



Assessment of the electrochemical state of steel reinforcement in water saturated concrete by resistivity measurement



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HIGHLIGHTS

- A new measurement technique for apparent electrical resistivity is presented.
- Court circuit effect overpasses the boundary effects by measurement over the rebar.
- Resistivity drop knowledge when performing measurement over the reinforcement.
- Large difference of corrosion current density notice between active and passive rebar.

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ABSTRACT

The surface resistivity of concrete with and without reinforcement was measured in the laboratory. Uncarbonated and carbonated concrete specimens were investigated corresponding to a passive and active state of corrosion, respectively. The concrete was water saturated, so the measurement medium was considered to be homogeneous. The measurements were performed directly over the rebar on reinforced specimens in order to minimize boundary effects. The presence of a rebar, with the resulting short-circuit effect due to the large differences of resistivity between concrete and steel, strongly reduced the measured resistivity. The magnitude of this reduction increased as the rebar reached a more active state. Other parameters influencing the short circuit effect, particularly concrete cover depth and concrete resistivity, were studied experimentally as well as numerically. The measurement results were inverted through a numerical simulation using COMSOL Multiphysics software. The Butler-Volmer relation was used to characterise the charge exchange at the steel-concrete interface. This inversion process determined the real resistivity of concrete as well as the electrochemical parameters of the embedded reinforcing steel bar. The methodology combining both measurement and inversion is relevant to evaluate the corrosion state of reinforcement. By comparing the electrochemical parameters of a passive and active rebar, the corrosion state can be determined with the proposed methodology.

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1. Introduction

Corrosion is one of the most studied problems in steel reinforced concrete structures durability. Most damage in concrete structures is caused by corrosion of the reinforcement, which leads to cross sectional losses in the steel bar and weakening of the steel – concrete bond. Corrosion of the reinforcement is related to the liquid phase in the concrete porous system. The pore solution is highly alkaline, with a pH value around 13 [1–3], so the pore solution protects the steel bar by forming a very thin passive film that covers it. However, this film breaks down when the pH of the pore solution falls below a certain value (around 9 according to [1,2],

and 8 according to [3]), e.g. by natural carbonation of the concrete. In this case, the bar becomes depassivated and corrosion can start. Corrosion of the reinforcement is an electrochemical process, where reactions take place at the steel surface in contact with the electrolyte contained in the pores [4]. Thus the electrochemical state of an embedded reinforcing bar can be estimated through a study of the cover concrete.

The measurement of the electrical resistivity of concrete is performed by an NDT method commonly used in civil engineering. The measurement is based on the application of Ohm's law. The electrical resistivity of concrete depends on the nature of the liquid phase contained in the microstructure of the concrete, which controls the transport of ions through the concrete, so it is a good indicator of the electrochemical state of the reinforcement [3,5–8]. In general, a low concrete resistivity is related to a high probability

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of corrosion. Some researchers, e.g. Morris et al. [9], have studied the relationship between the corrosion state of a steel rebar and the concrete resistivity, and recommended some threshold values of resistivity for approximating the corrosion rate of the steel bar. However, there is a lack of studies on the use of resistivity, not only for resistivity assessment but also for characterization of the corrosion state of the reinforcement. The aim of this paper is to use a methodology consisting of resistivity measurement and numerical inversion to evaluate the different electrochemical parameters of a reinforcing bar, which indicate the polarization resistance and the passivation state of the rebar without requiring a direct physical connection to the reinforcement bar. In practice either alternating or direct current can be implemented for resistivity measurement. In the investigations described in this paper, a low frequency AC (5 Hz) is used.

2. Theoretical background

2.1. Resistivity measurement of reinforced concrete

Electrical resistivity is a physical quantity that represents the ability of a material to oppose the conduction of an electrical current. In steel reinforced concrete current flows in two different ways [10]:

- Electrolytic: current flows by transport of negatively and positively charged ions through the interstitial solution in the porous network.
- Electronic: current flows by transport of negatively charged electrons through the steel reinforcement, which is highly conductive.

The resistivity measurement is physically based on Ohm's law:

$$j = -\frac{1}{\rho} \Delta E \quad (1)$$

with j : local current density (A/m^2), ρ : electrical resistivity ($\Omega \cdot m$), ΔE : local value of the potential difference (V).

In civil engineering, the electrical resistivity of a material can be measured by direct application of Ohm's law to small specimens (measurement by transmission) or by making measurements on the surface of concrete structures using multi-electrode devices. The resistivity measured on the surface of a structure is called the apparent resistivity. It is not the real resistivity of the material but of all objects in the medium investigated and its magnitude is influenced by a variety of sources. One parameter that may lead to misinterpretation of the measured apparent resistivity is steel reinforcement. Its presence can disturb the normal conduction of the electrical current because its conductivity is infinitely higher than that of concrete. Polder [11] recommended that the measurements should be carried out as far as possible from the reinforcement. In order to reduce its effect, the device should be placed perpendicularly to the rebar as recommended in [5,12,13]. In a concrete structure containing a mesh of reinforcing bars, it has been suggested that the measurement should be made inside a mesh [14]. However, in practice this recommendation is not always a good option because the electrode spacing would have to be reduced and the results might become strongly local [15].

The resistivity measurement is affected by numerous factors, including the structure boundaries. The boundary effect has been reported by Telford [16], who explains that it relates to the theory of images. The electrical current is deviated on passing the edge. The electrical potential field is also modified near the boundary of a concrete element. The nearer the device is placed to a structure boundary, the more the resistivity measurement is influenced.

Therefore, the apparent resistivity always increases when measured close to the border [10,5,15,17,18]. The size of the specimen is also a factor influencing the reading, as reported in [19]. Hence the boundary effect is unavoidable and has to be taken into consideration when working on specimens of limited size.

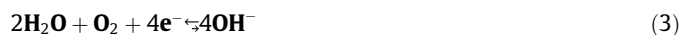
2.2. Electrochemical aspects of corrosion of steel reinforcement

2.2.1. Microcell corrosion system

In normal conditions, the pH of concrete is relatively high, about 13. In this alkaline environment, the reinforcing bar embedded in concrete is protected by a passive film and corrosion is not possible [1]. However, in the course of time, this protective film may be broken down by different phenomena such as carbonation or ingress of chloride ions, which initiate the corrosion process (depasivation of steel). Corrosion is an electrochemical process in which the steel bar is polarized in the pore solution. At the anode, iron is dissolved, creating free electrons (oxidation of iron) according to:



and, at the cathode, the formation of OH^- takes place, consuming the electrons produced at the anode by reduction of water according to:



If the steel bar has been uniformly depassivated, such as by carbonation, the anodic and cathodic sites are infinitely close, and the resulting corrosion is called microcell corrosion [20]. We should bear in mind that passive steel may be considered as a microcell corrosion system in which the corrosion rate is very low and thus is commonly discarded. The polarization behaviour of the electrochemical system at the concrete-rebar interface may be modelled by the Butler-Volmer equation, which gives the net current density j [A/m^2] flowing through the metal-electrolyte interface of a uniform system forced at potential E (V_{ref}):

$$j = j_{corr} \left[\exp\left(\ln(10) \frac{E - E_{corr}}{\beta_a}\right) - \exp\left(-\ln(10) \frac{E - E_{corr}}{\beta_c}\right) \right] \quad (4)$$

where $\ln(10)$ is the natural logarithm of 10 (≈ 2.303)

E_{corr} is the free corrosion potential of the uniform corrosion system at equilibrium (V_{ref}).

j_{corr} is the corrosion current density (A/m^2) corresponding to the exchange current density of the uniform corrosion system.

β_a and β_c are the anodic and cathodic Tafel slopes, respectively, of the electrochemical system (V/dec).

At equilibrium ($E = E_{corr}$) the oxidation and the reduction rates are equal and there is no net current flow at the steel-concrete interface. This equilibrium can be broken when an imposed external current is flowing through the interface, and consequently the steel bar becomes polarized.

Electrochemical states of active and passive uniform corrosion systems may be qualitatively classified as follows (indices 'a' and 'p' refer to active and passive uniform systems, respectively):

- Corrosion potential: $E_{corr,a} < E_{corr,p}$,
- Corrosion current density: $j_{corr,a} > j_{corr,p}$,
- Anodic Tafel slopes: $\beta_{a,a} < \beta_{a,p}$,
- Cathodic Tafel slopes: $\beta_{c,a} \approx \beta_{c,p}$.

2.2.2. Polarization resistance

At the interface between the electrode and the electrolyte solution, there is a polarization resistance, which describes the transfer of current from the metal electrode to the electrolyte solution. In

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