ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING

Vol. X 2010 No. 2

New non-destructive method for linear polarisation resistance corrosion rate measurement

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Corrosion of steel reinforcement is one of the most common causes of end service life in reinforced concrete structures. Corrosion is initiated and propagates unseen beneath the concrete cover and it is difficult to evaluate the severity of the problem. The most promising electrochemical method is the Linear Polarisation Resistance method which can provide a direct evaluation of the instantaneous rate of corrosion. The main drawback to this technique is that it requires a localized breakout of the concrete cover to provide an electrical connection to the steel reinforcement. This article describes an adaptation of the LPR method and the four-point Wenner resistivity method to give an assessment of the rate of steel corrosion without the requirement for a direct connection to the reinforcement. The measurements have been performed in cooperation with Construction and Infrastructure Group in University of Liverpool.

Keywords: *corrosion, concrete, non-destructive testing, resistivity methods*

1. Introduction

In recent years corrosion of steel reinforcement become a leading problem facing the civil engineering industry. Initiation of corrosion usually happens when the passivating alkaline environment provided to the steel bars by the surrounding concrete is neutralized by carbonation or disrupted by chloride ingress. Corrosion then propagates unseen until expansive corrosion products cause cracking or spalling of the concrete cover. Ongoing corrosion in adjacent uncracked regions will quickly cause further cracking to appear, which may be accelerated by the partial remediation [1].

In the last few years much attention has been given for developing portable methods for predicting remaining service life of the concrete structures. It is proper to note that the conventional corrosion assessment examination methods have been the half cell potential method [2] and the concrete resistivity method [3].

The half-cell potential technique requires breakout and an electrical access to the steel reinforcement. This should be connected to a high impedance voltmeter and a reference half-cell, in contact with the surface of the concrete. A number of measurements are taken on a regular grid and contour map of the potentials can be used to identify regions where corrosion activity is likely. Adjacent areas with a large difference in potential are indicative of corrosion activity (Figure 1a).

The concrete resistivity measurement technique was adapted from a method originally used for geophysical surveying [4]. A low magnitude AC current *I* at the spacing of "*a*" is passed through the concrete using two surface electrodes. A measurement of the potential *V* across the third points between the two current electrodes (Figure 1b) gives an evaluation of the electrical resistivity of the concrete in the surface region using the following equation:

$$\rho = 2\pi a \frac{V}{I} \tag{1}$$

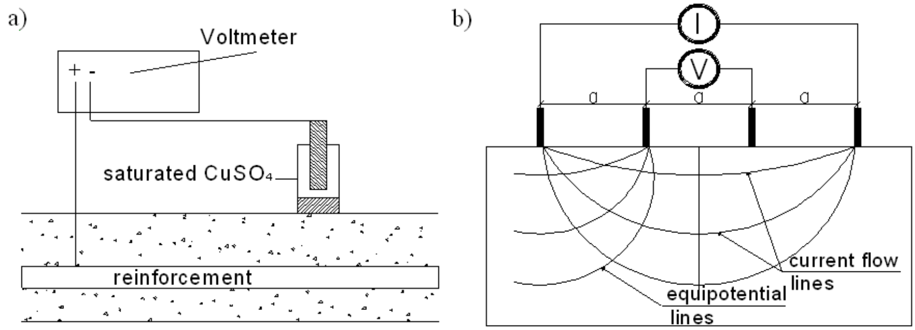

Fig. 1. Existing corrosion methods: a) half cell potential mapping,
b) concrete resistivity measurement

From a measurement of low resistivity, it can be inferred that if reinforcement corrosion is ongoing then the rate of corrosion is likely to be relatively high.

Both methods have their disadvantages and work best when used in combination. It is proper to note that these methods give an indication of the probability of corrosion location and corrosion activity and do not give a direct measurement of the instantaneous rate of corrosion.

The most popular of the electrochemical techniques is the Linear Polarisation Resistance (LPR) method [5–7]. The LPR method can be used relatively rapidly and portable instrumentation has been developed [8] suitable for use in the field test. The principal of LPR is based upon disturbing the corrosion equilibrium on the surface of steel reinforcing bars by the introduction of a small perturbative DC electrical signal using a surface counter electrode. The response of the equilibrium to this perturbation is measured with respect to a reference half-cell on the surface of the concrete (Figure 2). In the article a small current step ΔI may be used as the perturbative signal and the resulting potential is ΔE measured and the polarisation resistance R_p is given by:

$$R_p = \frac{\Delta E}{\Delta I}. \tag{2}$$

The corrosion interface comprises a capacitive double layer of charged ions C_{dl} on the surface of the steel bar together with a resistive interface, known as the charge transfer resistance. The electrical circuit can be used to describe the concrete cover and the corrosion interface and the charge transfer resistance is obtained by subtracting the concrete cover resistance often described as the solution resistance R_s from the polarisation resistance (Figure 3). The instantaneous rate of corrosion is proportional to the charge transfer resistance R_{ct}:

$$R_{ct} = R_p - R_s. \tag{3}$$

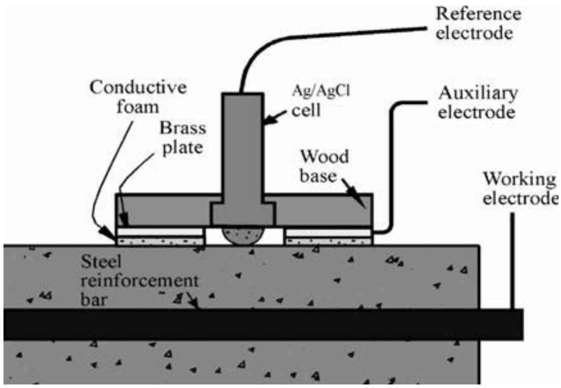

Fig. 2. Linear polarization resistance measurement [2]

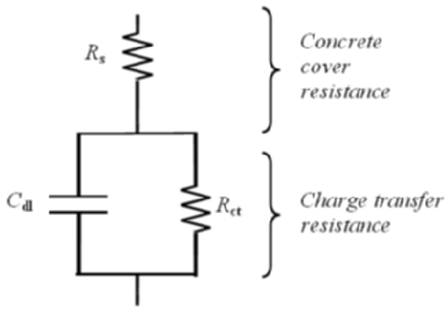

Fig. 3. Randle's equivalent electrical circuit

On the other side the corrosion current density i_{corr} requires knowledge of the area of steel being assessed "A" and is given by the Equation (4):

$$i_{corr} = \frac{B}{R_{ct} A}. \tag{4}$$

where a constant B is known as the Stern–Geary constant [9]. Typical values of corrosion rates from LPR measurements are presented in Table 1.

Table 1. Typical corrosion rates from LPR measurements [5]

Corrosion classification	Corrosion current density i_{corr}	Corrosion penetration rate
Passive/very low	Up to 0.2 μA/cm^2	Up to 2 μm/year
Low/moderate	0.2 μA/cm^2 to 0.5 μA/cm^2	2 μm/year to 6 μm/year
Moderate/high	0.5μA/cm^2 to 1.0 μA/cm^2	6 μm/year to 12 μm/year
Very High	> 1.0 μA/cm^2	> 12 μm/year

This article describes on a novel adaptation of the resistivity and LPR methods to provide an evaluation of the instantaneous rate of corrosion without the need the connection to the steel reinforcement and without the need to evaluate the area of perturbation.

2. New corrosion rate assessment method

The proposed method takes advantage of the short-circuit effect of a steel bar on the resistivity method rather than avoiding it. Galvanostatic resistivity measurements were taken using a modified electrode array. To ensure the stability of potential during the 30 sec equilibrium period, the two inner standard resistivity probes were replaced with two copper-copper sulphate reference electrodes (Figure 4a). A small current signal was provided by a standard laboratory galvanostat and the resulting change in potential measures using a high impedance voltmeter (Figure 4b).

If a conventional AC four-point resistivity measurement is taken directly over a steel bar and oriented parallel to the bar then this will maximize the reduction effect of the short-circuiting bar on measurement of the apparent resistivity. The AC signal will pass easily through the capacitance C_{dl} regardless of whether the surface of the bar is corroding rapidly (i.e. R_{ct} is small) or if it is corroding slowly always passive (R_{ct} is large).

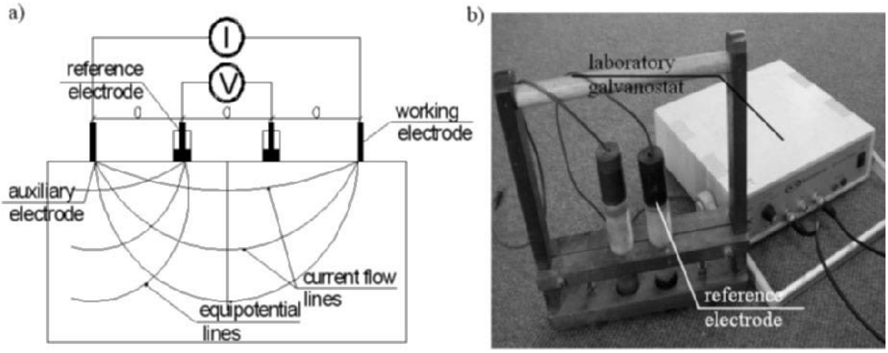

Fig. 4. New corrosion assessment method:
a) scheme of the method, b) view of the equipment

If the same four-point resistivity measurement is again taken at the same location and orientation but using a DC galvanostatic current then the effect of steel bar on the apparent resistivity measurement would be expected to be influenced by the rate of corrosion on the bar surface. Using a DC signal the current can no longer pass through the capacitance C_{dl}, after a suitable equilibrium period.

If R_{ct} is quite small then the apparent resistivity measurement should be close to a similar measurement taken over the bar using an AC signal. However if R_{ct} is large then the apparent resistivity should be close to a measurement taken using an AC signal but when no bar is in the close vicinity.

3. Experimental procedure

For this pilot study three concrete slab specimens size 400 × 300 × 100 mm were available, each containing a single short 30 mm diameter steel bar made form steel class A-III 34GS. Each of these bars had a different concrete cover (10 mm, 20 mm and 30 mm) and different ongoing corrosion rates. The slabs were made from concrete class C 20/25 and from Portland cement CEM I 42,5R and aggregate of maximum size 5 mm. To facilitate the establishment of an electrical connection, each bar was cast with one end protruding from the concrete (Figure 6). The actual rate of corrosion for each specimen was verified by taking a LPR measurement within a short time of the resistivity measurements. The surface counter electrode was sufficiently large that it was assumed that the entire surface area of the short bar was effectively polarized by the perturbing current step.

Fig. 5. Concrete resistivity measurement system (CNS Equipment)

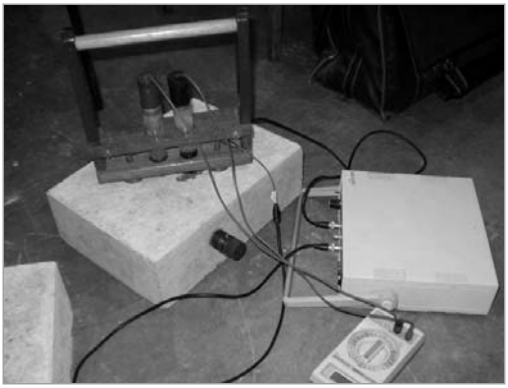

Fig. 6. The view of laboratory stand

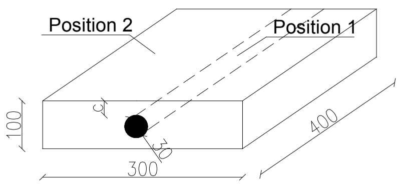

Fig. 7. Resistivity measurement locations on concrete specimen

Measurements were taken of the AC resistivity (Figure 5) both directly over and remote from the steel bar at Position 1 and Position 2 (Figure 7). The Position 2 should be located not closer from the edges than the slab thickness. In this test it was exactly 100 mm. These measurements establish the extent of maximum influence of the bar on the actual concrete resistivity. The galvanostatic DC resistivity measurement was then taken at Position 1. In this test the suitable equilibrium period was 30 second which is not independent from the size and material of the specimen. It is proper to note that the DC resistivity measurement must be taken exactly over the reinforcement.

4. Results

From the traditional Linear Polarization Resistance corrosion techniques it was established that two of the bars were corroding actively with corrosion current densities of 8.47 μA/cm^2 and 7.28 μA/cm^2. From this it was expected that the surface of the steel bar would have a relatively small charge transfer resistance R_{ct} and that a DC measurement of resistivity over the bar should give an apparent resistivity much closer to the resistivity from an AC resistivity measurement over the bar than that of the actual concrete resistivity. Figure 8 shows that for both specimens over a small range of ambient temperatures, ρ_{DC} is much closer to $\rho_{AC,bar}$ than to $\rho_{AC,\mathrm{conc}}$.

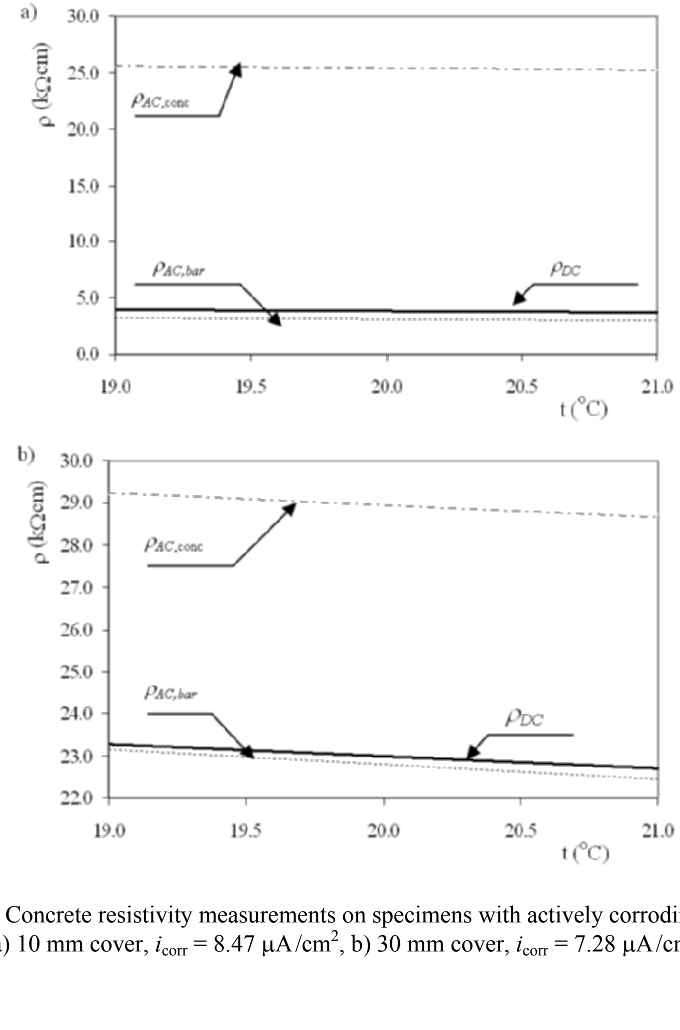

Fig. 8. Concrete resistivity measurements on specimens with actively corroding bars: a) 10 mm cover, i_{corr} = 8.47 μA/cm^2, b) 30 mm cover, i_{corr} = 7.28 μA/cm^2

Only one reinforcing bar exhibited a much lower corrosion current density of i_{corr} = 0.46 μA/cm^2 which was close to passivity. For this bar with a cover of 20 mm a much larger charge transfer resistance R_{ct} on the surface of the steel bar is expected and the presence of the bar should have small effect on a DC resistivity measurement (Figure 9). Over the range of ambient temperatures investigated, ρ_{DC} is much closer to $\rho_{AC,\mathrm{conc}}$ then to $\rho_{AC,bar}$.

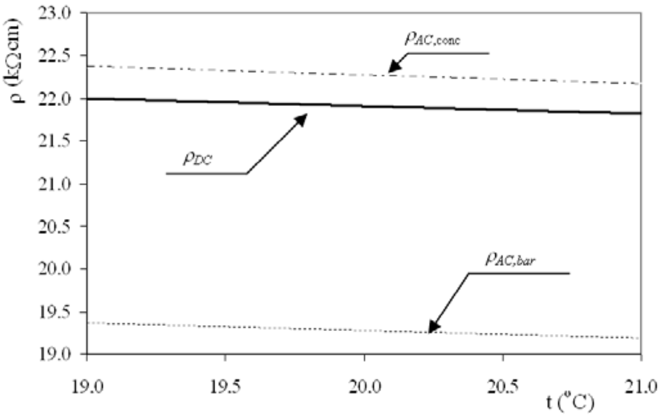

Fig. 9. Concrete resistivity measurements on specimen with passive bar, 20 mm cover, i_{corr} = 0.46 μA/cm^2

5. Conclusions

This study has shown that the short-circuit influence of an embedded steel bar in the vicinity of a concrete resistivity measurement can be used to evaluate the rate of ongoing corrosion on the surface of the bar. The measurements and analyses clearly shows that new method using a novel DC resistivity approach in conjunction with conventional AC resistivity measurements offers a means of assessing directly the instantaneous rate of corrosion using a procedure which is relatively quick and which does not require breakout of the concrete cover.

Further measurements are required to terminate the combined method limitations. Especially to validate the method with a range of different bar sizes and a wider range of covers. In addition concrete with a wider range of resistivity should be investigated.

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Nowa nieniszcząca metoda pomiaru stopnia korozji z użyciem polaryzacji liniowej

Korozja stali zbrojeniowej w betonie jest jedną z głównych przyczyn degradacji konstrukcji żelbetowych. Korozja jest inicjowana i propagowana przez otulinę zbrojenia i wobec tego jest niezmiernie trudno ocenić znaczenie tego problemu. Najbardziej obiecującą elektrochemiczną metodą jest metoda polaryzacji liniowej, za pomocą której można w sposób bezpośredni wyznaczyć stopień korozji. Główną wadą metody jest konieczność odkucia betonowej otuliny w celu zapewnienia elektrycznego dostępu elektrody do zbrojenia. Artykuł opisuje adaptację metody polaryzacji liniowej wraz z metodą Wennera pomiaru oporności betonu do oceny stopnia korozji stali zbrojeniowej w betonie bez konieczności bezpośredniego kontaktu ze zbrojeniem. Badania zostały przeprowadzone przy współpracy z Construction and Infrastructure Group z University of Liverpool.