Cement & Concrete Composites 31 (2009) 545–554

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Examples of reinforcement corrosion monitoring by embedded sensors in concrete structures

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ARTICLE INFO

Article history:
Received 1 September 2008
Received in revised form 14 January 2009
Accepted 30 May 2009
Available online 7 June 2009

Keywords:
Electrochemical techniques
Linear polarization
Corrosion rate
Service life

ABSTRACT

An increasing number of concrete structures are being monitored to enhance their durability. However, the literature provides only some guidance for the interpretation of the monitoring results [Broomfield JP. Corrosion of steel in concrete, understanding investigation and repair. 2nd ed. UK: Taylor & Francis; 2006; Andrade C, Alonso C. On-site measurements of corrosion rate of reinforcements. Constr Build Mater 2001;15(2–3):141–45; EN 206 2000. Concrete—Part 1: specification, performance, production and conformity]. Past experience shows the difficulty of interpreting the data collected due to the influence of temperature and moisture, and of using these data to predict future evolution of any deterioration processes.

This paper presents several examples of recorded data for corrosion potential, electrical resistance and corrosion rates, along with a methodology to obtain a representative corrosion rate, averaged per year. The representative value can be used in corrosion predictive models to calculate the remaining service life.

1. Introduction

Corrosion of reinforcement is one of the main durability problems for concrete structures. The corrosion is induced by two main factors: carbonation of the concrete cover and penetration of chlorides contained either in the marine environment or in chemicals in contact with concrete. Corrosion of reinforcement induces structural damage that affects the serviceability and the safety of concrete structures. The structural risk associated with corrosion is promoting the use of embedded sensors, which can indicate the need for repair of the structure before reaching dangerous levels of damage [1,2,4].

In consequence, sensors have been installed in several critical structures, but difficulties arise when interpreting the results because the corrosion parameters are affected by temperature and moisture [5]. Although parameters correlated to the corrosion process (such as corrosion potential, galvanic currents, concrete resistivity or water content) can be monitored, the only parameter able to quantify the corrosion process is the corrosion rate, I_{corr}.

Very few studies have been published on the in situ monitoring of the corrosion rate and the influence of climatic changes and, in particular, of temperature, T [6,7]. All the studies conducted in the laboratory are based on controlled conditions of relative humidity, RH, and T. Only few studies have reported on the effects of the natural climatic cycles on the corrosion rate [8–12].

Apart from the monitoring of different complementary parameters, this paper presents I_{corr} results obtained from the monitoring of three concrete structures. The relationship between temperature and corrosion rate is also shown.

To account for the variation of I_{corr} due to the environment, it is necessary to establish a methodology for determining the representative value of the corrosion rate in one structure. This paper also illustrates how to calculate a representative corrosion rate using the data collected by sensors or single corrosion rate measurements when monitoring is not possible.

2. On-site electrochemical techniques for corrosion measurement

2.1. Corrosion potential and resistivity maps

Due to its simplicity, the measurement of corrosion potential, E_{corr}, is the method most frequently used in field determinations. From these measurements, potential maps are drawn revealing those zones that are most likely to undergo corrosion in the active state [13]. However, such measurements are qualitative, which makes data interpretation difficult [14]. The same argument can be extended to measurements of resistivity, ρ [15], which are used sometimes jointly with E_{corr} mapping. The ρ values indicate the moisture content of the concrete [16], which is related to the

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doi:10.1016/j.cemconcomp.2009.05.007

corrosion rate when the steel is actively corroding, but which may mislead the interpretation in passive conditions. In Fig. 1, a corrosion risk map of a slab is represented. The risk level has been calculated by a combination of these two parameters: E_{corr} and ρ. The risk level or incidence probability presented in Fig. 1 takes into account the classification made by ASTM C867 [13] for the E_{corr} results, mixed with a parallel classification of resistivity results in which lower resistivity provides higher corrosion risk.

2.2. Polarization resistance

The only electrochemical parameter which allows one to quantitatively estimate the corrosion rate is the polarization resistance, R_p [17]. The R_p measurement has been extensively used in the laboratory. It is based on the application of a small electrical perturbation to the metal by means of a counter and a reference electrode. Provided that the electrical signal is uniformly distributed throughout the reinforcement, the $\Delta E/\Delta I$ ratio defines R_p.

The corrosion current, I_{corr}, is inversely proportional to R_p, i.e.,

$$I_{corr} = B/R_p \tag{1}$$

where R_p is expressed in kΩ cm^2 and B is a constant resulting from a combination of the anodic and cathodic Tafel slopes. The standard unit of I_{corr} is μA/cm^2.

The Tafel constant, B, takes values between 12 and 52 mV in the case of reinforcement measurements. In general, higher corrosion results in lower measured values for the Tafel constant. For conditions in which it is not possible to calculate B, due to the destructive nature of the test, it is recommended a B value of 26 mV be used as an averaged value to reduce the error for estimating this parameter. This procedure can, however, be a problem if I_{corr} needs to be calculated exactly, mainly when steel is passive [18]. In general, the use of an average value for B has not been problematic for the on-site corrosion evaluation in concrete.

The relatively high resistivity of the concrete results in I_{corr} values that are too low, if compensation of the voltage drop across the electrolyte resistance is neglected or not adequately performed. This IR drop is the product of current, I, and resistance, R. This is due to the fact that the calculated R_p is the sum of the resistance related to the corrosion process and the resistance associated with the electrolyte. The potentiostats to be used for R_p measurements have to be able to calculate the ohmic drop, or to compensate for its influence during the recording of the R_p measurement. Direct estimation of true R_p values from $\Delta E/\Delta I$ measurements is usually not feasible in large concrete structures. This is because the applied electric signal tends to vanish with distance from the counter electrode, CE, rather than spread uniformly along the working electrode, WE. Therefore, the polarization by the electric signal is not uniform, and it reaches a certain distance that is named the critical length, L_{crit}. Hence, $\Delta E/\Delta I$ measurements on large structures using a small counter electrode provides an apparent polarization resistance ($R_{p\ ap}$) that differs from the true R_p value depending on the experimental conditions. Thus, if the metal is actively corroding, the current applied from a small CE located on the concrete surface is 'drained' very efficiently by the metal and it tends to confine itself to a small surface area. Conversely, if the metal is passive and R_p is high, the current applied tends to spread far away (e.g., around 50 cm) from the application point. Therefore, the apparent R_p approaches the true R_p for actively corroding reinforcement, but when the steel is passive, the large distance reached by the current needs a quantitative treatment.

2.3. Modulated confinement of the current (guard ring) method

There are several ways of accounting for a true R_p value, among which the most popular is the use of a guard ring [19], which confines the current in a particular rebar area, as Fig. 2 depicts. The equipment used is able to automatically make the IR compensation in the R_p determination. The measurement is made by applying a galvanostatic pulse, lasting from 30 s (corroding) to 100 s (passive), from the central counter electrode. Then, another counter current is applied from the external ring. This external current is modulated by means of two reference electrodes called "ring controllers", located between the central counter electrode and the external ring, in order to achieve the required counterbalancing electrical field. These twin electrodes permanently control the external ring by means of detecting the current lines coming from the central counter electrode in order to adjust them within the predetermined area, which enables a correct confinement, and therefore, calculation of R_p. This method then makes an electrical delimitation of the area instead of determining it. So, as the measurement area is delimited by the guard ring, the use of the confinement method allows the evaluation of corrosion in certain localized areas. In this way, it is possible to determine the zones in a real concrete structure in which the rebar is corroding, and quantify the velocity of this deterioration. Even when this method is not able to distinguish directly between generalized and localized corrosion, as the measurement area is reduced to a small part of the rebar, it is useful for the localization of active pitting areas in a concrete structures. The interpretation of the corrosion rate maps obtained from the measurements made in the structure can help diagnose the causes that led to corrosion.

It should be noted that not all guarded techniques are efficient. Only that using a modulated confinement controlled by the two small twin sensors for the guard ring control placed between the central auxiliary electrode and the ring (Fig. 2) is able to efficiently confine the current within a predetermined area. The use of guard rings without this control leads to high values of I_{corr} for moderate and low values. Accordingly, the error introduced in the case of very localized pits is high [20,21].

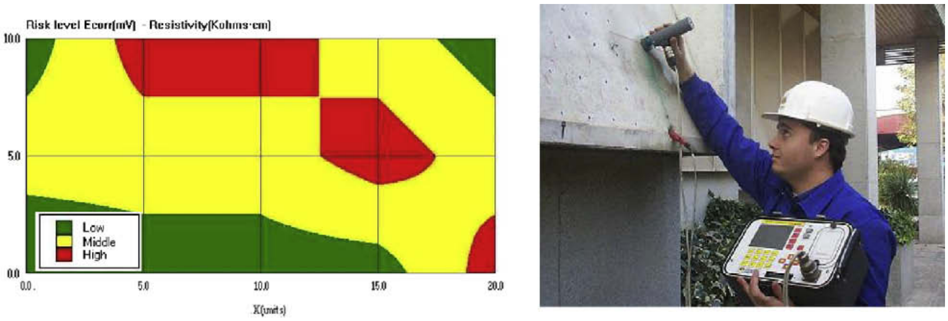

Fig. 1. (a) Corrosion risk map of a reinforcement slab calculated from the combination of E_{corr} and ρ measurements; and (b) on-site measurement with a portable corrosion rate meter (Gecor 08).