Embedded Sensors for the Monitoring Of Durability in Spain

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ABSTRACT

There are an increasing number of concrete structures that are being monitored in order to control their durability. However almost no results of the interpretation of the values obtained can be found in the literature. The experience until now shows the difficulty of interpretation of the data collected due to the influence of temperature and moisture on them and how to use these data to predict future evolution of the process. Of the corrosion parameters to be monitored and evaluated, corrosion potential, concrete resistivity and corrosion rate (measured by the polarization resistance method, R_p), seem to be the most useful parameters to be correlated with the environmental parameters for the characterization of the corrosion process.

In this paper, several examples of on site records of the corrosion potential, concrete resistivity and corrosion rates obtained from different structures in Spain are presented. The results obtained allow correlating corrosion and environmental parameters.

INTRODUCTION

The reinforcement corrosion is one of the main durability problems in concrete structures. It induces several structural damages which affect the serviceability and the safety of concrete structures. The structural risk is promoting the use of embed sensors which could give warning about the need for repair of the structure before reaching dangerous levels of damages.

In consequence, sensors are installed now in several critical structures but the problem arises when interpreting the results because all corrosion parameters are affected by changes of temperature and moisture.

About the corrosion parameters to be monitored and evaluated, corrosion potential, concrete resistivity and corrosion rate seems to be the most useful parameters to be correlated with the environmental parameters for the characterization of the corrosion process. In one hand because of its simplicity, the measurement of E_{corr} (corrosion potential) [ASTM C876-91] is the method most frequently used in field determinations. However, such measurements have only a qualitative character, which may make data difficult to be interpreted. The same that said for the potential can be stated on Resistivity, ρ, measurements, which have a direct correlation with the moisture content in the concrete covering [Millard et al 1992] [Andrade et all 1999]. In the other hand, the only electrochemical parameter with quantitative ability

regarding the corrosion rate is the so-called Polarization Resistance, R_p, so, more complicated sensors and measurement systems are needed for the monitoring of this parameter [Andrade and Gonzalez 1978] [Feliú et al 1990] [Feliú et al 1996] [Rilem TC 154-EMC Recommendation]. For the traditional R_p measurements as well as for the E_{corr} measurement, an electrical contact with the embedded rebar is needed. A new promising able to measure the corrosion without any electrical contact with the rebar is now under development [Andrade et al 2008].

In this way, and depending on the monitored structure, different sets of sensors have been designed. Each sensor implements the needed electrodes to carry out all the electrochemical and environmental parameters mentioned before. That is, each sensor has normally a reference electrode (for example Ti, Mn/MnO2 or Ag) and a stainless steel counter electrode for the corrosion rate and resistivity measurements. Temperature is measured by a thermocouple and in some cases, a water content sensor is also included.

EMBEDDED SENSORS USED

The type of embedded sensors used can be observed in Fig. 1. Depending on the structure in which they are going to be installed (new structures or existing structures), different group of sensors able to be attached to the concrete surface or embedded inside the concrete cover have been designed [Martínez and Andrade 2009].

Each group of sensors installed is composed by different electrochemical sensors or electrodes depending on the parameter to be measured. In one hand some sensors, as are the ones needed to evaluate corrosion rate or concrete resistivity, need an electrical impulse to be activated (active sensors). These sensors need to be connected to an electrochemical device (galvanostat-potentiostat) able to apply the signal and to record the sensor response. A stainless steel disk electrode is commonly used as counter electrode for the injection of the electrical signal in the corrosion rate and resistivity measurements. For the measurement of the corrosion rate, potential attenuation method [Feliú et al 1996] is the most useful to be used with permanent sensors. For these measurements, the sensor shown in Fig. 1B is used.

On the other hand there are other sensors (passive sensors), which don't need any impulse or electrical activation, and the parameter can be recorded directly through a data-logger. This is the case of corrosion potential sensors or water content sensors, which measure the difference of potential between the rebar and a reference electrode (in the case of corrosion potential sensors), or the potential variation between two metals embedded in mortar (water content determination). Ti, Mn/MnO$_2$, Ag and Pb are the most used reference electrodes for the corrosion potential evaluation. In the sensor group, a temperature sensor is also installed.

A)   B)   C)

Fig. 1.   A) Embedded sensors for electrochemical measurements installed in a dock in the south of Spain. B) Surface sensors installed inside a bridge. C) Passive sensors installed in Zarzuela Racecourse.

STRUCTURES MONITORED AND RESULTS OBTAINED

The structures whose results are presented are: 1) a bridge in the south part of Spain (the sensors installed are shown in Fig. 1.B). 2) A loading platform in a harbor in the south of Spain (sensors of Fig. 1A). 3) A Spanish pilot container for radioactive waste storage (structure shown in Fig. 5). 4) The Zarzuela Racecourse in Madrid, structure designed by E. Torroja in 1934 (sensors of Fig. 1C).

Electrochemical and non electrochemical measurements were made in the three first structures installing a Geologger measurement system. The system has a Galvanostat-Potentiostat build inside and up to 50 available channels and can be pre-programmed activating an alarm system when the values overpass a predefined range. In the case of the Zarzuela Racecourse, only passive sensors were installed, so, in this case portable data-loggers were installed.

Fig. 2.   Examples of structures monitored in Spain.

Bridge in the south of Spain

The bridge (Fig. 2.1) has a post-tensioned deck with a metallic girder. The concrete was contaminated with chlorides during mixing due to salt in the mixing water. Due to this contamination, corrosion started in the bridge from its casting. Sensors were installed in order to monitor 32 points near the four piles of the bridge. The results of some of the sensors are shown in Fig. 3, in which temperature, corrosion potential, corrosion rate and resistivity parameters are monitored. It can be noticed that due to the presence of chloride in some parts of the bridge, corrosion rate values higher than 0.2 $\mu A/cm^2$ are detected.

Loading platform in a harbor in the south of Spain

The harbor structure (Fig. 2.2) was a hollow cube in a dock of around 30 m side. 14 groups of sensors were embedded during the construction at different dept, as Fig. 4 shows. As could be expected in an underwater structure, in which the concrete pores are almost saturated with salt water, resistivity values are lower than 10KΩcm. Even when the resistivity is so low, the results show no corrosion, however, the values of E_{corr} in this structure are not easy to interpret due to the saturated condition.

Spanish pilot container for radioactive waste storage

A particular example of the use of embedded sensors is the case of storage facilities of low and medium radioactive wastes in El Cabril (Córdoba) (Fig. 2.3) [Andrade et al 2006]. There, a pilot reinforcement container has been instrumented from 1995 by embedding 27 set of electrodes. The parameters controlled are: temperature, concrete deformation, corrosion

potential, resistivity, oxygen availability and corrosion rate. The impact of temperature on several of the parameters is remarkable, and therefore, care has to be taken when interpreting on-site results.

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.

Regarding the resistivity, it 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. From the 27 groups of sensors installed, only less than 10% of them have failed. The rest show a good response even ten years after their installation. As an example, Fig. 5 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 (Icorr $< 0.1 \mu A/cm^2$).

The recording during 10 years has enabled several deductions among which can be stressed that the temperature influences very much the responses of the sensors and that a progressive decrease of the amount of oxygen is detected without being this noticed by the values of the corrosion potential. The progression of hydration is well reflected by the electrical resistivity and the strains are very good detectors of the presence of water in liquid state.

As an example among the 27 groups of sensors, Fig. 6 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 around 22 ºC and at higher temperatures.
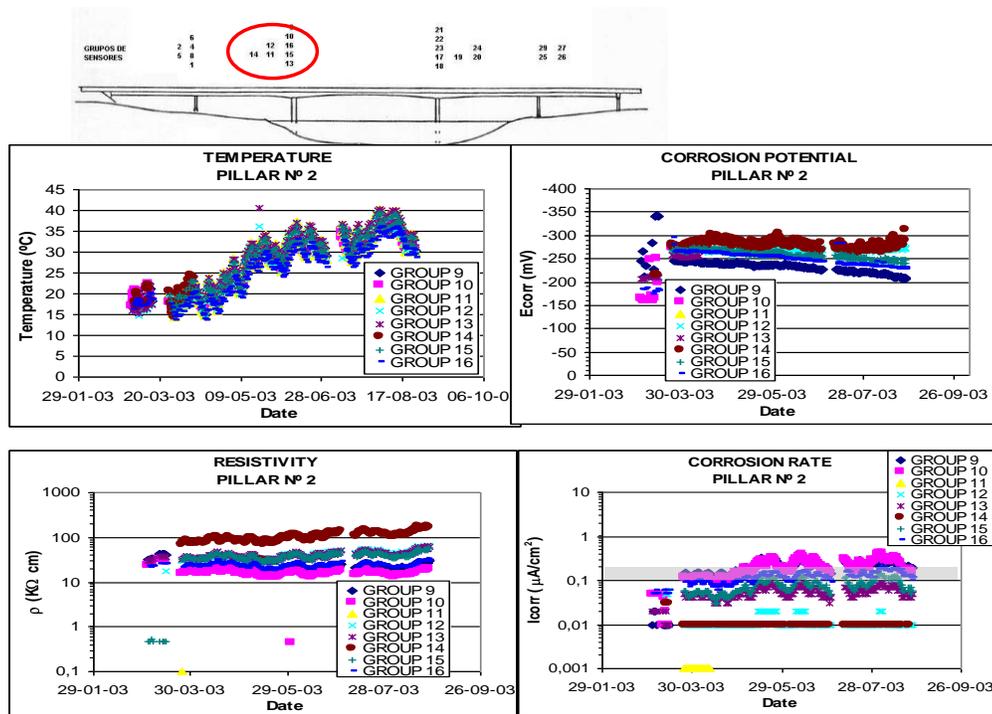

Fig. 3.   Results obtained through corrosion surface sensors installed inside a bridge.

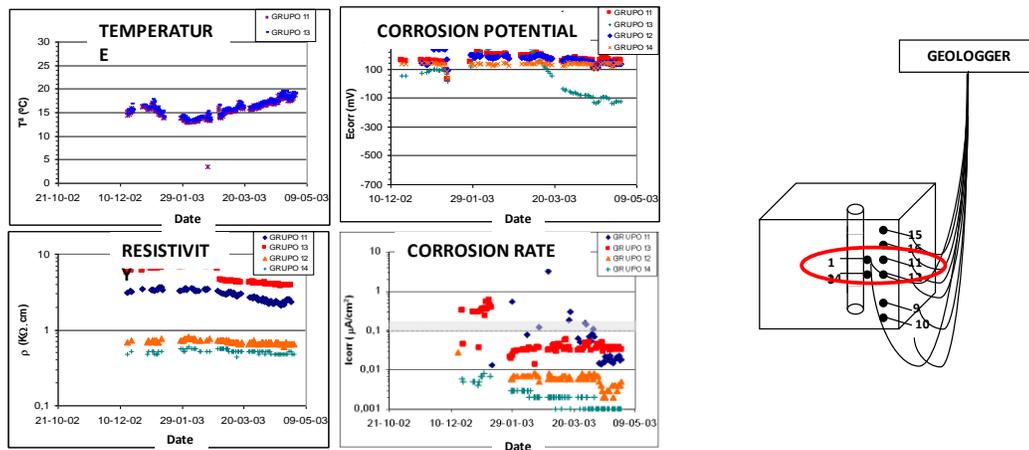**Groups 11, 12, 13 Y 14**

Fig. 4.   Results obtained in the harbour situated in the south part of Spain

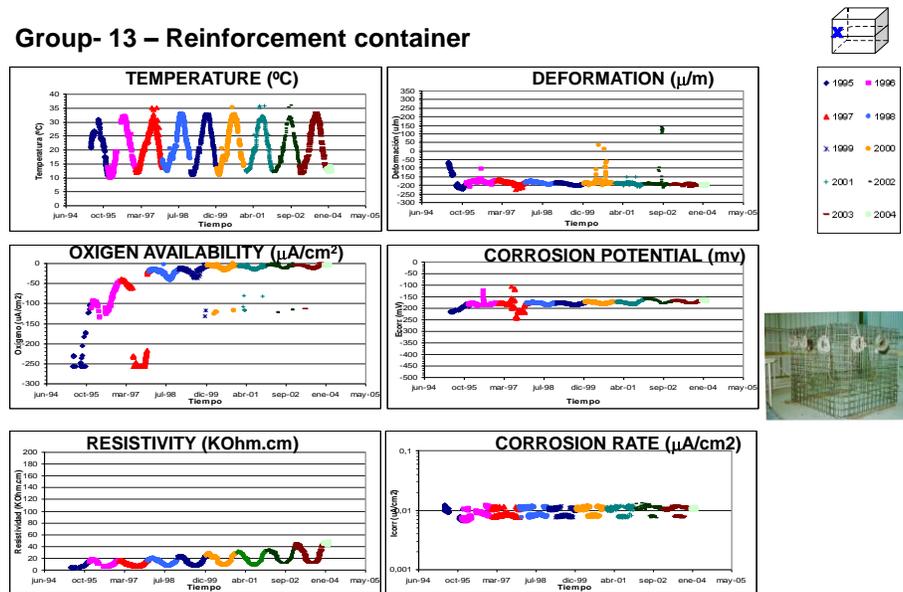**Group- 13 – Reinforcement container**

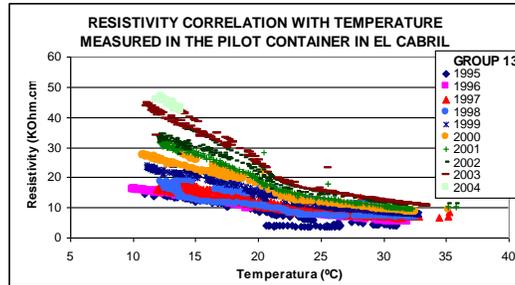Fig. 5.   Parameters registered on the concrete pilot container since 1995 to 2004.

Fig. 6. **Correlation between resistivity and temperature measured in buried conditions**

Zarzuela Racecourse

The Zarzuela Racecourse in Madrid was projected by the Engineer Eduardo Torroja and architects Arniches and Domínguez in 1934 [Hipódromo de la Zarzuela, Informes de la construcción 1962]. Due to the Spanish Civil war, it was not inaugurated until 1941, and the stands were declared National Heritage in 1980. There have been horse races steadily until 1996, year in which activity ceased. In 2003 Spanish National Heritage found a consortium for the Zarzuela race course exploitation, and in 2005, after nine years closed, the Race Course is re-opened. The restoration process described in this paper was undertaken in 2008.

The three decks of the structure are considered an art in terms of engineering. It is formed by thin concrete sheets of a hyperboloid shape with variable thickness between 65 cm in the area of pillars and 6 cm at the edges, supported up by a single pillar as cantilever to 13 m high. That is possible thanks to intelligent intertwined armed design and installation of steel bracing liabilities (Fig. 2.4).

During the hole service life of these structures no important maintenance works were undertaken. For this reason, and despite the good mechanical work of steel, it was started physic and physical-chemical deterioration processes due to its long period of exposure to the atmosphere, which has caused the corrosion of reinforcement by carbonation. The corrosion attack has been accelerated in some places due the loss of the upper waterproofing foil of the shell.

Considering the importance of this building, the authorities decided to undertake a restoration project where it is contemplated the installation of a continuous monitoring system. After removing all the paint in the lower part and the waterproofing in the upper part of the decks by water under pressure, an assessment of the extent of corrosion was required. It was possible to measure the carbonation front, and to apply a non-destructive electrochemical method based on the polarization resistance technique to verify the corrosion rate (Fig. 8a).

The corrosion rate (evaluated by the modulated confinement method by means of the corrosion rate meter Gecor 08 [Feliú et al 1990] [Andrade and Martínez 2005]) was quantified in different areas of the three decks (Fig. 7). The results indicate that almost all the structure is corroding due to the concrete carbonation. The majority of the values registered are in the range of moderate corrosion rates (between 0.5 and 1 $\mu A/cm^2$), as is shown in the example of Fig. 8b.

Other corrosion indicators, as are the corrosion potential and the resistivity, were also evaluated. E_{corr} was measured with a $Cu/CuSO_4$ reference electrode. The majority of the

values measured were in the range between -250 and -350 mV, what means an intermediate corrosion risk [ASTM C876-91]. Talking about concrete resistivity, very high values (higher than 200 KΩ.cm) were measured. These high values are due to the delaminations and voids present in the concrete, which do not allow a properly electrolytic contact for the measurement. For this reason, they do not correspond with the real concrete cover resistivity.

After the corrosion assessment, the concrete detached areas were removed and the rebars were cleaned and passivated. All the area was repaired with specific cement based mortar, and cracks were filled injecting resin and then sealed.

Electrochemical sensors able to indicate the risk of corrosion of reinforcement were installed in the decks and in the ties (Fig. 1C). These sensors enable the monitoring of the water content and the corrosion potential, in order to predict the need of maintenance interventions. As an example, some of the first results obtained are presented in Fig. 10.

The E_{corr} tend to less negative values with time what means that the steel is being passivated. In the case of water content sensors, the response is measured in mV (difference of potential between two metals embedded in the sensor). Values around 0mV means no liquid water, so, the new waterproofing system is working properly
All the temperature sensors have the same behavior and the correlation of the temperature with the electrochemical parameters is now under study.
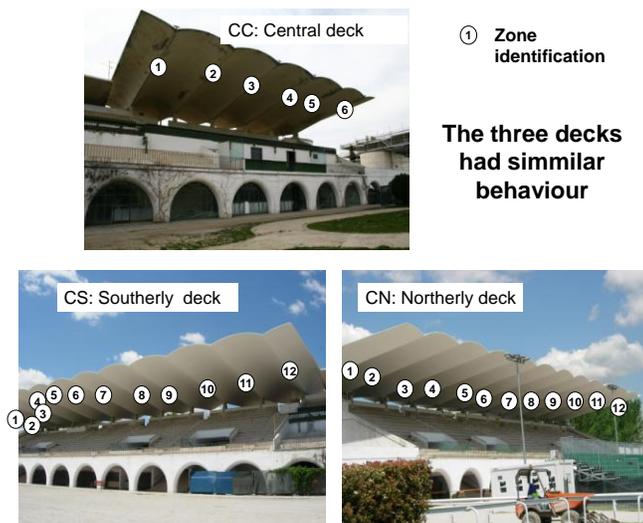

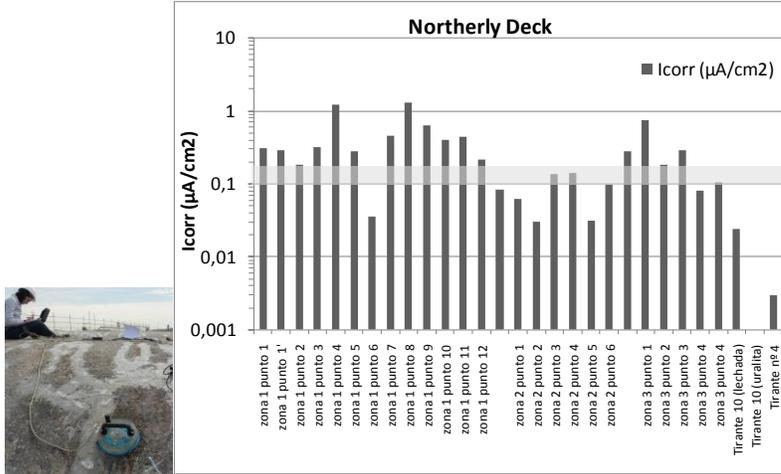**Fig. 7.   Different zones evaluated in the three decks.**

Fig. 8. Left: Sensor and device used for the corrosion rate measurements. Right: I_{corr} values registered in the northerly deck.
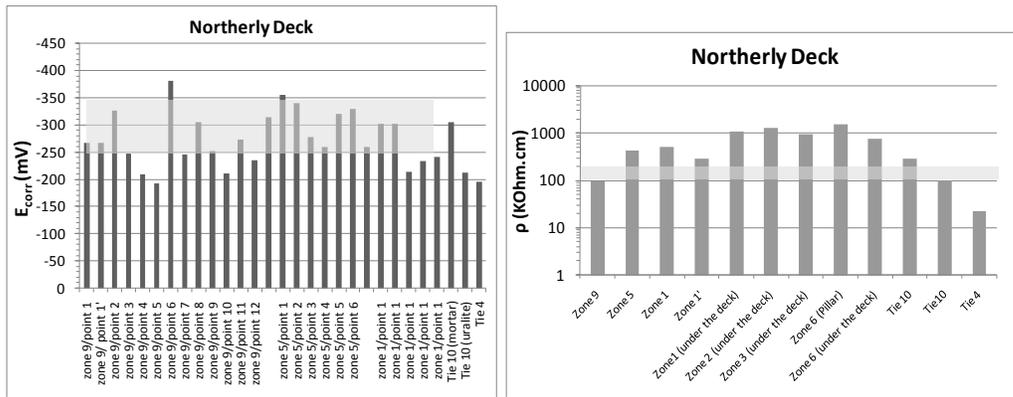

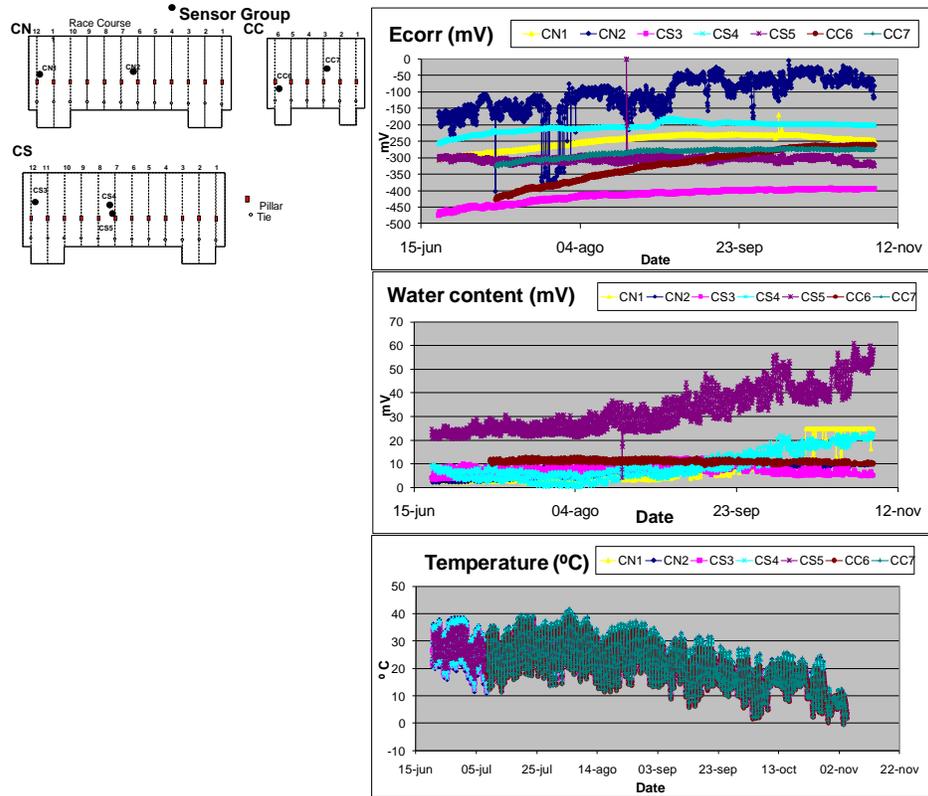**Fig. 9.** E_{corr} and resistivity results obtained in the northerly deck.

Fig. 10.   Some of the results obtained from the embedded sensors

CONCLUSIONS

- The introduction of small sensors in the interior or at the surface of the concrete can be considered as one of the most promising development in order to monitor the long term behavior of concrete structures.

- The four examples shown in present paper demonstrate that this monitoring is possible and presents different sensors and methods able to work in the alkaline concrete media for several years.

- Even when parameters as corrosion potential or concrete resistivity are useful for the determination of the corrosion state of the structure, the corrosion process only can be quantify 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 to determine the representative value of the corrosion rate obtained in one structure.

ACKNOWLEDGEMENTS

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