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The Use of Electrical Resistivity as NDT Method for the Specification of the durability of Reinforced Concrete

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Abstract

The specification of service life of reinforced concrete structures by means a no-destructive parameter is being a subject of increasing interest. In present communication a proposals is made on using the electrical resistivity to estimate the service life of structures, whether new or existing, taking into account both the initiation and propagation periods. The main advantage is that resistivity is an easy, fast and inexpensive non destructive measurement technique, which can be used for routine quality control of concrete and for monitoring of structures. For the time to corrosion onset, the electrical resistivity represents the porosity and its connectivity and therefore can be used to model transport processes. Due to the interaction of chlorides and carbon dioxide with cement solid phases, the resistivity has to be factorised by a "reaction factor" accounting for it. Concerning the propagation period, the electrical resistivity is an indication of the moisture content of concrete and therefore, it has a certain relationship with the corrosion of reinforcement. A model is proposed in which the resistivity is introduced in the square root of time law.

Résumé

Il a un intérêt croissant à la spécification de la durée de vie des structures en béton armé par des moyens non-destructifs. Dans cette communication, est présentée l'utilisation de la résistivité électrique pour estimer la durée de vie des structures, qu'elles soient nouvelles ou existantes, en tenant compte à la fois de l'initiation et de la propagation de ces périodes. Son principal avantage est qu'elle est une technique unique, d'utilisation facile, rapide et peu coûteuse, qui peut être utilisée pour le contrôle de la qualité du béton et pour le suivi des structures périodiques. La résistivité électrique représente la porosité et sa connectivité et peut donc être utilisée pour modéliser les processus de transport. En raison de l'interaction des chlorures et du dioxyde de carbone avec les phases solides du ciment, la résistivité doit être factorisée par un "facteur de réaction". S'agissant de la période de propagation, la résistivité électrique est une indication de la teneur en humidité du béton et, par conséquent, il est en relation avec la corrosion de l'acier. Un modèle est proposé dans lequel la résistivité est introduite dans la loi de la racine carrée du temps.

Keywords

Durability, reinforced concrete, NDT method, indicator, resistivity

1 Introduction

There is an increasing demand to incorporate into the current standards more advanced concepts related to concrete durability, due the need to control of production quality and better prediction, in particular the corrosion of the reinforcement. There are several proposals based on modelling the mechanisms of attack for predicting of service life [1-2], but just few of then are based on the "performance" concrete or so called "durability indicators" [3].

However, it is known that the estimation of durability without considering the real properties of prepared concrete can to result on erroneous response.

In present paper a proposal is presented that tries to be comprehensive by responding to the demand related to the introduction of performance parameters, or durability indicators, and that being suitable for quality control could also be applicable for modelling for predicting service life. The chosen durability parameter is the electrical resistivity of concrete [4-6]. Its basis and use for prediction is presented briefly applied to the corrosion of reinforcements and some examples are shown on the application of the model. The service life of reinforcements, t_l, is usually modelled by assuming two periods: the time to initiation of corrosion t_i and its propagation, t_p. Thus, $t_l = t_i + t_p$.

The calculation of the duration of t_l is usually undertaken by considering that the aggressive penetrates through concrete cover by diffusion [2] and therefore, Fick's law is used to calculate a diffusion coefficient. Providing that the aggressive threshold (pH-drop front in the case of carbonation or a certain chloride amount) is defined, the end of t_i indicates the initiation of t_p. At the proposed model, the limit state can being established as the initiation of corrosion or as the lost of steel bar section (P_x) once corrosion is started.

2 The resistivity as NDT durability indicator

The electrical resistivity (ρ, unit Ω.m), inverse of conductivity, is the property of the material that reflects the ability to transport electrical charge. This is a volumetric measurement of the electrical resistance (R_e), which by Ohm's Law is expressed as the ratio of voltage and current applied ($R_e = V/I$).

The resistivity presents a comprehensive character regarding to the concrete microstructure. The potential difference or the current applied by means of two electrodes is carried through aqueous phase of concrete pore network by the electrical carriers (ions), so, the electrical resistivity of water saturated concrete is an indirect measurement of the concrete pore connectivity. Archie discovered in study developed in 1942 [7], that it is possible to formulate the resistivity of a porous medium by the equation (1), where ρ_o is the resistivity of aqueous phase concrete, the constant *a* dependents on the composition of the material, and *m* represents all the parameters relating to the structure the pores of the material (constraint and tortuosity of porous [8-9]). The variable ϕ means the saturated volumetric fraction of water (in water-saturated concrete, ϕ = total porosity). It means that as higher is the saturated volumetric fraction of water, lower is the electrical resistivity.

$$\rho = a \cdot \rho_o \cdot \phi^{-m} \qquad (1)$$

The electrical resistivity then provides indications on the pore connectivity and therefore, on the concrete resistance to penetration of liquid or gas substances, and so resistivity is a parameter which accounts for the main key properties related to reinforcement durability.

2.1 Factors influencing on resistivity value

For the sake of a comprehensive presentation, it is worth to mention that it is necessary considering the effects of age, water saturation level and temperature on resistivity values.

It is known that the resistivity of concrete increases with time (t) due the refinement of the pore structure. The advance of hydration of cement phases leads to a lowering in porosity of the concrete which is reflected in both mechanical strength and resistivity. This law may have different power exponents for OPC than for blended cements [11] and should to be taken into account for estimating resistivity at different ages.

Regarding to water saturation degree in porous network, the variation on ρ is due to that in semi-saturated condition the ion conduction occurs through the layer of water adsorbed on the walls of the pores [12]. With respect to the influence of temperature, it has an important effect on resistivity, which only can be generalized if the ρ values are standardized to a reference temperature that it is proposed to be 25ºC [5] [13]. An increase in temperature should increase diffusivity, D, and corrosion rate, V_{corr}, however this increase in temperature may at the same time may produce an evaporation, which in turn would effect on the opposite in both, D and V_{corr}. Therefore, the incorporation of temperature effects on models is, by large, still very seldom.

2.2 Resistivity and diffusivity

The ability of resistivity to quantify diffusivity is based in one of the Einstein laws which relates the movement of electrical charges to the conductivity of the medium [10], where D_s= effective or steady-state diffusion coefficient, $k_{Cl,CO2}$ is a factor, which is dependent to the external aggressive concentration, ρ_{es} is the resistivity (in this case of concrete saturated of water) and σ the conductivity (inverse of resistivity) (2). This relation is shown in graphic form in figure 1.

$$D_e = \frac{k_{Cl,CO2}}{\rho_{es}} = k_{Cl,CO2}\ \sigma \qquad (2)$$

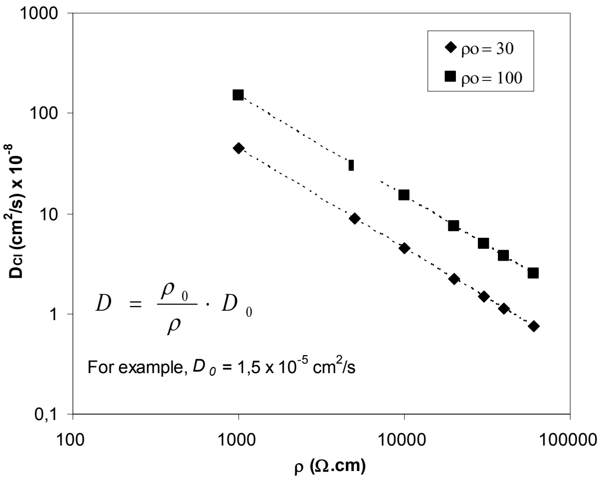

Figure 1. *Relation between resistivity and diffusivity as calculated from Einstein law [10]*

In consequence, if $k_{Cl,CO2}$ is established, the diffusion coefficient of the chloride ion or carbonation in concrete can be calculated providing that there is not interaction between aggressive and the cement solid phases, because the obtained D_s does not take into account the binding (that is why usually is named as "effective").

However, the chloride and carbonation binding has to be taken into account. This is made in the proposed model by means of introducing a new factor, ($r_{Cl,CO2}$= reaction or binding factor). This reaction factor is a "retarder" of the penetration of aggressive. The expression ρ_{es}*$r_{Cl,CO2}$ is as well named "apparent resistivity" (ρ_{app}), as written in equation (3).:

$$D_{ns} = \frac{k_{Cl,CO2}}{\rho_{es} \cdot r_{Cl,CO2}} = \frac{k_{Cl,CO2}}{\rho_{app}} \qquad (3)$$

The "binding factor" (r) represents the number of times the effective resistivity ρ_{es} is apparently increased. It can be calculated from the comparison between diffusion coefficients in steady (D_s) and non-steady state conditions (D_{ns}). When doing the relation between D_s and D_{ns} however it has to be considered that D_s is referred to the concentration in the pore solution and that D_{ns} is referred to the aggressive concentration in the mass of the concrete.

2.3 Resistivity and corrosion rate

Thanks to the relationship between ρ and the saturation degree of concrete, it is possible to apply the resistivity for interpretation of the value of the corrosion rate V_{corr}. The degree of saturation of concrete will be reflected in the taken electrical resistivity of concrete under any exposure condition (which is named ρ_{ef}) and the availability of oxygen at the reinforcement.

Some studies [6] established the direct relationship between the resistivity and the intensity of corrosion and can be expressed by the equation (4), where k_{corr} is a constant with a value of 3x104µA/cm2·kΩ·cm. The intensity of corrosion is related to V_{corr} by means the Faraday's law.

$$I_{corr} = \frac{k_{corr}}{\rho_{ef}} \tag{4}$$

3 Service life model based on concrete resistivity

The model proposed here is based on the measuring of electrical resistivity for its use as the main parameter for determining both t_i and t_p periods [14], taking into account the established relations.

In order to predict the corrosion onset it is necessary to have an equation in which the resistivity could be the rate determining parameter in function of the time. Considering the despassivation instant as a limit state (t_i), it is assumes the simplest equation "square root of time", for estimating the penetration of the aggressive front and time $x_i= V_{CO2,Cl}*\sqrt{t}$. The factor of relation V represents the ease or velocity of penetration, $V_{Cl,CO2}$, then, $t_i = x^2/V_{CO2,Cl}$.

In the case of considering the propagation of corrosion (t_p), taking into account the loss in rebar diameter, or pit depth, (P_x) as the limit corrosion attack,, the service life of structure can be written by the form (5):

$$t_l = t_i + t_p = \frac{x_i^2}{V_{CO_2,Cl}} + \frac{P_x}{V_{corr}} \tag{5}$$

3.1 Calculation of the initiation period

How to relate $V_{Cl,CO2}$ to the resistivity?. This can be made through another of Einstein equations when explaining the random walk of an ion in an electrolyte [8], $x_i = \sqrt{(D.t)}$ which indicates that $V_{Cl,CO2}=\sqrt{D}$ and therefore equal to $\sqrt{(k_{Cl,CO2} / \rho_{es}*r_{Cl,CO2})}$. Rearranging this expression it results for the initiation period the equation (6).

$$t_i = \frac{x_i^{\ 2} \cdot \rho_{app}}{2 \cdot k_{Cl,CO2}} = \frac{x_i^{\ 2} \cdot \rho_{es} \cdot r_{Cl,CO2}}{2 \cdot k_{Cl,CO2}} \tag{6}$$

It might be enough the use of ρ_{app} as a Durability Indicator were fixed ranks can be related to the aggressively classes as is the case of air permeability, water absorption tests or the "Rapid chloride Permeability test" which measures coulombs [15].

3.2 Calculation of the propagation period

As mentioned before, the resistivity value is dependent to the water saturated conditions at each moment of an exposed structure. In order to calculate the t_p, it can be assumed a certain year averaged concrete moisture content in each exposure class and in function of it, year averaged ρ_{ef} values can be attributed to each one for certain exposure conditions (considering both moisture and temperature) (7).

$$t_p = \frac{P_x \cdot \rho_{ef}}{k_{corr}} \quad (7)$$

The ρ_{ef} value could being estimated on the time (t) from the concrete resistivity measured under saturated condition (ρ_{es}), at 28 days of life, by means an expression which takes into account the aging factor reflected by a power exponent for each type of cement (n) 11, and considering an environment factor (ξ) which represents the concrete moisture condition, that is ρ_{ef}:$f(t,n,\xi)$.

The final expression is written as (8):

$$t_l = t_i + t_p = \frac{x^2 \rho_{es} r_{Cl,CO_2}}{k_{Cl,CO_2}} + \frac{P_x \cdot \rho_{ef}}{k_{corr}} \quad (8)$$

3.3 Example of application

Assuming a limit state of depassivation in 50 years (equation 6 instead of 8 to be used), an example is given in table 1 for chloride attack and carbonation using a k_{Cl} = 20000 and k_{CO2}= 2000 $\Omega\cdot cm^3$/year.

Taken these values as "characteristics" they mean that the concrete resistivity in water cured during 28 days concrete has to be higher in 95% of the results than the values of the table, providing ρ_{app} is calculated from the direct measurement of the ρ_{es} in the specimen and multiplied by the reaction factor, ρ_{app}= $\rho_{es}\cdot r_{Cl,CO2.}$

Table 1. *Values of characteristic resistivity to be complied by concretes in function of cover depth*

Apparent Resistivity (ρ_{app}) in $\Omega\cdot$m, under saturated conditions at 28 days of curing		
Cover (mm)	Carbonation	Chlorides
20	250	2500
30	120	1110
40	63	625
80	15	160

4 Conclusions

The formulation of the method as a standard needs the following steps:

I. The definition of service life period of structure.
II. The classification of exposure aggressivity (environmental actions) to which to refer the characteristic ρ_{app}, k_{Cl} and k_{CO2}, the cover thickness and the rest of parameters involved in the method.
III. The establishment of the r_{Cl} and r_{CO2} for the particular cement and concrete (by testing by the cement or concrete manufacturer.
IV. The measurement of ρ_{es} at 28days in the same concrete specimens used for mechanical strength.
V. The comparison of the ρ_{as} obtained with the table of characteristic values such as Table 1 or the calculation of expected service life the through equation 6.

The use of resistivity as the NDT parameter for the durability specification of reinforcement can be made: a) by establishing certain characteristic values to be achieved in standardized conditions as performance requirement or durability indicator or b) by calculating concrete cover thicknesses according to exposure aggressively through certain equations as a manner of a model. Being a non destructive measurement it results optimum for routing on-site quality control.

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