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Sensores para la Determinación de la Durabilidad de Construcciones de Hormigón Armado

Sensors for Determining the Durability of Reinforced Concrete Constructions

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Abstract

The durability of reinforced concrete structures is severely affected by corrosion. This phenomenon entails high economic costs due to the large infrastructure built with this material in developed countries, both roads and buildings. This review shows and discusses different techniques now available for monitoring and controlling reinforced concrete structures by means of sensors. These sensors are sophisticated devices that provide information about the factors inducing the processes of corrosion, and they are very useful for predicting the service life of structures and optimizing the repair strategies. This work analyses different sensor systems and compares their applications, taking into account such factors as location, calibration and evaluation data. Finally, some examples of sensor applications and diverse strategies for developing new sensor systems in the near future are presented.

Keywords: Sensors, reinforced concrete, corrosion, durability, structures

Resumen

La durabilidad de las construcciones de hormigón armado está gravemente afectada por los fenómenos de corrosión. Este problema supone un gran coste económico en los países desarrollados debido a la gran infraestructura construida en ellos, tanto vial como edificatoria. En esta revisión se exponen las distintas técnicas disponibles actualmente para monitorizar y controlar mediante sensores las estructuras de hormigón armado. Mediante estos tipos de control existentes es posible obtener información relevante sobre los factores que favorecen los procesos corrosivos, cuya información es de gran utilidad para poder predecir la vida útil de las estructuras y optimizar las estrategias de reparación. Se han comparado entre sí los distintos sistemas de sensores y sus aplicaciones, teniendo en cuenta los factores de ubicación, calibración y evaluación de datos. Finalmente, se presentan varios ejemplos de aplicaciones de sistemas y diversas estrategias a seguir en el desarrollo de nuevos sensores.

Palabras clave: Sensor, hormigón armado, corrosión, durabilidad, estructuras

1. Introduction

Since the 1990's, European regulations have assigned increasing importance to the study of the durability of concrete structures reinforced with structural steel (Richardson, 2001). The actions that condition the durability of the structures are those derived from the chemical, physical and biological deterioration processes, which have a constant impact on them. The action of oxidizing agents, acids, salts or bacteria are some examples thereof. These deterioration processes modify their strength, stiffness and aspect; therefore, they have a significant influence on their safety and functionality (Garcés et al., 2008).

Recent worldwide economic studies carried out by NACE International (National Association of Corrosion Engineers) estimate the direct cost of corrosion around 3-4% of the global Gross Domestic Product. If the existing corrosion control technology is applied, this cost could be reduced by approximately 20-35% (saving of 375-875 billion dollars) (Koch et al., 2016).

The traditional way of knowing the deterioration level of a damaged reinforced concrete is based on tests obtained through destructive techniques, where samples are taken from operating structures, which are then replaced by special repair mortars (Sing et al., 2007). However, it is important to know the condition of reinforcements, in order to minimize the intervention costs. Consequently, new technologies have been developed, such as sensors for monitoring the condition of reinforcements quickly and accurately (Almeraya et al., 1998; Song and Saraswathy, 2007).

Thus, this work presents a state-of-the-art review of the sensors for determining the durability of this type of constructions. Finally, a number of relevant examples are described in relation to the application of sensors, as well as different strategies that can be adopted for their future development.

2. Measurements Required for the Durability Study

Nowadays, the most widely used methodologies for determining corrosion processes are the electrochemical ones (Sing et al., 2016); (Ou and Li, 2010); (Zaki et al., 2015); (Schiegg and Dauberschmidt, 2008). However, the traditional destructive techniques are still used for controlling

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corrosion, with the aim of contrasting the results (González, 2007). Table 1 summarizes the information needed for the study and evaluation of durability (Broomfield et al., 2002); (Yoo et al., 2003).

Table 1. *Summary of the measurements usually applied for studying the durability of reinforced concrete structures (Broomfield et al., 2002); (Yoo et al., 2003)*

STRUCTURE	***REQUIRED MEASUREMENTS***
Reinforcement	*Corrosion Potential*
	Current Density
Concrete (coating of the reinforcements)	*Conductivity/Resistivity*
	Oxygen Transfer
	Presence of Chlorides and pH Variation
	Temperature and Moisture

Concerning the measurements taken on the reinforcements, the corrosion potential (Ecorr) measures the potential difference between a reference electrode and the steel attached to the reinforcement [6]. These results provide approximate values of corrosion risk rates, in accordance with the North American standard ASTM C-876-99 and the Spanish standard UNE 112083:2010 (Table 2).

Table 2. *Corrosion risk in percentage based on the corrosion potential using a saturated calomel electrode (SCE)*

Ecorr (SCE)/mV	***Corrosion Risk***
> - 200	*10 %*
- 200 a – 300	*50 %*
< - 350	*90 %*

The corrosion speed, measured in μm/year, provides information about the effect of corrosion by unit of time, and it is indirectly determined by potentiometer techniques, such as the polarization resistance (Rp) (Duffó and Farina, 2009) or the Tafel extrapolation method (Arva et al., 2002). The galvanic current density (Icorr) recorded by the reduction process in the cathode also provides data on the corrosive activity (González et al., 2004).

On the other hand, regarding the measurements required for the study of durability, which are carried out in the concrete covering the reinforcements, the factors controlling the corrosion speed and allowing to be monitored are the electrical resistivity of concrete and the oxygen transfer (Yoo et al., 2003), (Duffó and Farina, 2009). The conductivity or resistivity of concrete in the corrosion activity area also provides information about the general corrosion risk (Arva et al., 2002), (González et al., 2004),(Langford and Broomfield 1987), see Table 3. With regard to the oxygen transfer, it can be measured in a solution through a combination of two metal electrodes and one reference electrode (Correia et al., 2006), (Castañeda and Corvo, 2004).

Table 3. *Corrosion risk based on the electrical resistivity of concrete (Langford y Broomfield ,1987), (Alonso et al., 1988), (Sagoe-Crentsil y Glasser, 1989), (López y González, 1993), (Broomfield, 2006)*

Resistivity (kΩ·cm)	***Corrosion Risk***
< 5	*Very high*
5 – 10	*High*
10 – 20	*Moderate-Low*
> 20	*Low or None*

The presence of chlorides or pH variations are also parameters that electrochemical sensors can measure in the concrete, and they are an early warning of the possibility of corrosion in the reinforcements (Dong et al., 2011), (Angst et al., 2009), (Artero et al., 2012). Finally, the moisture inside the concrete pores, together with the temperature acting as a catalyzer, can contribute with additional information on the corrosion processes (McCarter et al., 2001), (Barroca et al., 2013).

3. Sensors for Measuring Durability Parameters

Sensors for determining the durability have been developed since the beginning of the 20th century. Until now, one of the biggest obstacles has been to correctly implement the laboratory work in the real application field (Schiegg and Dauberschnidt, 2008). Therefore, these sensors require the compliance of a series of basic characteristics (Table 4) in order to make a proper technological transfer from the laboratory to the industry.

Table 4. *Sensor Characteristics Required*

Characteristics	***Description***
Optimal Construction	*Optimization of the constructive design of sensor systems (Machado, 1994; Galán et al., 2000).*
Adequate Resistance	*Robustness suitable to their future application (Alegret, 1992).*
Minimum Size	*Small dimensions, portable and easy to manipulate (worden et al., 2003).*
High Durability	*Sensors that are stable in the long term (Matthew & Dean, 2006).*
Low Price	*The most economic technology and materials for their construction should be selected (Hart & Wring, 1997; Albareda et al., 2000).*
High Precision	*Reliability, reproducibility, sensitivity and detection limits fitted to their use (Garcés et al., 2008).*

3.1 Sensors and Physical Measuring Techniques

The techniques and sensors described in the present work aim at monitoring and controlling the condition of reinforced concrete in relation to the deterioration problems caused by the corrosion phenomenon (Ahmad 2003). According to the existing literature, most of the sensors used for this purpose are guided by electrochemical principles. Nevertheless, we should also highlight the advantage of certain systems using physical monitoring techniques, because they measure indirect parameters that provide information about corrosion; for example, the measurements of mass and volume of the reinforcement steel (Cabrera, 1996). Among all physical techniques used, the only ones assessing corrosion quantitatively are thermography, magnetic flows and optical systems.

Thermographic sensors transform the measured infrared and invisible radiation into visible readings through different techniques that can be applied for measuring deformations and cracking (Meola, 2013). Recently, a non-destructive technique for detecting corrosion has been developed, which is based on a combination of induction heating and infrared thermography (Kobayashi and Banthia, 2011). This technique is based on the principle that compounds derived from corrosion have a bad thermal conductivity and inhibit the heat diffusion that is generated in the steel bar due to induction heating.

On the other hand, the techniques based on magnetic flows force strong magnetic fields to pass through the reinforced concrete structure (Maki et al., 2001). In this manner, reinforcement steels are magnetized, and the magnetic field produced by the metal elements is measured. This systems allows detecting the imperfections and anomalies of reinforcements, because discontinuities are recorded as unique anomalies by the sensor. Some of the sensors that use magnetic field methods have been developed with the technology of Micro-Electro-Mechanical Systems (MEMS) in order to obtain small-dimension devices (Guangtao et al., 2010).

Another type of sensor used for monitoring corrosion is manufactured with fiber optic technology. This type of sensors can detect moisture, expansion and cracking in the reinforced concrete, which allows observing the condition of a structure and predict its service life (Kung, 2014). Its operating principle is based on recording wave length variations of the light when it is reflected (Górriz ,2009). A system has been recently developed under these technological principles, which uses a network of sensors introduced in a carbon fiber mesh embedded in the reinforced concrete structure (Figure 1). This system generates deformation/cracking measurements, while acting as a structural reinforcement (Bremer et al., 2017).

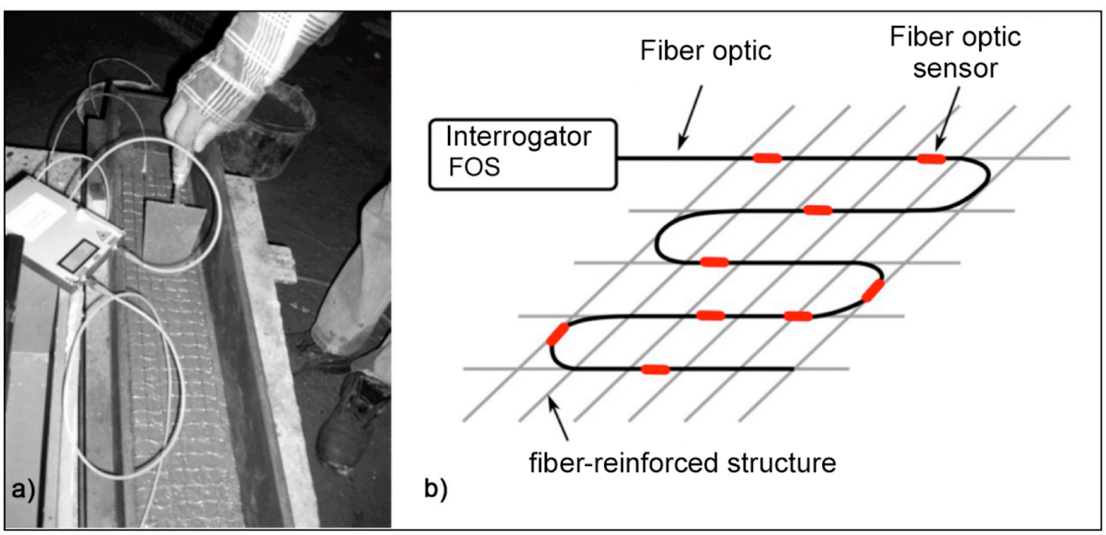

Figure 1. *Introducing the sensor in a piece of concrete (a) and diagram of a fiber-reinforced structure functionalized with fiber optic sensors (b) (Bremer et al., 2017)*

3.2 Sensors and Chemical Measuring Techniques

The development of new chemical sensors have entailed a large scientific productivity since their discovery in 1906 by Cremer (Alegret et al., 2004), (Frize, 2014). These electrochemical sensors are the most popular devices for controlling durability (Toko y Habara, 2005), (Burkert et al., 2006), (Froche, 2017),(Legin et al., 1997), (Schiegg, 2002), (Bergmeister, 2004), (Sensortec, 2006), (Mihell y Atkinson, 1998), (Morata et al., 2013), (Brite/EuRam, 2002), (Andringa et al., 2006). The characteristics that make them appropriate for studying reinforced concrete structures are: simplicity for collecting data, high sensitivity and small-scale manufacturing capacity. Moreover, these sensors can be introduced inside the studied medium and, for example, they can be embedded in the structure (Martínez and Andrade, 2009).

Electrochemical sensors can be classified into three large groups: potentiometric, amperometric and conductometric (CSIC, 1987). (Figure 2) shows a classification of the main electrochemical techniques ((Romero, 2014) based on the criteria of different authors (Kissinger and Heineman, 1996), (Harvey, 2000), (Zoski, 2007).

An oxidation-reduction process occurs in the faradic-type of electrochemical technique, and its purpose is to study the processes in the interface between the medium and the electrode. Among the faradic techniques we can highlight the static technique, where there is no current flow (I=0), and the dynamic one, where there is a current flow (I≠0). On the other hand, non-faradic techniques are focused on the studied medium and the most important technique is the conductometry.

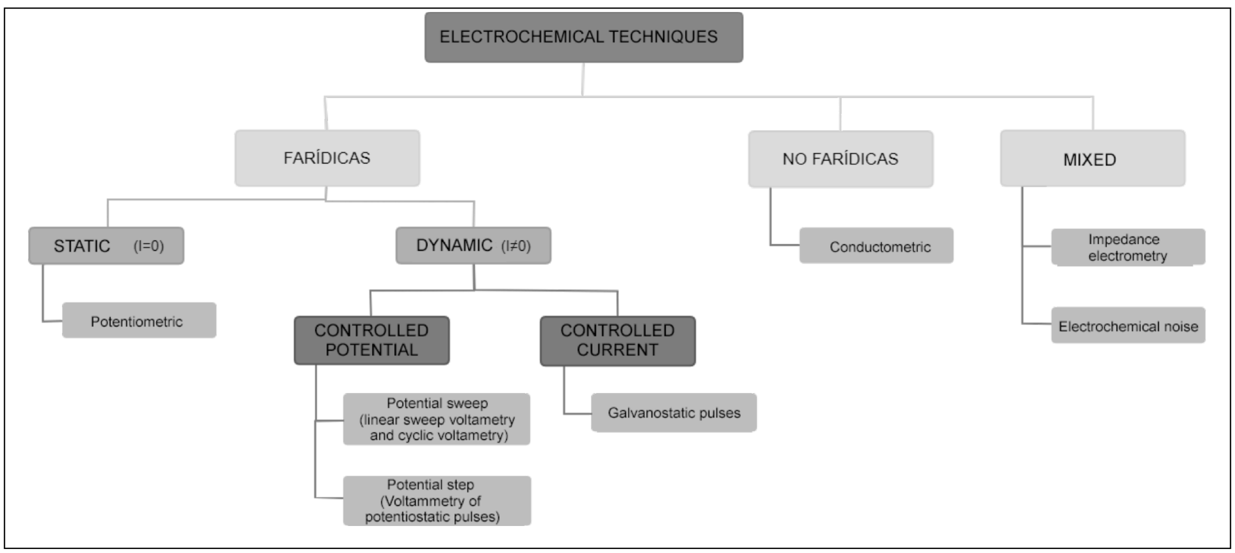

Figure 2. *Diagram of the main electrochemical techniques. Modified from (Romero, 2014)*

3.2.1 Potentiometric Sensors

The sensors that use potentiometric techniques measure the potential between the reference electrode (RE) and the working electrode (WE), when they are introduced in an electrolytic medium without a flowing current (Taylor and Schultz, 1996), (Webster and Eren, 2017). The reference electrode (RE) shows a stable potential that is indifferent to the composition of the studied structure and it should be strong and easy to connect. Table 5 shows the most common reference electrodes (Webster and Eren, 2017). They are either metal electrodes or membrane electrodes, which are specific or ion-selective (Skoog et al., 1997).

Table 5. *Common Reference Electrodes (Webster and Eren, 2017)*

Type of Electrode	Electrode Reaction	Potential at 25ºC V va. EHN
Calomel Hg/Hg_2Cl_2, Cl	$Hg_2Cl_2 + 2e- \leftrightarrow 2Hg + 2Cl^-$	$E = 0.276 - 0.059 \log [Cl^-]$ KLC, sat, E = 0.244 V coef. temp.: - 0.65 mV/ºC
Copper/Copper- sulphate $Cu/CuSO_4$, Cu^{2+}	$Cu^{2+} + 2e- \leftrightarrow Cu$	$E = 0.6151 - 0.295 \log [SO_4^{2-}]$ K_2 SO_4sat. E = 0.710 V
Silver/Silver chloride Ag/AgCl, Cl^-	$AgCl + 1e- \leftrightarrow Ag + Cl^-$	$E = 0.2224 - 0.0591 \log [Cl^-]$ coef. temp.: - 0.6 mV/ºC
Mercury/Mercurous sulphate	$Hg_2SO_4 + 2e- \leftrightarrow 2Hg + SO_4^{2-}$	$E = 0.340 - 0.0195 \log [Cu^{2+}]$ coef. temp.: - 0.9 mV/ºC
Zinc/Sea water	$Zn^{2+} + 2e- \leftrightarrow Zn$	$E \approx - 0.80$ V

However, in order to install sensors inside the reinforced concrete structure, they have to meet certain requirements such as being stable and invariant to the thermal and chemical changes in the concrete, tolerant to different weather conditions, capable of letting a small current flow with minimum polarization, and stable in the long run without needing maintenance (Duffó et al., 2007). Therefore, other embeddable, reference and pseudo-reference electrodes have been developed and studied, such as graphite, Pt, Ti/RuOx (MMO), Ti/TiO2 and MnO_2, where the latter is the most interesting, because it can behave as a true reference in an alkaline medium such as concrete (Milano et al., 2010), (Lu et al., 2009). This type of internal reference electrodes are usually embedded close to the reinforcement in order to minimize the problems derived from the resistivity of concrete (Elsener, 2003).

When applying this measurement technique, the recorded potential is conditioned by the material of the electrodes, the concentration and nature of the species in the studied media, and the temperature. Therefore, electrodes have to be subjected to rigorous temperature and cleaning controls to prevent possible interferences in the measurement. The measuring of balance potentials indicates the concentration of a substance and its evolution during a chemical reaction process (CSIC 1987).

Sensors based on potentiometric techniques, which are used for corrosion monitoring, can measure the corrosion potential, the penetration of chlorides and the pH.

The measuring of the corrosion potential is a non-destructive method, because the state of the metal is not altered, and it provides data about the reinforcements' corrosion risk. This technique allows using external references or embedded in the concrete (Figure 3).

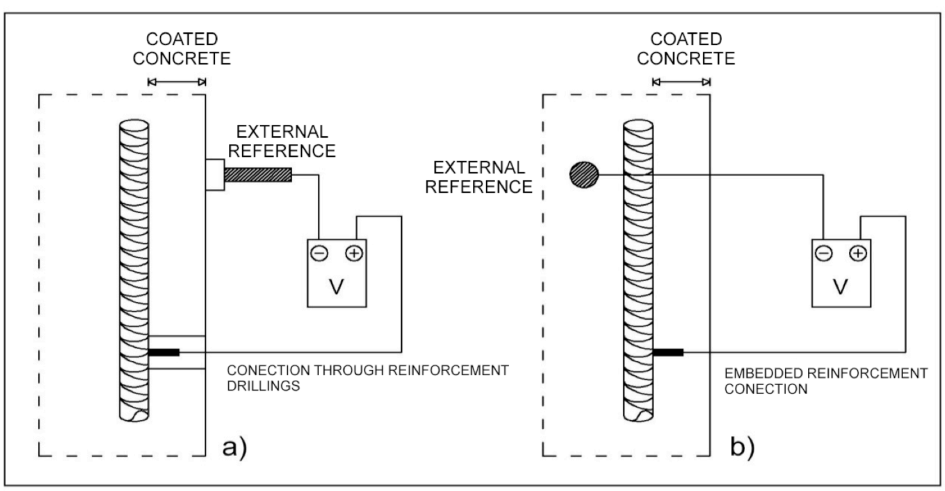

Figure 3. *Diagram of corrosion potential measurements through sensors in reinforcements already executed (a) and embedded ones (b)*

With regard to the potentiometric sensors for measuring the activity of chloride ions (Cl -), it is possible to use Ag/AgCl electrodes made with an anodized silver wire (Aranda et al., 2015), but they report stability problems in the long run.

This kind of potentiometric sensors have been studied in aqueous solutions (Labrador 2009), in solutions simulating the pore water of concrete (Alves et al., 2006), (Vera, 2010) and in hardened concretes and mortars (Duffó y Farina, 2009), (Dong et al., 2011), (Alves et al., 2006), (Climent-Llorca et al., 1996), (Terol et al., 2013). The Expansion-Ring-System, formed by an expansion-ring-anode and a cathode that are drilled into the concrete, was developed under these principles. The measuring piece is the expansion-ring-anode, which allows measuring the corrosion potential and the corrosion current between the anode and the cathode at different depths (Sensortec, 2006). Another type of sensor for existing structures is the so-called CorroRisk probe (Figure 4), which consists in metal nails with a cathode made of activated titanium mesh and a MnO_2 electrode. These nails are hammered into the existing structure and they are made of a material similar to the reinforcements; therefore, they are expected to corrode when the concrete reaches a critical concentration of chlorides (Froche , 2017).

Finally, potentiometric sensors also allow measuring the pH with electrodes that are sensitive to pH variations (Dong et al., 2011). However, their use is still limited due to the fact that the electrode has to be resistant to the medium and only those manufactured with MMO (metal/metal oxide) are used (Song et al., 1998), (Du et al., 2006), (Yu y Caseres, 2011). An example of electrochemical sensor that can be configured for both pH and chloride measurements are those developed with the thick-film hybrid microelectronic technology. This system enables the manufacturing of sensors that are inexpensive, resistant in the long run, miniaturized and reproducible through serigraph techniques that allow integrating different electrodes on the same support (Gandía at el., 2016),(Gandía et al., 2016a),(Martínez, 2005).

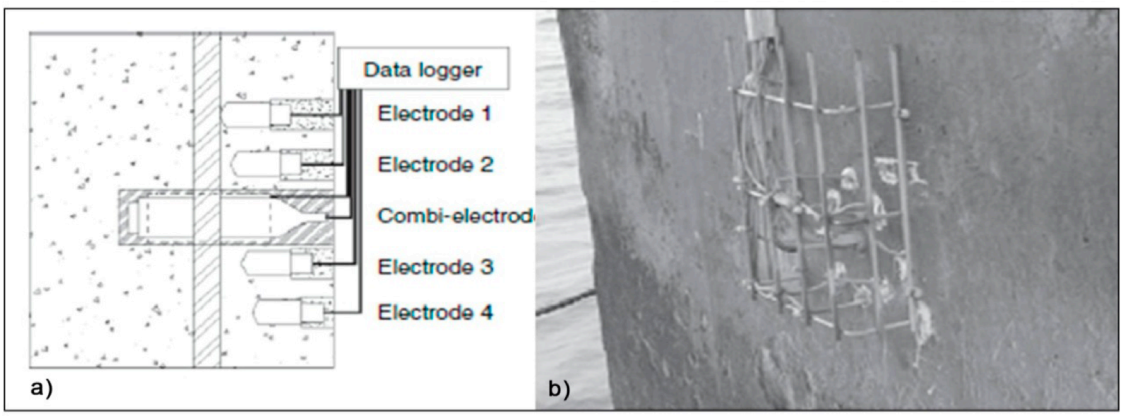

***Figure 4.** Design of the CorroRisk probe for determining the depth of critical chloride penetration levels in existing structures, section view (a) and mounted on a structure (b) (Froche, 2017)*

3.2.2 Amperometric Sensors

Amperometric sensors use dynamic methods of controlled potential (CSIC, 1987). This technique consists in applying a specific potential difference between two electrodes (Hulanicki et al 1991). Voltage variations can be applied through voltage-time functions such as the linear scan voltammetry (LSV) and the cyclic voltammetry (CV) (González, 2012). These methods allow measuring the current in the working electrode while doing a linear scan of the potential between the working electrode and the counter electrode (LSV) or a scan both in the direct and opposite direction (CV). The analyte oxidation or reduction is recorded as a peak in the signal, at the potential at which the species starts oxidizing or reducing. The most common reference electrode is Manganese oxide (MnO_2), which has a proven long-term stability in the concrete (Milano et al., 2010).

Corrosion monitoring sensor networks have been recently developed, which incorporate a pulse voltammetry device that allows measuring the intensity of corrosion for each point of the sensor network implemented in a reinforced concrete structure (Alcañiz et al., 2016) see (Figure 5). Together with their design, the same researchers have developed a specific software that processes the electric response of each sensor and analyzes the structure in real time (Ramón et al., 2016).

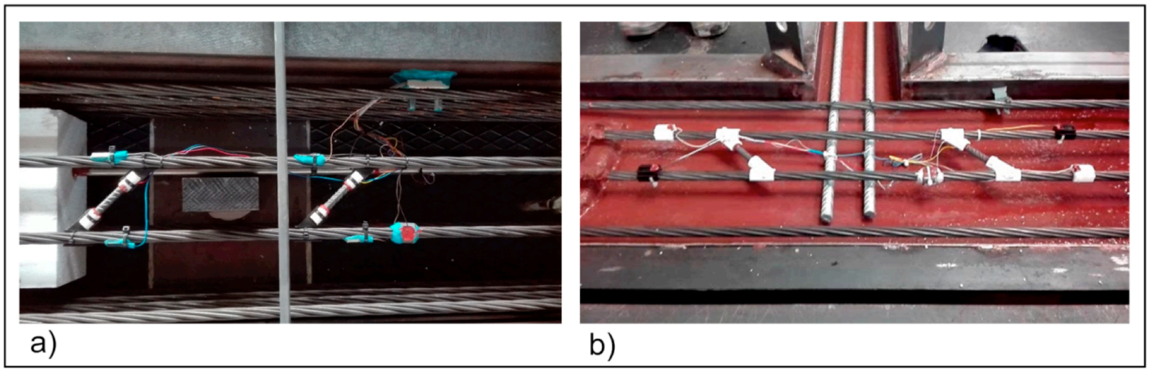

Figure 5. *Sensors placed in beams before (a) and after (b) the concrete mixing (Alcañiz et al., 2016)*

3.2.3 Conductometric Sensors

Conductometric sensors are devices composed of two inert electrodes made from noble metal, to which a voltage is applied through an alternating signal, which allows measuring the flowing current and, therefore, the electrical resistance of the studied sample, usually expressed in Ohm (Ω) (CSIC, 1987). This parameter is directly related to the porous structure of the material and the moisture (Alonso et al. 1988). That is why it is also used to indirectly determine other factors such as concrete curing, resistance to carbonation and chloride penetration (Andrade et al., 2009).

In order to determine the resistivity in hardened concretes, two methods are used whose procedures and calculations are indicated in standards UNE839881 and UNE83988-2: the direct two-electrode method (Jeong et al., 2013) and the Wenner four-electrode method (Broomfield et al., 2002), (Reis, 2006), where the latter is a much used alternative, which consists in establishing a known current flow between two electrodes to measure the voltage between the other two electrodes. Once you know the concrete resistivity, you can establish the corrosion probability of the reinforcements according to the values indicated in Table 3 (Feliu et al., 1989).

For example, the multiring electrode, currently available on the market, can measure the electrical resistance based on the depth (Figure 6). This sensor, developed by Sensortec (Sensortec, 2006), is composed of alternate stainless steel rings, separated from each other by a distance of 5 mm, and a polymer that allow measuring at different depths.

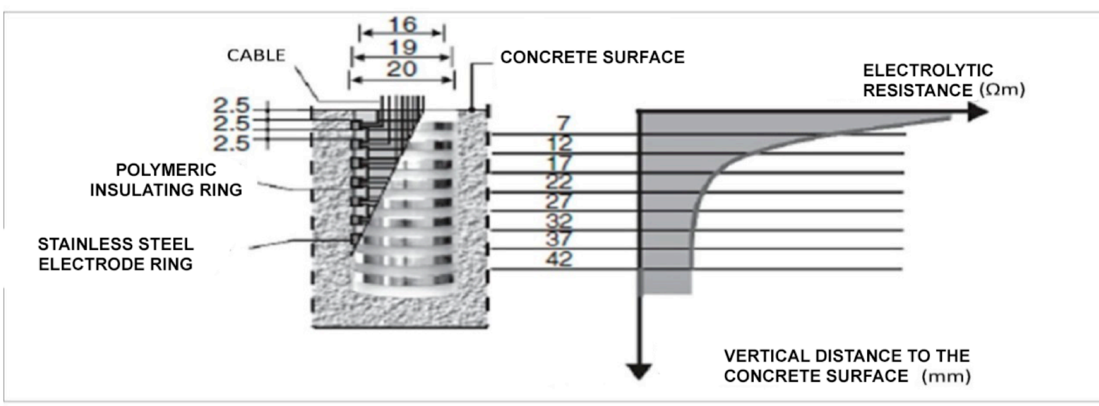

Figure 6. *Diagram of the multiring electrode for measuring resistance based on concrete depth (Sensortec, 2006)*

4. Calibration

Many sensor systems require calibration before they are inserted in the concrete and the manufacturer usually provides the adequate values. Next, Table 6 summarizes the sensors and sensor elements that require calibration prior to their use (McCarter and Vennesland 2004):

Table 6. *Sensors and sensor elements requiring prior calibration (Mc Carter and Vennesland, 2004)*

Sensors and Sensor Elements	**Calibration Required**
Reference Electrodes	In relation to a standard laboratory reference electrode in a saturated solution of calcium hydroxide and air.
pH Sensors	In relation to a standard pH glass electrode in three solutions with different alkalinity.
Chloride Sensors	In three standard chloride solutions with different chloride contents, saturated with calcium hydroxide.
Temperature Sensors	In relation to standard thermometers at three different temperatures.
Relative Humidity Sensors	On three standard solutions of saturated salts.
Resistance Sensors	In solutions of known resistance. The calibration constant can be obtained from the slope of the measured resistance against the resistivity curve of the solution.

5. Location

Depending on the type of sensor, it shall be embedded, in contact with the external surface or without contact, as Table 7 indicates.

Table 7. *Location of the sensors*

Classification of the sensors by location		
Embedded	***External in contact***	***External without contact***
Potentiometric (located in reinforcement) *Amperometric (close to the surface)* *Conductometric*	*Optical* *Conductometric* *Magnetic Flow*	*Thermographic*

Among all types of sensors by location, the external systems without contact have usually the highest manufacturing cost, since they need sophisticated and portable measuring devices. On the other hand, internal systems are less expensive, but the problem is that they are not reusable and they have to be designed to resist the structure's internal conditions and do without maintenance (Lynch and Loh, 2006).

Regardless of their location in relation to the interior/exterior of the structure, their real location depends not only on the morphology and design of the structure, but also on the economic cost of the control process. However, it is possible to determine three general locations: where there is exposure to aggressive substances (for example, seawater splash), in structurally critical places and in places not exposed to aggressive substances so they can act as controls (McCarter and Vennesland, 2004). For example, if highway bridges are taken as a reference (Figure 7), the most critical areas are the lower parts of the pillars, which are also affected by a high concentration of chlorides due to the contamination produced by the vehicle traffic (McCarter and Vennesland, 2004). Furthermore, in coastal areas, the critical areas of the structures are those exposed to seawater splashes (Schiegg and Dauberschmidt ,2008).

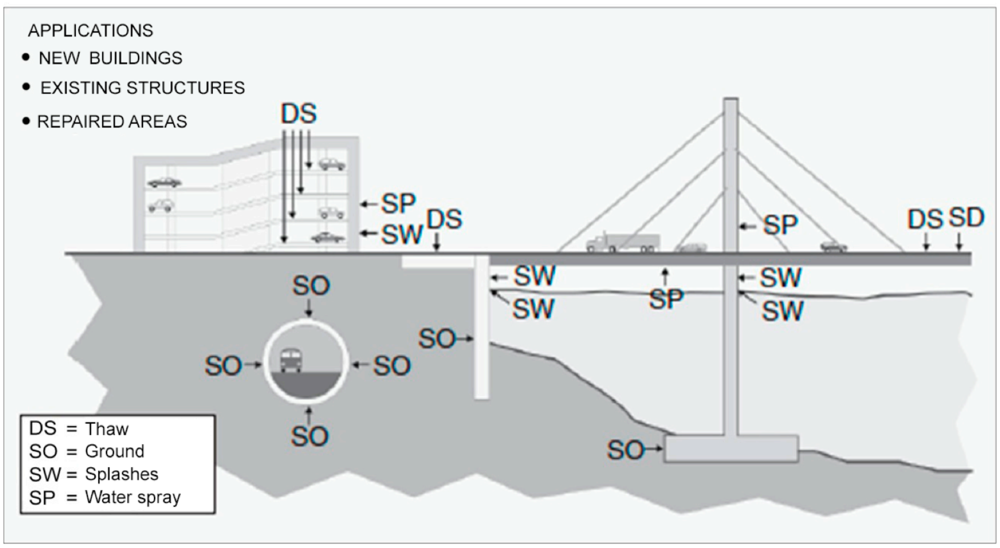

Figure 7. *Examples of sensor locations. Modified from (Schiegg and Dauberschmidt 2008)*

6. Selection and Limitations

The corrosion monitoring systems have several limitations concerning the durability of the monitoring system, the types of corrosion that can be monitored (cavitation or carbonation) and the lack of information in relation to the weak points outside the sensor's control area (Schiegg and Dauberschmidt 2008). Due to these limitations, monitoring cannot replace the regular visual inspections and detailed visual inspections in case a significant deterioration is detected in the structure.

On the other hand, the complexity of corrosive processes makes monitoring difficult. Therefore, a good choice of the monitoring system is essential to guarantee the service life, as well as an accurate, reliable and sensitive data collection (Barroca et al 2013). Among all the techniques reviewed, the non-destructive ones for on-site corrosion monitoring show a significant advantage with regard to the old sampling techniques, which are invasive and destructive (Ahmad 2003).

With the purpose of making a proper selection among different physical monitoring techniques, Table 8 summarizes the main applications, advantages and problems, in addition to references of examples from authors who have developed techniques and sensors for each type. According to this table, the only techniques that can be applied to the study of deterioration caused by corrosion are those based on thermography, magnetic flows and optical systems. The other techniques are used for measuring mechanical properties, deformations and faults. Generally, these techniques allow quick and simple measurements. However, their actual application on site entails several important problems, such as interferences and the fragility of the implemented systems. Another big inconvenient is the high production cost of these systems.

In relation to the studied electrochemical sensors, Table 9 shows a summary of their applications, advantages and problems, as well as references of the main examples from authors who have developed techniques and sensors. Among all of them, the qualitative limitation of the potentiometric sensors should be highlighted, because they only contribute with data about the corrosion potential that allow drawing potential maps and delimitating action areas (Castañeda, 2001). A great problem of this system in structures that are already in service is that each potential measurement requires intrusive borings. In order to obtain quantitative data of the state of the corrosion process in the structures, it is necessary to obtain the corrosion speed. With the amperometric and conductometric sensors you can measure the necessary parameters that allow determining, indirectly, the speed of corrosion (Andrade and Alonso, 1996).

The present work has singled out different types of electrochemical techniques that have been developed for monitoring corrosion, and has given examples of sensors used individually for each technique. Nevertheless, prototypes called multisensors have been developed recently, which use several of these techniques, thus enabling them to measure different parameters such as the density of the corrosion current, corrosion potential, oxygen flow, chloride content, internal temperature and electrical resistance (Duffó y Farina, 2009). Furthermore, this sensor prototype aims at reducing data collection and analysis techniques by using online systems that allow a remote data storage (Duffó et al., 2007), (Lynch y Loh, 2006),(Smalling ,2008).

Table 8. *Summary of the advantages, problems and applications of the main physical techniques for monitoring and controlling reinforced concrete structures. The last column on the right shows references of publications regarding examples of sensors using the present techniques*

TECHNIQUES	ADVANTAGES	PROBLEMS	APPLICATIONS	PUBLICATIONS
THERMOGRAPHY	1. Good results in thermal variations. 2. Portable system.	1. Affected by environment. 2. Fitted for laboratories only. 3. Needs prior calibration.	1. Detection of defects and cracking. 2. Corrosion in reinforcements	(Meola, 2013) (Kobayashi & Banthia, 2011)
MAGNETIC FLOWS	1. Quick and simple. 2. Does not need specialized staff.	1. Affected by external electromagnetic radiation.	1. Corrosion in reinforcements	(Maki et al., 2001) (Guangtao, 2010)
OPTICAL SYSTEMS	1. Fast data transmission. 2. Great durability. 3. Not affected by electromagnetic radiations.	1. Fragility of the system. 2. Affected by dirt and dust. 3. Requires precaution with wiring folding. 4. Needs prior calibration.	1. Deformations. 2. Temperatures. 3. Corrosion. 4. pH. 5. Shrinkage.	(Yun et al., 2010) (Kung, 2014) (Bremer, 2017)

Table 9. *Summary of the advantages, problems and applications of the electrochemical systems used for controlling and monitoring corrosion in reinforced concrete structures. The last column on the right shows references of publications regarding examples of sensors using the present techniques*

TECHNIQUES	ADVANTAGES	PROBLEMS	APPLICATIONS	PUBLICATIONS
POTENTIOMETRIC– Corrosion potential measurement	1. On-site 2. Easy to use 3. Inexpensive	1. Intrusive, needs boring. 2. Qualitative limitation. 3. Influenced by temperature. 4. Needs prior calibration.	1. Drawing of potential maps.	(Toko & Habara, 2005) (Burkert et al., 2006) (Force technology, 2017)
POTENTIOMETRIC – Chloride penetration measurement	1. On-site 2. Easy to use 3. Inexpensive 4. Non-destructive	1. The electrode is consumable. 2. Limited service life. 3. Influenced by temperature. 4. Needs prior calibration.	1. Presence of chlorides.	(Legin et al., 1997) (Schiegg, 2002) (Bergmeister, 2004) (Sensortec, 2006) (Force technology, 2017) (Gandía et al., 2016)
POTENTIOMETRIC – pH measurement	1. On-site 2. Easy to use 3. Inexpensive 4. Non-destructive	1. The electrode is consumable. 2 Influenced by temperature. 3. Needs prior calibration.	1. pH measurement.	(Mihell & Atkinson, 1998) (Gandía et al., 2016)
AMPEROMETRIC	1. On-site 2. Easy to use and robust 3. Inexpensive 4. Non-destructive	1. Interference of materials with the same redox behavior.	1. Indirect calculation of the corrosion intensity, corrosion potential and corrosion speed.	(Morata et al., 2013) (Brite/EuRam, 2002) (Force technology, 2017)
CONDUCTOMETRIC	1. On-site 2. Small, robust, quick response 3. Non-destructive	1. Needs calibration based on media and material strength.	1. Indirect calculation of the resistance, relative humidity and corrosion speed.	(Andringa, 2006) (Spiesz & Brouwers, 2013)

7. Application examples

Although we can already find corrosion sensors in some significant works, the actual use of sensors in the construction industry is still at an early stage. In the following paragraphs, several real-life examples are described concerning the application of monitoring techniques and sensors to ensure the optimal durability of the constructions. These are large-scale constructions involving very big budgets, whose durability has been put at stake due to their exposure to high corrosion risks.

7.1 Hangzhou Bay Bridge

One of the first applications of monitoring systems in the initial design was carried out in 2003, when the works of a 36-km-long bridge was initiated in Hangzhou, in the east of China, and whose service life was set at 100 years. Because it is located on a marine environment, this bridge is exposed to severe environmental conditions. Therefore, a long-term monitoring system was installed, which included sensors for measuring the penetration of chlorides and other systems that allow initiating cathodic protection measures if necessary (Raupach, 2006), (Spiesz y Brouwers, 2013), (Gan et al., 2010).

and the application age of a protecting coating that can stop the initiation of corrosion (Alexander, 2009).

7.2 Arch Shell Structure of the Allianz-Arena Soccer Stadium in Munich

In Europe, a few years later, monitoring systems were considered to obtain a more efficient design of the Allianz-Arena stadium in Munich, whose construction was built to celebrate the soccer World Cup in 2006. In order to provide a suitable infrastructure for the visitors, the stadium has the biggest parking space in Europe, whose shell structures are built with reinforced and prestressed concrete and must withstand surface frost and the presence of deicing salts. Due to its large dimensions, the option of protecting the shell with coatings was turned down due to the high cost involved, and instead, the decision was taken to act on the specific areas with corrosion risks. Therefore, a corrosion plan was prepared, which consisted in frequent inspections through a local monitoring system providing information on the corrosion risk at several depths. Based on the continuously updated data concerning the corrosion probability in the reinforcements, it is possible to locate the necessary points and the application age of a protecting coating that can stop the initiation of corrosion (Alexander, 2009).

7.3 Shell Structure of La Zarzuela Racecourse in Madrid

In Spain, the corrosion monitoring systems were put to the test in 2005 during the last repair works of the emblematic racecourse of La Zarzuela de Torroja. These interventions included the installation of permanent corrosion recording systems with the following types of electrochemical sensors: sensor detecting the presence of liquid water, sensor measuring the corrosion potential of the embedded reinforcement with Mn/MnO reference electrode and sensor measuring the temperature (Dragados et al., 2011) see Figure 8.

The incorporation of sensors allowed verifying that the repair of the shell structures had been concluded satisfactorily. This system of implementing permanent sensors will enable the future control of the building without undertaking destructive measurements (Dragados et al., 2011).

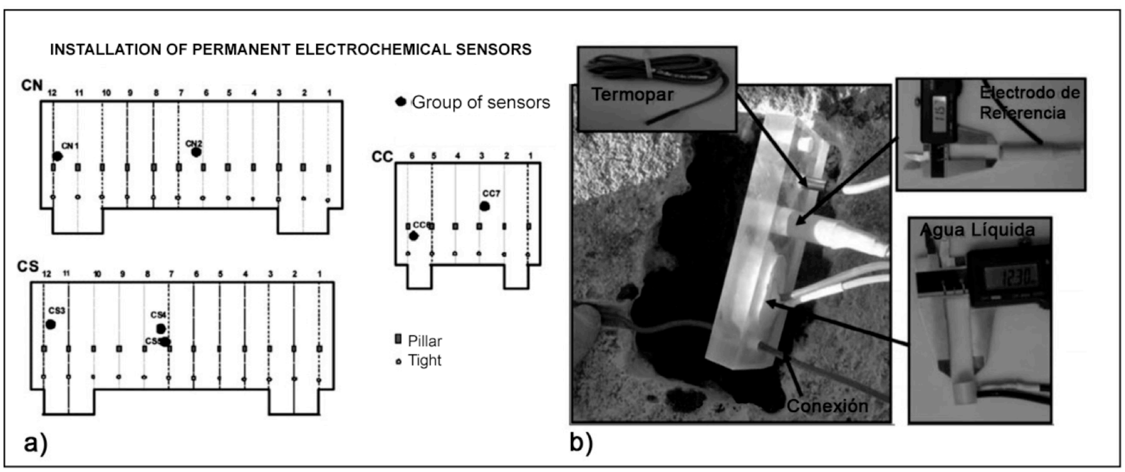

Figure 8. *Diagram of the location of the group of sensors in the shell structure (a) and diagram of the group of sensors (b). Modified from (Dragados et al., 2011)*

7.4 Idifor's Prestressed Concrete Floating Rafts in the Basque Country

More recently, researchers of the Polytechnic University of Valencia have patented and installed sensors for measuring the corrosion speed in prestressed concrete rafts designed for Idifor Technological Creations S.L., and located in the Basque Country (Figure 9). The data collection system is automatic and sends the information in wireless form to a central unit, which allows making a continuous follow-up of the corrosion processes, in real time (Zemlock et al., 2014).

Figure 9. *Floating raft in Mutriku (Basque Country) (a) and data collection module (b) (Zemlock et al., 2014)*

7.5 Tamina Bridge in Switzerland

Currently, the Federal Polytechnic School of Zurich is carrying out important studies regarding the effect of corrosion on the service life of reinforced concrete infrastructures (Angst and Elsener, 2017). Researchers are considering the possibility of using sensors for monitoring the corrosion in recently-built bridges like the Tamina Bridge, which was completed in June 2017. It is the longest reinforced concrete bridge in Switzerland, with an extension of 475 meters (Wit, 2017).

8. Conclusion

The corrosion in the reinforcements is the main cause of deterioration in reinforced concrete structures and, therefore, the main reason for doing repairs. Consequently, monitoring is a very useful and promising tool, because it allows permanently evaluating the condition of a structure and thus estimating the optimal intervention date.

A prior condition for a successful corrosion monitoring is to rely on a detailed design of the monitoring system. This requires a clear description of the monitoring objective and a subsequent selection of adequate sensors. Furthermore, the design of monitoring systems also includes a careful planning of the installation while the structure is being built, an early definition of the threshold values of the sensors, a description of the system's verification possibilities and a definition of the data collection rate.

A significant difference with regard to other industrial sectors, such as the chemical industry, is that in the construction industry the changes of relevant corrosion parameters in the structures occur quite slowly; consequently, a low data collection rate is recommended.

Currently, the capacity of newly developed monitoring systems, which are continuous and in real time, allows a more detailed assessment of the current and future condition of the structure, and even predicting its service life. Additionally, if these systems enable the automation, programming and the distribution of a large number of measuring points, a proper control system is feasible. With this purpose in mind, new software is currently being developed to improve the data collection and interpretation, and the incorporation of WiFi remote systems, which allow online data storage (Lynch and Loh, 2006), (Alcañiz et al,. 2016).

While the development and improvement of monitoring systems is still ongoing, certain types of corrosion sensors are already available on the market, which measure direct parameters such as corrosion speed, or indirect parameters like corrosion potential or resistivity (Alcañiz et al,. 2016), (Kuang-Tsan and Yang, 2010) (Zemlock et al., 2014). However, the current technology must still face the obstacle of their industrialization and commercialization, so that someday we will be able to install a sensor network throughout our existing buildings, which will allow knowing their condition immediately and having full control of possible deterioration risks.

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