Paper
03435

CORROSION2003

# CORROSION MEASUREMENT IN CONCRETE UTILIZING DIFFERENT SENSOR TECHNOLOGIES

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## ABSTRACT

Degradation of concrete structures due to corrosion of embedded steel reinforcement is an important problem with regards to durability and safety, with great economical consequences. One method for corrosion prevention is the application of corrosion inhibitors. Corrosion inhibitors can be applied as additives to new concrete during the batching process, or surface applied to existing concrete structures. This paper gives an overview of existing sensor technologies, previews new technologies, and proposes suitable methods for corrosion monitoring and inhibitor efficiency investigation on real structures. Many different sensor technologies have been developed, and new ones are under research. Advantages and disadvantages of different corrosion determination approaches are also discussed. Half-cell reference electrodes, linear polarization sensors, localized electrochemical impedance spectroscopy sensors and macrocell current sensors are based on electrochemical principles. Non-electrochemical sensors work on physical principles such as the Hall effect, magnetic flux leakage, magnetostrictive effect, eddy currents and on light modulation (Fiber optic sensors). Fiber optic sensors have many advantages such as immunity to chemical environments, long-term stability, and the ability to make distributed measurements of several parameters with a single sensor. However, they are underdeveloped in the field of concrete reinforcement corrosion. Fiber optic sensors can measure corrosion directly, or indirectly by measuring factors that influence the corrosion process (pH value, $Cl^-$ concentration, water content in concrete, $CO_2$), and can also detect cracks due to corrosion.

**Keywords:** non-destructive test methods, electrochemical sensor techniques, non-electrochemical sensor techniques

## INTRODUCTION

Corrosion of steel reinforcement is the main cause of deterioration in reinforced concrete, adding significant costs to the repair of structures worldwide. Application of corrosion inhibitors may be the best solution when concrete is exposed to chlorides from the environment, or when concrete is prepared with chloride contaminated water or aggregates. The purpose of this paper is to give an overview of existing as well as potential new sensor technologies, suitable for monitoring corrosion and corrosion inhibitor efficiency. Based on working principles, corrosion monitoring techniques can be classified as electrochemical or non-electrochemical, and having direct or indirect methods. Direct methods measure corrosion processes (corrosion potential, macrocell current, magnetic induction), while indirect methods monitor consequences or parameters that stimulate corrosion (cracking, delamination, $Cl^-$ ion content, pH value of pore water). Sensor technologies for corrosion measurement are presented in Table 1.

## ELECTROCHEMICAL SENSOR TECHNIQUES

### Embedded Reference Electrodes

The principle involved in this method is appearance of an electrical potential between reinforcing steel and a reference electrode. The half-cell consists of a metal rod immersed in a solution of its own ions.

Different reference electrodes are commercially available. Pseudoreference mixed metal oxide electrodes developed by Cescor consists of mixed metal activated titanium rod cast in porous cement backfill (Figure 1). A new probe for taking true potential measurements when stray currents are present was patented (Figure 2) [1]. The ERE 20-Embbedable reference electrode developed by the FORCE institute uses a manganese dioxide electrode in a steel housing surrounded by an alkaline gel [2] (Figure 3). The advantages of these sensors are long-term stability and greater sensitivity compared with classical potential mapping methods.

Austrian Engineer Biro Wietek manufactures a sensor in the form of wire wrapped around a steel bar to be monitored (Figure 4). The potential between the steel and electrode can be measured using half-cell. This method is suitable for measurement of localized pitting corrosion, which is difficult for ordinary point sensors [3].

### Corrosion Macrocell Current Probes

Macrocell current technique involves the measurement of galvanic current between carbon steel and stainless steel electrodes. The sensor consists of electrodes placed at different depths. An increase in current flow indicates the ingress of chloride ions. A zero resistance ammeter (ZRA) is used to measure current flow between electrodes. Several macrocell sensor configurations based on the same principle are commercially available (Figure 5). Probes for embedment into fresh concrete are the Corrowatch probe produced by Germann instruments [2], Schiessel probes [4] and Force Institute probes [5]. The expanding ring system (Figure 6) developed by M. Raupach is designed for insertion into holes, which can be drilled into the concrete [6].

**Linear Polarization Sensors**

In the linear polarization method, a potential scan is applied. The resulting current has linear dependence versus the potential. Corrosion currents are calculated using the Stern-Geary equation [7]. Different types of sensors are available on the market [8] (Figure 7).

The C-probe CP100 is a combination of a Silver/silver chloride reference half-cell and a graphite counter electrode. The CORROATER 800/800T, manufactured using carbon steel, measures corrosion rate of reinforcing steel in concrete. General Building Research Corporation of Japan developed mini-sensors.

**Electrical Resistance Method**

This method is based on the principle that the electrical resistance of metal is inversely proportional to its cross section. Resistance change measurements are made between the exposed probe and the protected probe. As corrosion occurs, it reduces the cross section of the exposed probe and resistance increases. This method is best suited for monitoring uniform corrosion and enables a periodic monitoring of the corrosion activity. The technique is very useful in seawater, underground structures and industrial plants where chloride attack is severe [9].

The 650C Corrosimeter concrete probe (Figure 8) consists of a steel electrode that measures the decrease in resistance in the presence of corrosion, which is the base for calculating the cumulative metal loss [10].

## NONELECTROCHEMICAL SENSOR TECHNIQUES

**Acoustic Emission**

Acoustic emission is the transient stress waves in a structure caused by the corrosion process, which induce micro cracking in concrete surrounding [11]. The local area monitoring system (LAM) was developed by support of the FHWA research program [12]. The LAM system (Figure 9) is designed to monitor acoustic emission activities from defects on small areas of bridges.

**Magnetostrictive Sensors**

A magnetostrictive technique is based on the principle that a magnetic material changes its shape when subjected to a changing magnetic field. Deformation results in elastic waves, which travel along the steel bar. Inversely, deformations in the magnetic material result in a change in magnetic induction of the material and in the voltage in the reception sensor. The magnetostrictive instrument (Figure 10) is composed of a transmitting sensor and a receiving sensor, which are identical. Each of the two sensors consists of a coil that encircles the reinforced bar or strand and a bias magnet that creates a bias magnetic field. The bias magnetic field is necessary because tested material needs to be in a magnetized state. The output signals of the receiver are displayed on an oscilloscope or a PC with an AD converter.

Bartels, Kwun and Hanley performed research on the use of magnetostrictive sensors to characterize corrosion in the pre-stressed strands and reinforcing bars [13]. The magnetostrictive technique provides an effective way of inspecting the strands and reinforcing bars.

**Fiber Optic Sensors**

Fiber optic sensors (FOS) are the most promising technique under investigation today. Generally FOS have many advantages when compared to other measurement methods. They have long term durability, immunity to electromagnetic fields and to severe working conditions, such as high and low temperatures, humidity, pressure, and chemically aggressive environments. The small diameter of the optical cable (0.1 mm) makes it possible to embed FOS into the structure. One optical fiber can measure several different parameters at different positions. Working principle of FOS is changing on some property of light – intensity, phase, polarization or wavelength. FOS are able to indicate many parameters such as temperature, electromagnetic field, stress, vibration, strain, chemical composition. Important parameters for corrosion monitoring are the pH value of pore water in concrete, as well as $Cl^-$ ion, water, and inhibitor content.

FOS can be extrinsic or intrinsic. Extrinsic sensors use optical fiber for guiding light to the sensitive element and back to the detector. Intrinsic sensors use optical fiber as a sensitive element [14] (Figure 11).

**Water Content Measurement**

Water content measurement using fiber optic sensors can be based on transformation of humidity into strain measurement. The first sensor on this principle was developed at Stratchlyde University. It contains a hydrogel layer and steel spiral around the fiber, which induces microbending of the fiber (Figure 12). Microbending results in light intensity loss. By feeding in quick pulses of light and monitoring the backscattered signal as a function of time, it is possible to measure humidity at different parts of structure [15].

**$Cl^-$ ion Content Measurement**

Indirect chloride ion detection technique is based on the Fajan's method of chloride analysis, with an improvement of using optical fibers for the light transfer from and to the sensing unit. A broadband input light signal is passing through the optical fiber coil situated in the silver nitrate solution. A chamber with the silver nitrate solution has a porous membrane at the top. The chloride ions will migrate through the membrane to the silver nitrate solution. The chloride ions react with silver nitrate to form silver chloride, with excess of silver ions. Silver ions adsorb onto the silver chloride molecule surface resulting in a positive charge. As a result, the indicator dichlorfluorscein changes color, which is detected by the optical sensor [16] (Figure 13).

**pH Value Measurement**

It is known that strongly alkaline environment promote the formation of a thin passive oxide layer that protects steel reinforcement from corrosion. Cement paste has a pH value about 11.5, but chloride ion diffusion decreases alkalinity, destroying the passive film, and corrosion occurs. So, pH is an important indirect parameter for corrosion determination. The pH value fiber optic method can be based on the evanescent field method. Evanescent field is a harmonic wave that penetrates a cladding medium, when light passing through the optical fiber. The evanescent field is used to selectively excite pH sensitive molecules in the cladding. As a result light intensity depends on the pH value of the medium surrounding the fiber optic sensor. Dyes suitable for pH value determination are pH sensitive cromopheres. Usage of different dyes makes it possible to identify a wide variety of inorganic and organic chemical compounds [13].

### Direct corrosion detection

A direct optical detection of corrosion is also possible. A direct method can be based on the principle that the color of steel changes when it corrodes, and if the optical sensor is placed directly on the reinforced bar, the color of reflected light also changes. The fiber surface may be coated with a substance reacting with the corrosion products.

## CONCLUSION

Today many corrosion monitoring sensor techniques based on different principles have been developed. This is a field with great potential for research and development. Generally, sensor technologies are more advantageous to use than other handheld non-destructive techniques, because they make continuous monitoring possible. The sensor is placed near measured the quantity to increase accuracy. The main disadvantage of sensor techniques is that point measurement can be made only at particular positions. This may be improved with sensors able to make distributed measurements. Fiber optic chemical sensing methods are underdeveloped in the field of concrete reinforcement corrosion and inhibitor efficiency investigation, but deserve attention.

## REFERENCES


[1] http://www.cescor.it

[2] http://www.germann.org

[3] http://www.a-bau.co.at

[4] Schiessl, P., Raupach, M., *Monitoring System for the Corrosion Risk of Steel in Concrete Structures*, Concrete International, 1992, No.7, pp. 52-55.

[5] Bjegovic D., Miksic, B., Stehly R., *Test Protocols for Migrating Corrosion Inhibitors (MCI) in Reinforced Concrete*, Emerging Trends in Corrosion Control - Evaluation, Monitoring, Solutions, Vol. 1, Academia Books International and NACE International, India Section, New Delhi, India, 1999, pp. 3-18.

[6] Raupach M., *Smart structures: Development of sensors to monitor the corrosion risk for the reinforcement of concrete bridges,* First International Conference on Bridge Maintenance, Safety and Management IABMAS 2002, Barcelona, 14-17 July, 2002.

[7] Sekulić, D.; Bjegović, D.; Mikulić, D.: *Monitoring behavior of reinforcement embedded in concrete*, Građevinar, vol. 52 (2000) No. 10, pp. 577-586.

[8] Bjegović D.; Mikulić D., Sekulić D.: *Non-destructive corrosion rate monitoring for reinforced concrete structures*, 15th World Conference on Non-Destructive Testing, Rome, 15-21 October 2000, Proceedings, Paper idn. 642.

[9] Devalapura, R.K., Kamel, M.R., Arumugasaamy, P., (1994), *Nondestructive techniques for corrosion evaluation of steel in concrete*, Corrosion and corrosion protection of steel in concrete, Proceedings of International Conference held at the University of Sheffield, Vol. 1, July 1994, 300-309.

[10] http://www.corrpro.com.htm

[11] Sekulić, D., Bjegović, D.; Mikulić, D., *Non-destructive Methods for Monitoring of Reinforcing Steel in Concrete*, Structural Faults & Repair, London 2001.

[12] http://www.tfhrc.gov/hnr20/nde/acoustic.htm

[13] Bartels, K.A., Kwun, H., Hanley J.J., *Magnetostrictive Sensors for the characterization of Corrosion in rebar and Prestressing Strands*, SPIE Proceedings, Vol 2946, 40-50, 1996.

[14] Dumanić E., Sekulić D., *Staklena vlakna – teorija i praksa (Fiber optic sensors - theory and practice)* http://www.igh.hr/Metar/Metar12/NS.html

[15] Inaudi, D., Casanova, N., Vurpillot, S., Glisic, B., Kronenberg, P., Lloret, S., *Lessons learned in the use of fiber optic sensor for civil structural monitoring*, The Present and the Future in Health Monitoring, Bauhaus-University, Weimar, Germany, Edifictio publisher (2000), pp 79-92, 2000.

[16] Fiber optic chloride threshold detectors for concrete structures, http://www.corrosion-doctors.org/Advances/FiberOptics.htm

[17] Ghandehari, M., Vimer, C.S., *An evanescent-field fiber optic sensor for pH monitoring in civil infrastructure,* 15th ASCE Engineering Mechanics Conference, Columbia University, New York, June 2-5, 2002.

**Table 1: Sensor technologies for corrosion measurement in concrete**

| ELECTROCHEMICAL METHODS | NON-ELECTROCHEMICAL METHODS |
|---|---|
| Embedded reference electrodes | Magnetostrictive sensors |
| Corrosion macrocell current probes | Acoustic emission |
| Linear polarization sensors | Fiber optic sensors |
| Electrical resistance method | |

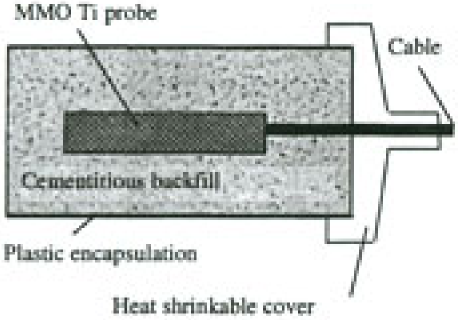


**Figure 1. Metal Oxide-Ti probe**

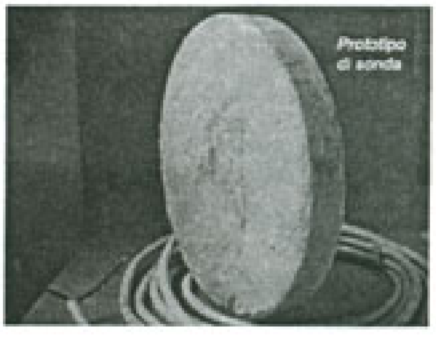


**Figure 2. New developed probe**

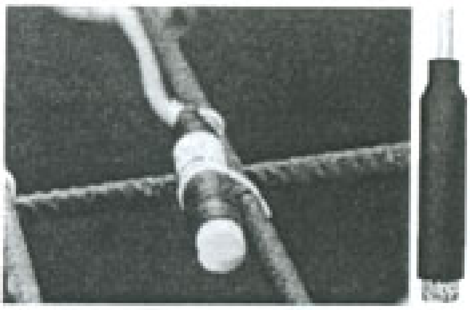

**Figure 3. $MgO_2$ probe**

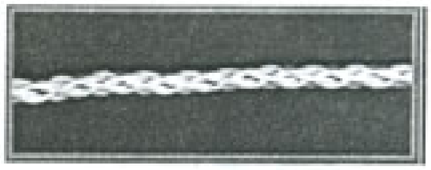

**Figure 4. Wire sensor**

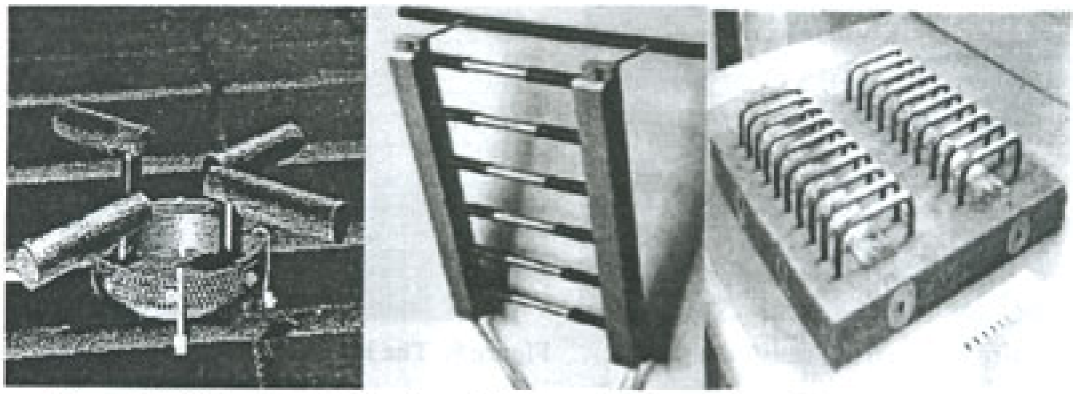

**Figure 5. Different configurations of Macrocell current electrodes**

**Figure 6. Expanding ring probe**

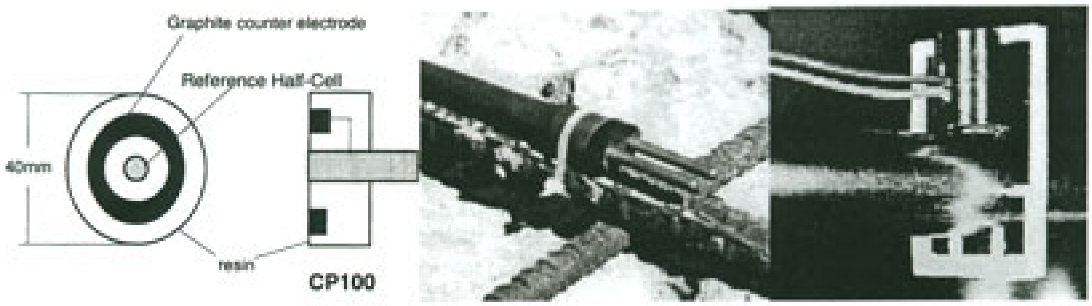


**Figure 7. Different types of linear polarization sensors**

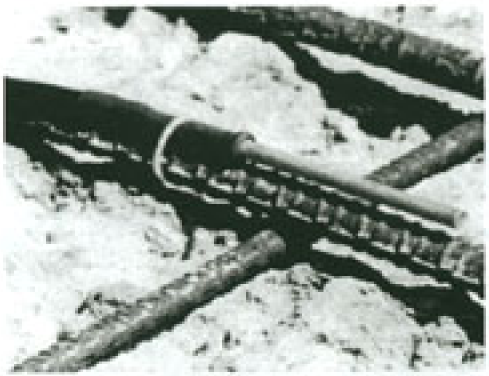

**Figure 8. Electrical resistance probe**

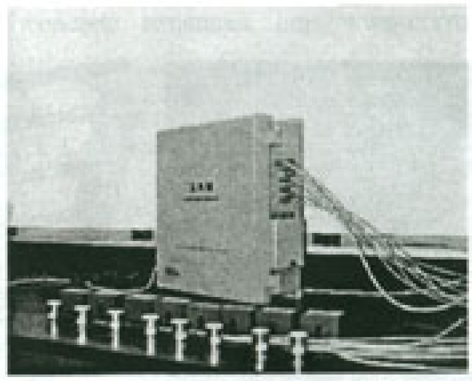

**Figure 9. The local area monitoring system**

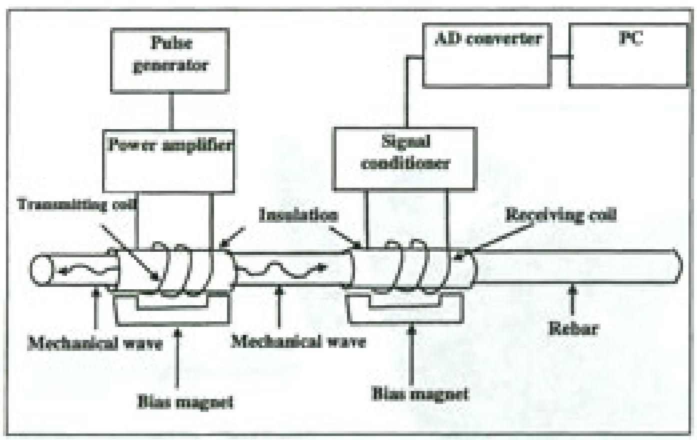


**Figure 10. Principle of magnetostrictive method**

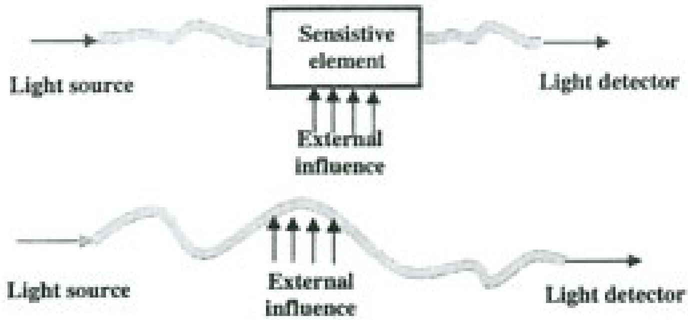


**Figure 11. Basic principle of fiber optic sensors, extrinsic sensor (upper) and intrinsic sensor (lower)**

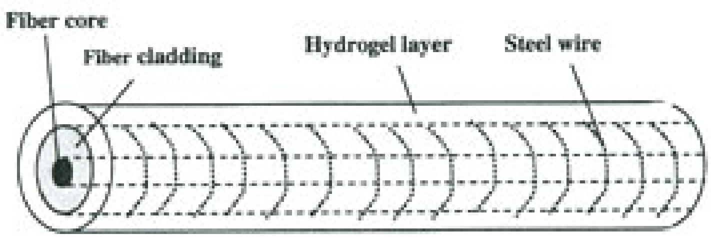


**Figure 12. Principle of hydrogel humidity sensor**

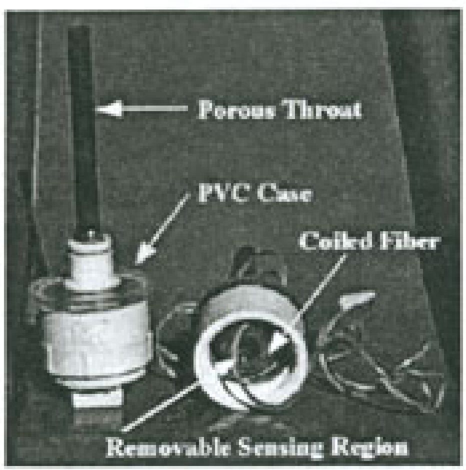


**Figure 13. Embeddable fiber optic sensor for the chloride ion concentration measurement**