Construction and Building Materials 53 (2014) 403–410

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Monitoring method for the chloride ion penetration in mortar by a thin-film sensor reacting to chloride ion

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HIGHLIGHTS

- A sensor reacting to chloride ion was developed using screen printing.
- The sensor with a weight ratio for Ag:Fe of 1:2 was proven to react to corrosion.
- Electrical resistance was confirmed to change with corrosion caused by salinity.
- The sensor could monitor the depth of salinity penetration from the mortar surface.

ARTICLE INFO

Article history:
Received 27 September 2013
Received in revised form 25 November 2013
Accepted 26 November 2013
Available online 27 December 2013

Keywords:
Monitoring method
Mortar
Chloride ion penetration
Sensor
Electrical resistance

ABSTRACT

The depth of chloride ion permeation from a concrete surface can be monitored in reinforced concrete structures. The purpose of this study is to develop and apply a thin-film sensor based on the measurement of changes in electrical resistance of the sensing elements in order to follow the chloride ion penetration in mortar. The proposed thin-film sensors were placed in mortar specimens intrinsically containing chlorides, and mortar specimens impregnated with chloride solutions then subjected to accelerated corrosion in a NaCl solution. For making a film sensor, a screen printer machine was used. Silver (Ag) paste and iron (Fe) powder were coated on the thin-film sensor that reacts to chloride ion in mortar. As a result of experimental testing, the appropriate ratio of Ag to Fe was >1:2. The electrical resistance of the sensors increased with the degree of corrosion behavior of thin-film sensor. The time to the first change in electrical resistance decreased along with the degree of corrosion as the distance from the mortar surface decreased. The proposed thin-film sensors are thus confirmed to be capable of monitoring the depth of chloride permeation in mortar with sufficient accuracy.

1. Introduction

The corrosion of steel reinforcements in a reinforced concrete structure starts from the surface of the steel reinforcement [1]. Thus, the presence of cracks on concrete surface implies that corrosion of steel reinforcement has made considerable progress inside [2,3]. Corrosion of steel reinforcement in concrete is the main cause for early performance degradation and the breakdown of reinforced concrete structures. Of the deterioration phenomena that occur in reinforced concrete structures, deterioration caused by steel reinforcement corrosion produces the most severe damage; the cost for maintaining and constructing these structures is very high, and it is difficult to determine the appropriate maintenance period [4,5]. Therefore, the prediction and early detection of corrosion of steel reinforcement is very important for the administrator to establish efficient maintenance and enhancement plans [6–8].

Currently, there are several researches being conducted for determining the appropriate maintenance period or repair process based on the extent of damage to structures, but the monitoring systems that focus on the penetration of chloride ion to the corrosion of steel reinforcement before steel reinforcement corrosion occurs are lacking. Additionally, maintenance of most concrete structures usually starts after deterioration occurs. Such measurements can be said to be repairs covering up the phenomena rather than maintenance in consideration of the future [9,10].

Thus, a sensor needs to be developed to monitor the penetration process of chloride (Cl^-) which affects the corrosion of steel reinforcement in concrete before it progresses, so that the proper maintenance period and appropriate repair method can be established. A system for non-destructive monitoring of building structures also needs to be developed.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.11.095

This study carried out a performance assessment for a developed thin-film sensor reacting to chloride ion. The reactivity of the sensor to changes in the salinity of the mortar was examined, and the monitoring of chloride ion penetration factors for a building by the sensor was considered at different depths. The sensor was built into the structure as shown in Fig. 1 and was monitored in real time. The penetration of chloride ions was detected by the electrical resistance of the corrosion of sensor.

2. Consideration of existing literature

Sensors are defined in the IEEE Standard Dictionary of Electrical and Electronics Terms (1996) 6th Edition and classified according to temperature instrumentation type and by devices for testing, production, instrumentation, diagnosis, etc. In other words, a sensor refers to devices having the functions of metering, detecting, determining, or measuring various types of quantities such as temperature, sound, pressure, and light and delivering them as signals or in the applicable unit of measurement [5]. For monitoring corrosion or chloride ion diffusion, the actual methods are divided into static measurements and polarization measurements. This study focused on the static methods as half-cell potential, macro-cell current and electrochemical noise measurements for corrosion monitoring which various sensors are applied [11].

During the corrosion process, corrosion macro-cells are formed with a distribution of anodic and cathodic areas. Different measuring configurations for in situ testing are developed. A step-type probe (Schieβl probe or ladder system) sensor system was designed to monitor the risk of corrosion from airborne chlorides penetrating concrete [4,12]. The system consists of the steel electrodes and insulting supports. The sensor can be built in a new construction or during the repair. Steel electrodes are placed at different depths which makes depassivation front monitoring possible [11,13]. Another configuration is a multi-probe system. The test unit is exposed to chloride ions diffusing from one side. Initiation of corrosion can be detected by a sudden rise in the anodic current. This test method has an advantage in providing direct indication of electrochemical activity in the system [11,13–18].

Upon the pumping of concrete, this probe is placed close to the steel reinforcement, providing a monitoring signal hourly. If iron is initially put under strong alkaline conditions, a passive film forms on the iron surface, and hence, no corrosion occurs [4,11,12]. At this point of time, even if the iron is electrically connected to metal with an ionization tendency less than that of closely placed steel reinforcements (e.g., stainless steel), almost no flow of current occurs between the two types of metal. However, if the passive film on the iron surface is damaged by the penetrating corrosion factors and if corrosion is progress further, the amount of current from the iron to the stainless steel increases according to the degree of corrosion. Sequential measure of the electrical reaction at the iron surface at different depths allows the penetration depth and speed of the corrosion factors to be monitored [1,19].

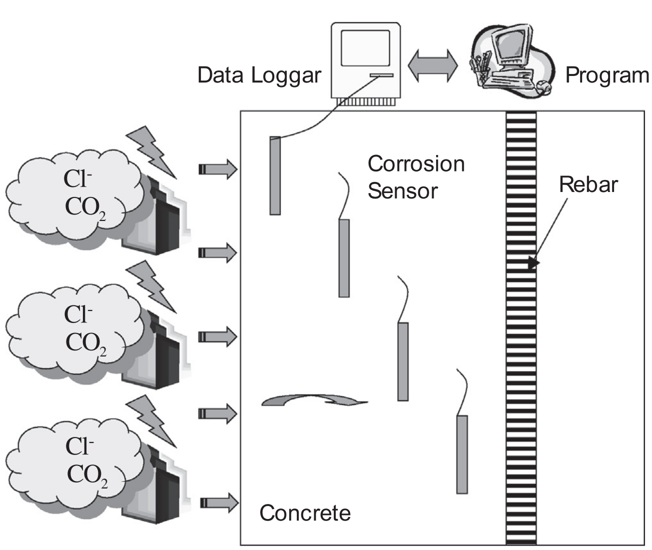

Fig. 1. Sensor reacting to chloride ion in the structure.

On the other hand, wire sensor system was developed to monitor the factors that cause corrosion along the depth. Whereas the Schieβl probe sensor system measures the electrical flow with iron by inserting a type of metal (noble metal), this sensor places a thin iron wire at a depth, and monitors the change in wire resistance between both ends; the wire disconnects in reaction to corrosion factors [20,21]. Another wire sensor covered by PVC in the form of a wire is wrapped around the steel to be monitored. A potential between the steel and electrode can be measured by using the half-cell. The advantage of the method is great sensitivity, which makes the method suitable for measurements of pitting corrosion at the large concrete structures [11,22].

Finally, corrosion sensor system by sputtering was developed. Sputtering is a method of applying a metal or oxide (target) using plasma on the material surface [23,24]. However, there are weaknesses to deposition technology using sputtering: it is complex; it takes a long time to mass-produce sensors; the sensor is attached to a specific substrate; and the attachment stress with the substrate is weak [23–26]. Therefore, a screen printer machine was used for making a film sensor in this study. To improve the previous disadvantage, Ag paste and iron Fe powder were coated on the thin-film sensor that reacts to chloride ion in mortar environment: it is not complex; it take short time to mass-produce sensor; the sensor is small size; and the sensor has high response speed with electrical resistance.

The comparison of electrochemical methods for chloride ion diffusion and corrosion characterization in reinforced concrete is summarized in Table 1.

3. Sensor development

3.1. Sensor system using a screen printer

Screen-printer technology adds a basic solution (Ag paste) that can be printed. If this solution is not put in, screen printer equipment cannot be used. However, this study attempted to print a sensor reacting to chloride ion using screen-printer technology by mixing a suitable amount of 99.9% pure iron powder (powder size 10 μm) with Ag paste to develop a sensor that reacts in the same manner as iron. Screen-printer technology is a simple silk screen method for producing a sensor by masking and etching using a photolithographic method [25,27]. In addition, because the sensor drawing can be replaced, various sensor forms can be produced. Thus, the method of printing the sensor directly onto the substrate with screen-printer technology was employed.

Fig. 2 shows a mask drawing. For printing (Fig. 3), a mask was attached to the silk screen equipment, and the substrate was bonded to the silk screen equipment. Printing started after the Ag paste and iron powder were mixed and applied on the mask.

3.2. Sensor development methods

3.2.1. Design of sensor

Drawing of the sensor is shown in Fig. 4. This drawing was previously developed by sputtering technology [24], but its various weaknesses were mitigated using screen-printer technology. The