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Integrated Sensor Network for Monitoring Steel Corrosion in Concrete Structures

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ABSTRACT

The developed Integrated Sensor Network (ISN) allows a non-destructive monitoring of the rebar condition at different parts of the structure. The corrosion sensor allows the accurate determination of the corrosion rate (µm/year). Moreover, additional sensors are integrated in order to detect relevant changes in the concrete electrochemical condition.The ISN has been published as an international invention patent (reference number WO 2016/177929 A1). The system is based on an economic, simple, reliable and durable technology, which makes its implementation viable on new and repaired reinforced concrete structures (RCS). Therefore, it is also possible monitoring non-accessible parts such as deep foundations or submerged and buried zones. In any case, no technical personnel are needed because the acquisition, storage and transmission of data is autonomous. In this way, it is possible a remote corrosion assessment of several RCS. In addition, the system needs minimum maintenance works and shows low failure rates.The ISN has been installed for corrosion monitoring of a marine prestressed structure built with Formex®, an Ultra High Performance Fibre Reinforced Concrete (UHPFRC). Five zones of the structure are being monitored. After seven months of monitoring, the corrosion rate (C_{RATE}) stands around 0.2 µm/year, lower than the corrosion rate of the conventional concrete specimens installed (0.5 µm/year). In any case, C_{RATE} is under 1.16 µm/year, the threshold above which the corrosion begins to be considered significant.

Keywords: Concrete, Corrosion, Sensor, Monitoring, Ultra High Performance Concrete Fibre Reinforced (UHPFRC).

1.0 INTRODUCTION

Corrosion of rebars in reinforced concrete structures (RCS) leads to the formation of expansive products, which induce adhesion loss and coating detachment. In fact, the majority of premature structural failure of load-bearing elements does not occur by overloading, the main reason is the reinforcement corrosion (Garcés *et al*. 2008). Therefore, it is of great interest to introduce sensors inside reinforced concrete structures to provide real-time information about the state of rebars.

It is possible to monitor structures durability by using embedded sensors in the cover area of the reinforcements (Andrade *et al*. 2001). The use of sensors to monitor the durability of existing reinforced concrete structures is a relatively novel aspect in construction, although there are recent examples of sensor monitoring in real structures (Castillo *et al*. 2011; Duffó and Farina 2009; Figueira 2017), many of these systems are underdeveloped and show several long-term problems. For corrosion control, the mostly used sensors are of electrochemical type (Gandía-Romero 2014).

Robust electrochemical sensors have recently been developed and allow their application for corrosion monitoring in reinforced concrete structures. Ramón *et al*. (international invention patent WO 2016/177929 A1) developed the Integrated Sensor Network (ISN) we want to highlight. It uses specific measurement equipment developed by the research group. The system includes corrosion sensors, a novel measurement protocol and a methodology for data analysis, which allows determining the corrosion potentials and the local corrosion rates in the reinforced concrete structures in a reliable and continuous way (Alcañiz *et al*. 2016). Besides, sensors to detect variations in pH (Gandía-Romero *et al*. 2015; Gandía-Romero *et al*. 2016) and Ag/AgCl type electrodes for the determination of chlorides in mortars and concretes have also been incorporated (Gandía-Romero *et al*. 2016).

Several results obtained in a real application are presented below. The ISN has been implemented as proof of concept, specifically in reinforced concrete floating rafts manufactured within the European project H2020 SME INSTRUMENT (SELMUS-738777). It is based on a research and development project with the company Research & Development Concretes S.L., entitled "Monitoring system of marine corrosion processes in high performance concrete trays". In this project, the corrosion state is monitored at 5 specific points of the structure and the gathered test data can be accessed remotely through a 4G connection.

2.0 EXPERIMENTAL

The ISN has been developed to monitor corrosion processes simultaneously in different zones of a structure. They will be hereinafter referred to as control points (CP).

2.1 Floating rafts

IDIFOR Company designed and manufactured the floating rafts. Its structure was composed of six master beams (20 meters long), which support several secondary beams (27 meters long and perpendicular), all of them made of Formex® (Fig. 1). Thirty-four lines of wooden pontoons were placed on top for mooring the cultivation ropes, generating a structural framework. The rectangular plant dimensions were 20 x 27 meters (540 m^2) and its weight was 53 T. It was supported by 6 steel + GRP floats. The concrete used is Formex®, an Ultra High Performance Fibre Reinforced Concrete (UHPFRC).

Five control points (CP) are included in the monitored rafts (four points placed in the beams and one in a test specimen made with an ordinary Portland concrete) (Fig. 1).

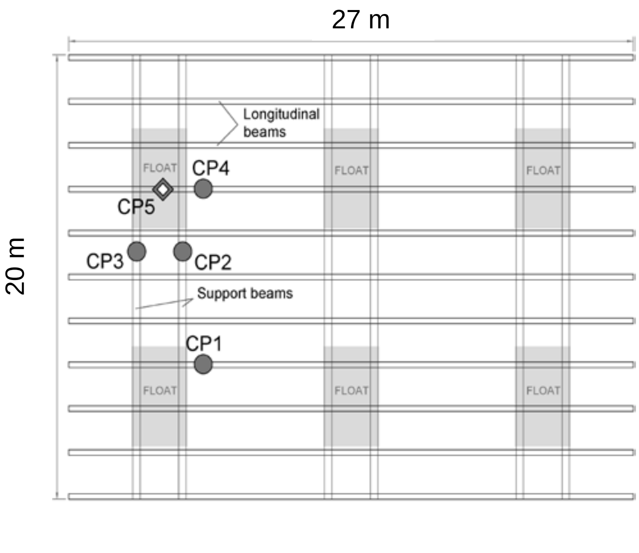

Fig. 1. Floating rafts scheme and control points (CP) placement

2.2 Sensors

The electrodes and sensors were manufactured in the ETSIE Electrochemistry laboratory in the Universitat Politècnica de València. The electrodes for the corrosion sensors were made of a mild steel rebar of 12 mm in diameter. Their ends were encapsulated with PVC, with an exposed area of 20 cm^2. The electrical connection was protected with epoxy resin and it remained hidden at one of the ends. In each CP, two sensors were implemented in order to verify the measurements reproducibility. The reference sensor was a mixed metal oxide (MMO) type in solid state. The auxiliary electrode was a stainless steel bar of 12 mm in diameter and 1 m long. A K type thermocouple was installed as a temperature sensor. The implementation was performed in LUFORT precast facilities in Turís. (Fig. 2).

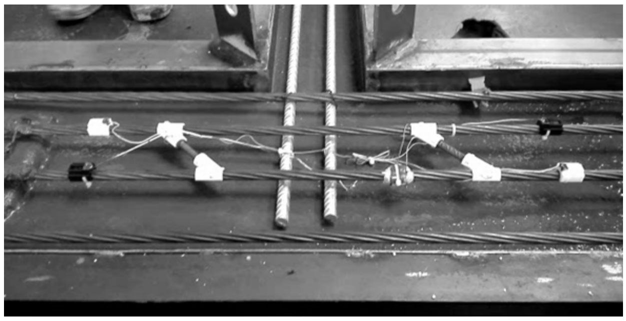

Fig. 2. Concreting process at the precast production plant. Sensors assembled when tendons were already stressed.

The system includes additional sensors in order to complement the data obtained from the corrosion sensors. These are thick film sensors made with resistive pastes that contain different metal oxides to measure pH (Ru/Ru^2) and chlorides activity (Ag/AgCl) variations.

2.3 Measurement system

Two systems were developed to perform the measurements. The first system is a portable potentiostat developed in the IDM. A specifically designed software application controls the first system. The main approach of this portable equipment are in situ measurements, e.g. to check in detail some of the control points (CP) of the structure (Fig. 3).

The second system, the ISN, has been conceived to be permanently installed in a structure and monitor all CPs simultaneously. The ISN includes the development of control and data acquisition software. It consists on a central module and a series of measurement nodes distributed throughout the structure (as many as CP) (Fig. 1). Each measurement node consists of a miniaturized version of the portable equipment (Fig. 4) and the set of sensors to be evaluated. The electronic device perform the necessary measurements for the corrosion evaluation in each CP.

The central module houses a mini-computer Rapsberry Pi (RPi) that manage all the information generated in the measurement nodes autonomously by means of specifically developed software, which

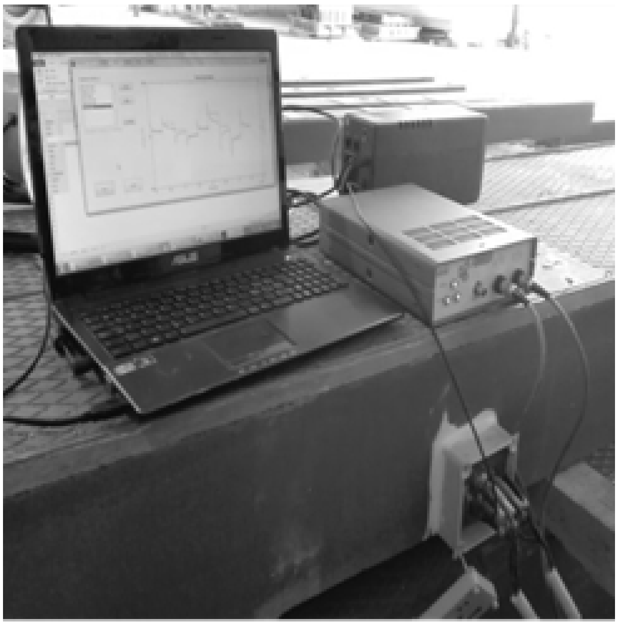

Fig. 3. In situ measurements using the portable potentiostat developed in the IDM. One of the precast beams was tested before the raft assembly

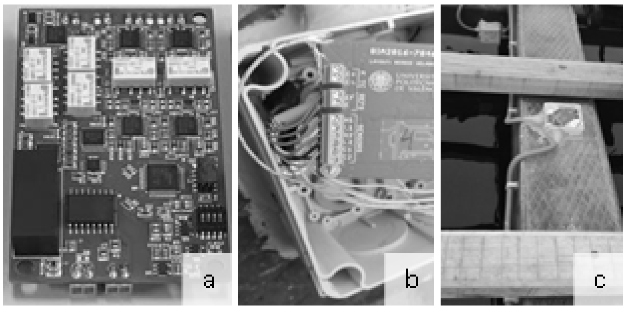

Fig. 4. a) Printed circuit board with an integrated miniaturized potentiostat; b) and c) Circuit board installed as a measurement node at one of the control points (CP) inside a specific waterproof box.

uses a RS-485 bus to communicate with the electronic devices. This allows to schedule the measurements. The software stores the gathered information in files, which are available through a TCP/IP connection. The ISN can be power supplied via photovoltaic systems or the conventional electrical grid.

The measurement of the corrosion rate (C_{RATE}) is based on the application of a sequence of short potentiostatic pulses of different amplitudes after determining the corrosion potential (E_{CORR}) of the sensors. The current-time response is fitted to a theoretical model in order to construct the polarization curve within the usual overpotential range needed to calculate C_{RATE} via standard methods. The proposed potentiostatic pulse method (PPM) was validated against the Linear Resistance Polarization method (LPR) (ASTM G102-89; ASTM G59−97) traditionally used for in situ corrosion concrete measurements (Berke, *et al*. 2011; RILEM TC 154-EMC 2004). For that, C_{RATE} values from a set of samples with different corrosion level were compared.

3.0 RESULTS

3.1 Previous validation

Figure 5 shows the corrosion rate (C_{RATE}) of a set of samples using the proposed PPM method versus LPR method, respectively. It is clear that C_{RATE} values calculated by the PPM are very close to what were determined by the LPR. The linear relationship between the methods becomes stronger as the corrosion rate level rises.

The main advantage of the validated method lies in is its ability to obtain C_{RATE} without significantly affecting the rebar condition (low amplitude and short time pulse).

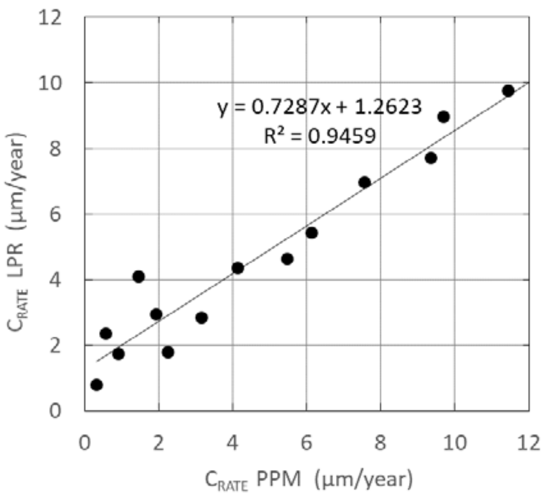

Fig. 5. Plot of corrosion rate (C_{RATE}) of samples with different corrosion level calculated from the proposed PPM method versus LPR method

The hardware was tested with different electronic circuits with passive elements, such as resistances and capacitors. The relative error was in all cases below 1.29%.

3.2 Corrosion potential

The corrosion potential (E_{CORR}) results obtained in a continuous and remote way are shown in Fig. 5. The E_{CORR} values displayed are versus a saturated KCl calomel reference electrode. After seven months of monitoring, the corrosion sensors in the all the beams (nodes 1 to 4) provide an E_{CORR} higher than –0.20 V. This value is associated with a low corrosion risk (ASTM C876−15). The E_{CORR} of the test specimen (CP 5), made with an ordinary Portland concrete, is slightly closer to reach a moderate corrosion level.

3.3 Corrosion rate

Figure 6 shows the corrosion rate (C_{RATE}) monitored during seven months. In general, data have been changing with time towards smaller values. It is an indicative of a passivation process, which is a usual process at early stages, where the passive layer is stabilizing due to favourable conditions (highly alkaline pH). In any case, C_{RATE} is above 1.16 µm/year, the threshold above which the corrosion begins to be considered significant (UNE 112072:2011).

When Ultra High Performance Fibre Reinforced Concrete (UHPFRC) was used (in beams CP1 to CP4), C_{RATE} was always lower than 0.2 µm/year. In the test specimen (CP 5), made with an ordinary Portland concrete, an upward trend is observed with C_{RATE} values close to 0.5 µm/year. This is logical since the quality of the specimen concrete is different, so it is expected that in the short-medium term its value may be between 1.16-5.8 µm/year, which means that it is at a low level of corrosion (UNE 112072:2011).

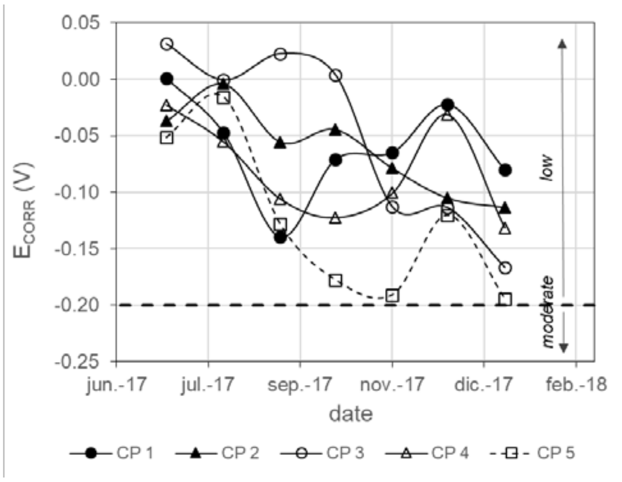

Fig. 5. Corrosion potential (E_{CORR}) monitoring of one the UHPFRC rafts

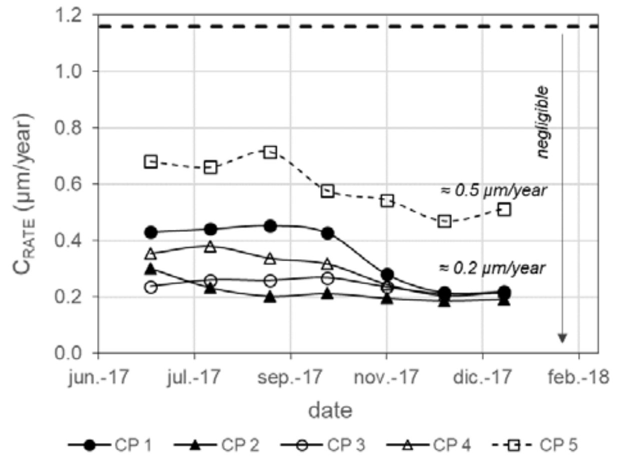

Fig. 6. Corrosion rate (C_{RATE}) monitoring of one the UHPFRC rafts

4.0 CONCLUSIONS

- An integrated sensor network (ISN) has been developed and implemented to monitor the key parameters needed to assess the corrosion state of a reinforced concrete structure.

- The corrosion rate (C_{RATE}) and corrosion potential (E_{CORR}) results obtained in the monitored raft show that the corrosion level is negligible.

- The small C_{RATE} difference between Ultra High Performance Fibre Reinforced Concrete (UHPFRC) beams and the ordinary Portland concrete specimen was clearly recorded. This indicates a high level of measurement accuracy.

- The following advantages for the ISN have been found: 1) It is a non-destructive methodology; 2) Allows multi-zone monitoring; 3) Low failure rates; 4) It is accurate and highly durable; 5) Data acquisition, storage and analysis is autonomous.

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References

Alcañiz, M. *et al*. 2016. “Sensor, Red de Sensores, Método Y Programa Informático Para Determinar La Corrosión En Una Estructura de Hormigón Armado.”

Andrade, C., Isabel Martínez Sierra, C. Alonso, and J. Fullea. 2001. “Nuevas Técnicas Avanzadas Para La Medida in Situ de La Corrosión En Hormigón Armado.” *Materiales de Construcción* 51(c):97–107.

ASTM C876 − 15. *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete*. West Conshohocken, PA, 2015.

ASTM G102-89(2015)e1. *Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements*. West Conshohocken, PA, 2015.

ASTM G59 − 97 (2014). n.d. *Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements*. West Conshohocken, PA, 2014.

Berke, Neal S., Vtctor Chaker, and David Whiting. 2011. *Corrosion Rates of Steel in Concrete*.

Castillo, A. *et al*. 2011. "Evaluación Y Monitorización de La Durabilidad de Las Cubiertas Del Hipódromo de La Zarzuela de Madrid." *Assessment and Monitoring of Durability of Shell Structures in Zarzuela Racecourse Madrid* 63(524):33–41.

Duffó, Gustavo S. and Silvia B. Farina. 2009. "Development of an Embeddable Sensor to Monitor the Corrosion Process of New and Existing Reinforced Concrete Structures." *Construction and Building Materials* 23(8):2746–51.

Figueira, Rita. 2017. "Electrochemical Sensors for Monitoring the Corrosion Conditions of Reinforced Concrete Structures: A Review." *Applied Sciences* 7(11):1157.

Gandía-Romero, J. .., E. García-Breijo, J. Soto, M. Valcuende, and Universitat Politècnica de València. 2015. "Sensor Para La Determinación de La Profundidad Y Velocidad de Carbonatación Del Hormigón."

Gandía-Romero, J. M. 2014. "Sensores Electroquímicos Aplicados Al Estudio de La Corrosión En Estructuras de Hormigón Armado." Universitat Politècnica de València.

Gandía-Romero, J. M. *et al*. 2016. "Characterization of Embeddable Potentiometric Thick-Film Sensors for Monitoring Chloride Penetration in Concrete." *Sensors and Actuators, B: Chemical* 222:407–18.

Gandía-Romero, J. M. *et al*. 2016. "Potentiometric Thick-Film Sensors for Measuring the pH of Concrete." *Cement and Concrete Composites* 68:66–76.

Garcés, Pedro, Terradillos Miguel, Climent Llorca, and Emilio Zornoza. 2008. *Corrosión de Armaduras En Estructuras de Hormigón Armado*. Editorial. edited by Editorial Club Universitario. San Vicente (Alicante).

UNE 112072:2011. 2011. "Laboratory Measurement of Corrosion Speed Using the Polarization Resistance Technique." *Aenor* Aenor.

Vennesland, Øystein, Michael Raupach, and Cid Andrade. 2007. *Recommendation of Rilem TC 154-EMC: "Electrochemical Techniques for Measuring Corrosion in Concrete"—measurements with Embedded Probes*.