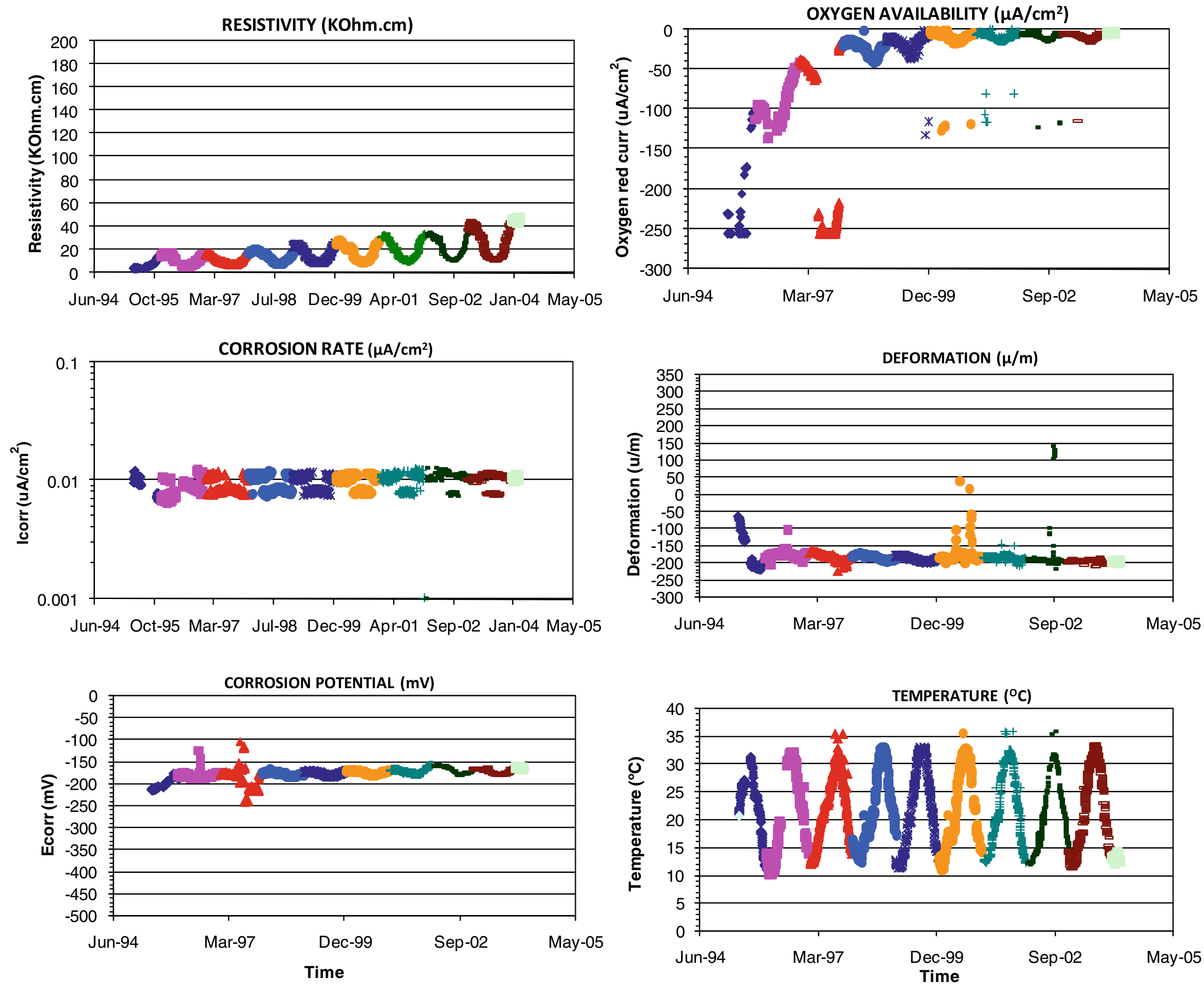

Fig. 11. Data recorded on a drum placed inside of the concrete pilot container (GROUP 13) from 1995 to 2004.

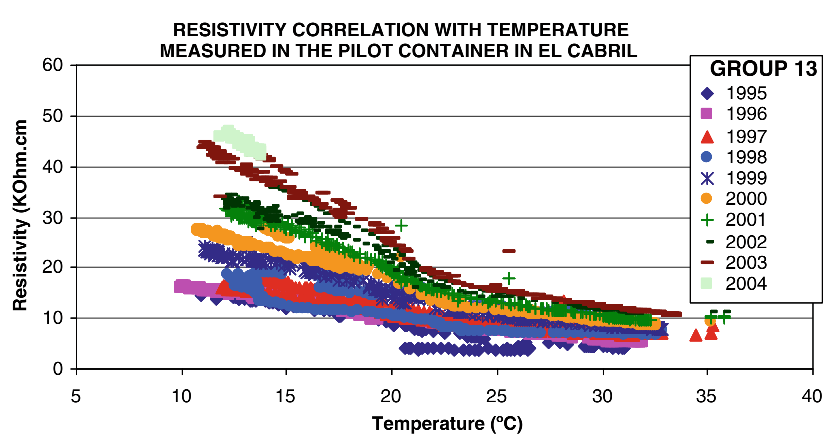

Fig. 12. Correlation between resistivity and temperature measured in buried conditions.

relation between I_{corr} and ρ when plotted in a *log – log* diagram is linear with a slope of -1 ($I_{corr} - 3 \times 10^4/\rho$). In consequence, the procedure proposed is the following:

- After having measured the corrosion current, cores should be extracted close to the measurement points. The cores are then conditioned to a moisture of 85% RH (for structures sheltered

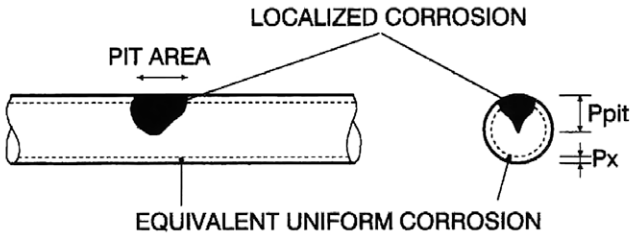

Fig. 13. Homogeneous or uniform corrosion equivalent to a localized corrosion showing a single pit with a corrosion depth of P_{pit}.

Table 1
Estimation of the averaged corrosion rate.

Estimation of $V_{corr,\ REP}$	Method of estimation
(1) From *direct* measurements of I_{corr}	*Integration* of the curves I_{corr}–time
(2) From a *Classification* of ambient aggressivity	By assigning a value to each *ambient class*. See Table 2
(3) Indirectly, from a *concrete characteristic* related to I_{corr} as pore water content or concrete resistivity	(a) From *pore water content* by an algorithm (b) From concrete *resistivity* taking account of its evolution with time and with pore water content

Table 2
Average corrosion rates $V_{corr,\ REP}$ for the exposure classes of EN206 [3].

Exposure class		$V_{corr,\ REP}$ (μm/year)
0	No risk of corrosion, very dry	0
XC1	Dry or permanent wet	0
XC2	Wet rarely dry	4
XC3	Moderate humidity	2
XC4	Cyclic wet dry	5
XD1	Moderate humidity	4
XD2	Wet, rarely dry	30
XD3	Cyclic, wet and dry	30
XS1	Airborne salt conditions	30
XS2	Submerged	Not corrosion expected or 10
XS3	Tidal, splash and spray zones	70

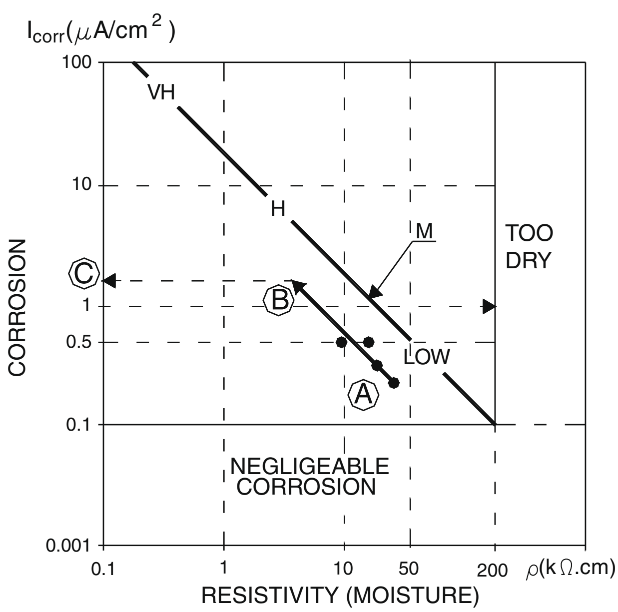

Fig. 14. Graph I_{corr} – ρ where VH – very high, H – high, M – moderate, L – low. (A) Measurement points, (B) extrapolation to minimum ρ, and (C) maximum expected I_{corr}.

from rain) or vacuum water saturated (for non sheltered or submerged ones). When the moisture content of the cores has reached equilibrium, their minimum electrical resistivity, ρ_{min}, is measured.

- Finally, the values of the I_{corr} – ρ registered on-site are plotted in the graph, as shown by points A in Fig. 14. The extrapolation to the maximum I_{corr} is made to reach the ρ_{min} (point *B*) at 85% HR or core saturation.

The I_{corr}^{rep} is calculated by averaging $I_{corr,\ single}$ and the maximum value achieved in the laboratory $I_{corr,\ max}$, i.e.,

$$I_{corr}^{rep} = \frac{I_{corr}^{sing} + I_{corr}^{max}}{2} \tag{2}$$

5. General comments

- The introduction of small sensors in the interior or at the surface of the concrete is one of the most promising developments in monitoring the long-term behaviour of concrete structures.
- The three case studies presented in this paper demonstrate that corrosion monitoring is possible using different sensors and methods. Moreover, the sensors continue to work in the alkaline concrete media for several years.
- Even though measurements of corrosion potential or concrete resistivity are useful for characterizing the corrosion state of a structure, the corrosion process can only be quantified by the corrosion rate measurement, I_{corr}.
- Due to the variation that I_{corr} presents in real structures exposed to the environment, it is necessary to establish a methodology for determining the representative value of the corrosion rate that corresponds to the concrete structure.

Acknowledgements

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