ECCOMAS Thematic Conference on
Computational Methods in Tunnelling (EURO:TUN 2007)
J. Eberhardsteiner et.al. (eds.)
Vienna, Austria, August 27-29, 2007

A NDT PERFORMANCE METHOD BASED ON ELECTRICAL RESISTIVITY FOR THE SPECIFICATION OF CONCRETE DURABILITY

C. Andrade[1], O. Río[1], A. Castillo[1], M. Castellote[1] and R. d'Andrea [1]

[1] Institute of Construction Science "Eduardo Torroja", CSIC, Madrid, Spain
e-mail: andrade@ietcc.csic.es

Keywords: service life, electrical resistivity, reinforced concrete, natural exposure conditions.

Abstract. *Prediction of the time to reinforcement corrosion and service life duration is being a subject of increasing interest. In present communication a proposals is made on using the electrical resistivity to calculate both the initiation and propagation periods. The main advantage is that resistivity is an inexpensive non destructive measurement that can be used for routine quality control. 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 reaction of chlorides and carbon dioxide with cement 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 cement. A model is proposed in which the resistivity is introduced in the square root of time law.*

1 INTRODUCTION

Regarding concrete durability Codes and Standards in general contain provisions related to: a) the concrete materials: cement, water, steel and aggregate types, concrete mix proportions, mechanical strength, b) the limit of dangerous substances, such as chlorides or sulphates, c) limitations to the crack width transversal to the reinforcement and d) the recommended cover thicknesses in function of exposure classes. However, there is an increasing demand to incorporate into the current standards more advanced concepts related to concrete durability, due the need to better foresee and prevent distresses, in particular the corrosion of the reinforcement. Several proposals exist based in modelling the mechanisms of attack [1], [2] or in the so called "performance" concepts or the use of "durability indicators" [3]. Nevertheless, their effective incorporation into the standards seem to be slow and a worldwide controversy exists on which is the best approach, due to the lack of enough tradition and experience of these new proposals.

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 to several concrete mixes. The service life of reinforcements, tl, is usually modelled by assuming two periods: the time to initiation of corrosion ti and its propagation, tp. Thus, $t_l = t_i + t_p$. The calculation of the duration of tl is usually undertaken by considering that the aggressive penetrates through concrete cover by diffusion [2] and therefore, Ficks law's is used to calculate a Diffusion coefficient able to predict the concentration of the aggressive at a certain depth, at several periods of time.

Providing that the aggressive threshold (pH-drop front in the case of carbonation or a certain chloride amount) is defined, the end of ti indicates the initiation of t_p. The initiation of corrosion established a limit state. The propagation period, t_p, is calculated by assuming a constant or averaged corrosion rate. In a similar manner than for t_i the "limit state" or maximum corrosion has to be defined first in order to account for the length of the period. For the sake of present paper the corrosion onset will be considered for a chloride threshold value of 0.4% by cement weight. For the propagation period a single limit does not exist.

2 CONCRETE RESISTIVITY AND CONCRETE POROSITY

The model proposed here based in the measuring of electrical resistivity makes use of this parameter as the main one determining both t_i and t_p periods [3]. This is due the comprehensive character of the resistivity regarding concrete microstructure. Thus, the electrical resistivity of water saturated concrete is an indirect measurement of the concrete pore connectivity. The potential difference or the current applied by means of two electrodes is carried through concrete pore network by the electrical carriers (ions). As higher is the porosity, lower is the resistivity due the higher volumetric fraction of pores. Regarding the porosity, consideration has to be paid to tortuosity [7], [8] as the pore shape seems to have a strong influence. However for the sake of present proposal, tortuosity can be a part of the "geometric cell constant" which relates resistance and resistivity and it does not need to be directly expressed in the formulation. On the other hand, while resistivity is related to porosity and connectivity, in non-water saturated concrete it is as well an indication of its degree of saturation.

Regarding the influence of the chemical composition of pore solution, its impact in the total resistivity is small providing the concrete remains alkaline. At high pH values the pore solution resistivity varies from 30-100 Ωcm, which is comparatively very small taking into

account that the concrete resistivity after several days of hardening is in the range of several hundreds Ω•cm. When concrete carbonates, then the pore solution is much more diluted and the electrical resistivity of the pore solution may significantly increase and start to be influencing the volumetric value. In chloride contaminated concrete, the chlorides lowers the concrete resistivity but not too much (it can decrease to half value of that without chlorides), as the resistivity of an alkaline solution is not lowered very much by the presence of chlorides.

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 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 [7]:

$$D_e = \frac{k_{Cl}}{\rho_{es}} = k_{Cl}\ \sigma \qquad (1)$$

where De= effective diffusion coefficient, k_{Cl} is a factor, which depends on the external ionic concentration, ρ_{es} is the resistivity (in this case of concrete saturated of water) and σ the conductivity (inverse of resistivity). This relation is shown in graphic form in Figure 1

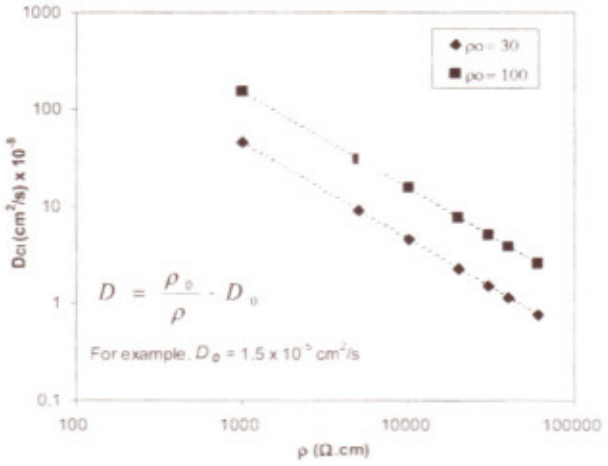

Figure 1 : Relation between resistivity and diffusivity as calculated from Einstein law

In consequence, if kCl is established, the diffusion coefficient of the chloride ion into the concrete can be calculated providing that not reaction of chlorides exist with the cement phases, because the De so obtained does not account for binding (that is why usually is named as "effective"). A value of k_{Cl} of $20x10^{-5}$ can be used for external chloride concentrations of 0.5 to 1 M.

However, the chloride binding has to be taken into account. This is made in the proposed model by means of introducing a new factor, (r_{Cl}= reaction or binding factor). This reaction factor is a "retarder" of the penetration of chlorides. Above equation maintains its mathematical structure but can be now written as:

$$D_{Cl} = \frac{k_{Cl}}{\rho_{es} \cdot r_{Cl}} \qquad (2)$$

Where an "apparent" electrical resisvity, ρ_{as}, in saturated conditions is defined as $\rho_{as} \cdot \rho_{cs} \cdot r_{Cl}$.

In the case of carbonation, its advance into the concrete depends on the moisture of the material, the type of the cement and the dioxide carbon concentration on the atmosphere. Therefore, equation can be also applied to carbonation by providing another constant k_{CO2} for the specific atmospheric exposure. In addition, in a similar manner than for chlorides a reaction factor, r_{CO2}, taking into account the amount of alkaline material able to bind CO_2, has to be introduced:

$$D_{CO2} = \frac{k_{CO2}}{\rho_{cs} \cdot r_{CO2}} \tag{3}$$

Thus, expressions of the diffusion coefficients of chlorides and carbon dioxide in terms of the apparent electrical resistivity, ρ_{as}, in saturated concrete have been deduced.

2.2 Influence of age and temperature in the resistivity

For the formulation of the model it is not strictly necessary more than taking into account the value of the resistivity after 28 days of wet curing (by maintaining it in a wet chamber or submerged in water) to obtain $\rho_{cs,\,28d}$, as the reference parameter like in the case of mechanical strength. However, for the sake of a comprehensive presentation, it is worth to mention that models exist for the accounting of the effects of age and temperature on the resistivity values.

It is known that the resistivity of concrete increases with time due the refinement of the pore structure. This evolution is very similar to that of the increase of mechanical strength although some differences exist when it considers different cement types. The advance of hydration of cements phases leads to a lowering in porosity of the concrete which is reflected in both mechanical strength and resistivity (see figure 2).

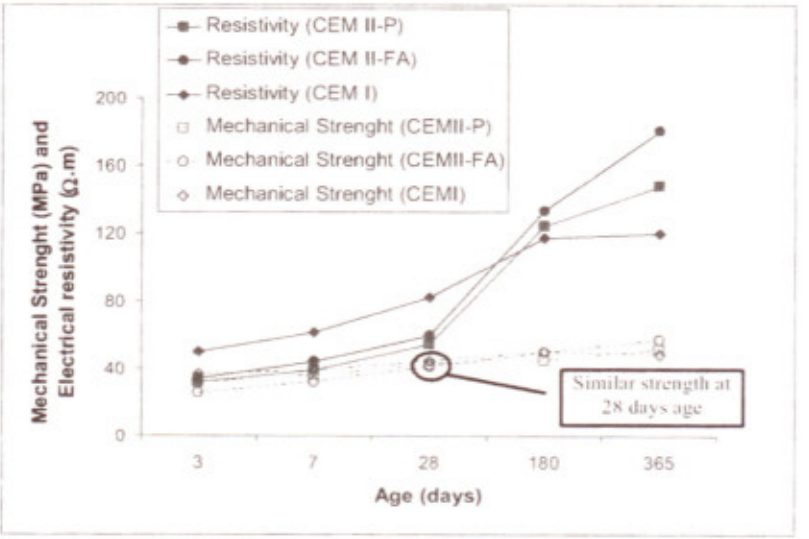

Figure 2 : Evolution of resistivity and mechanical strength obtained from three concrete mixes with different types of cement and same water content.

This law may have different power exponents for OPC than for blended cements. There are values in the literature [9] and work is being done for its quantification.

With respect to the influence of temperature, it has an important effect on resistivity, which only can be generalized if the ρ values are standarized to a reference temperature that it is proposed to be 25ºC [5]. This influence could be considered by the following expression:

$$\rho_{cs,28d} = \rho_{cs,t} \cdot e^{m} \qquad (4)$$

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. In present case, it is incorporated by suggesting to measure $\rho_{cs,\ 28d}$ at 25ºC. The standardization of resistivity from other temperatures has been explained in [10]

2.3 Service Life Model Based On Concrete Resistivity

It might be enough the use of ρ_{as} as a Durability Indicator were fixed ranks can be related to the aggressivity classes as is the case of air permeability, water absorption tests or the "Rapid chloride Permeability test" which measures coulombs [11].

In the figure 3 it can be appreciated an example of the effectivity of ρ as Durability Indicator. In this case, it is being presented a potential fit of relation between non-stationary chloride diffusion coefficients (Dns), obtained from pounding test at 3 months, and electrical resistivity obtained at 28 days of wet curing, both parameters corresponding to 27 different concrete mixes. It can be observed in the figure that could be possible to define ranges of value to the resistivity in order to indicate different classes of durability of concrete in according to its D_{ns} value. Furthermore, this example validates the theory of Einstein law mentioned before and presented in the figure 1.

The same analysis based on resistivity could be done relating this last one to different parameters linked to phenomena of penetration of aggressive from atmosphere, like carbonation rate.

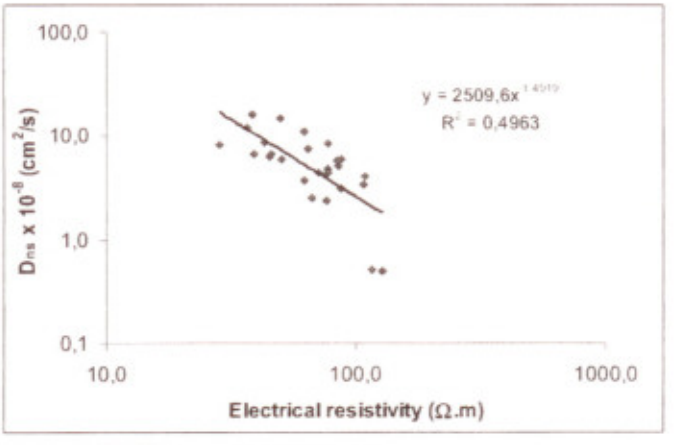

Figure 3 : Relation between non-stationary chloride diffusion coefficient and electrical resistivity obtained at 28 days. Analysis of use of ρ as Durability Indicator.

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. The simplest equation is the so named "square root of time". Assuming a square root relation between 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, CO_2} and therefore the service life can be written in the form:

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

being P_x the limit corrosion attack depth (loss in rebar diameter or pit depth) and V_{corr}, the corrosion rate.

2.3.1. Calculation of the Initiation Period

How to relate V_{Cl}, CO_2 to the resistivity?. This can be made through another of Einstein equations when explaining the random walk of an ion in an electrolyte [7]:

$$x = \sqrt{2Dt} \tag{6}$$

which indicates that $V_{Cl, CO2} = \sqrt{2D}$ and therefore equal to $\sqrt{2\, k_{Cl, CO2} \cdot \rho_{es}\, r_{Cl, CO2}}$. Rearranging this expression it results for the initiation period the following equation:

$$t_i = \frac{x_i^2 \cdot \rho_{es} \cdot r_{Cl,CO2}}{2 \cdot k_{Cl,CO2}} \tag{7}$$

2.3.2. Calculation of the Propagation Period

When the reinforcements start to corrode, it has been found a relation between corrosion rate and electrical resistivity of the type [1]:

$$I_{corr} = \frac{k_{corr}}{\rho_{ef}} \tag{8}$$

where k_{corr} is a constant with a value of $3x10^4 \mu A/cm^2 \cdot k\Omega \cdot cm$.

The resistivity, ρef, in this case is that of the concrete at its actual degree of saturation and therefore can be that of water saturated conditions or not. In order to calculate the tp, it can be assumed a certain year averaged concrete moisture content in each exposure class and in function of it, averaged Icorr and ρ values can be attributed to each one (considering both moisture and temperature).

$$t_p = \frac{P_x \cdot \rho_{ef}}{k_{corr}} \tag{9}$$

$$t_l = t_i + t_p = \frac{x^2 \rho_{es} r_{Cl,CO_2}}{k_{Cl,CO_2}} + \frac{P_x \cdot \rho_{ef}}{k_{corr}} \tag{10}$$

The main parameter in this equation is the concrete resistivity measured in saturated conditions, and at 25ºC: ρes, at 28 days of life, and ρef given as year averaged value for certain exposure conditions.

With regard to the other parameters $r_{Cl,CO2}$ and $k_{Cl,CO2}$, the first one should be linked to the type and amount of cement and therefore, to the extension of reaction of the penetrating substance with cement phases, and $k_{Cl,CO2}$ values are factors which should account for the environmental concentration of aggressive (exposure class)

2.4 Example of application

Assuming a limit state of depassivation in 50 years, an example is given in table 1 for predicting the chloride attack and carbonation on this period of time.

Firstly, it is assumes environment parameters corresponding to chloride attack, where k_{Cl} = 20000 Ω·cm^3/year, and to carbonation, where k_{CO2}= 2000 Ω·cm^3/year. In regarding to reaction factor r, could be possible for a known type of cement, r_{Cl} = 2 and r_{CO2} = 8, for the cases of chloride attack and carbonation, respectively.

Taken these values as "characteristics", and applying them to the equation 7, they mean that the concrete resistivity (ρ_{es}) in water cured during 28 days concrete has to be higher in 95% of the results than the values given on the table 1.

Resistivity (ρ_{es} - Ωm) in saturated conditions at 28 days of curing		
Cover (mm)	*Carbonation*	*Chlorides*
20	31	1250
30	14	556
40	8	313
80	3	139

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

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

1. The classification of exposure aggressivity (environmental actions) to which to refer the characteristic ρas, the cover thickness and the rest of parameters involved in the method.
2. The establishment of k_{Cl} and k_{CO2} for each exposure class, as well as the averaged Vcorr.
3. The establishment of the r_{Cl} and r_{CO2} for the particular cement and concrete (by testing by the cement or concrete manufacturer.
4. The measurement of ρ_{es} at 28days in the same concrete specimens used for mechanical strength.
5. The calculation of $\rho_{as}=\rho_{es}\cdot r_{Cl,CO2}$
6. The comparison of the ρas obtained with the table of characteristic values such as Table 1 or the calculation of expected service life the through equation 10 or 11.

The use of resistivity as the key parameter to model durability of reinforcements can be made: a) by establishing certain characteristic values to be achieved in standarized conditions as performance requirement or durability indicator or b) by calculating concrete cover thick-

nesses according to exposure aggressivity through certain equations as a manner of a model. Being a non destructive measurement it results optimum for routing on-site quality control.

3 CONCLUSIONS

The use of electrical resistivity, as a Durability Indicator, can be possible by defining some ranges of values for classifying the concrete according to the service life period necessary for a specific environment condition.

On the order hand, the need to provide concrete with target durability has stimulated the development of models to predict service life. These models are based in parameters figuring concrete permeation on resistance to penetration. In general, diffusion coefficient derived from analytical solutions to differential equations as the reproduction of real boundary and initial conditions of the differential equations is not obvious or easy.

The method here presented is based in a general fundamental of Einstein law relating electrical resistance or conductance with the diffusion coefficient. Stating certain assumptions this basic law can be applied to the advance of carbonation front or chloride threshold, and to the representation of steel corrosion progression. The general expression of service life is:

$$t_f = t_i + t_p = \frac{x^2 \cdot \rho_{cc} \cdot r_{Cl,CO_2}}{k_{Cl,CO_2}} + \frac{P_s \rho_{cl}}{k_{corr}}$$

This model can be used for calculating cover thicknesses from actual resistivity values or the minimum resistivity for a certain cover thickness. Resistivity can be as well used as a performance parameter to be fulfilled by standard specimens at a certain age or as durability and corrosion indicator.

Being the measurement of resistivity a non destructive method, it can be as well used for on-site quality control.

REFERENCES

[1] Tuutti, K. 1982, 'Corrosion of Steel in Concrete', Swedish Cement and Concrete Research Institute (CBI) no.4-82, Stockholm.

[2] Page, C.L., Short, N.R. & El Tarras, A. 1981, "Diffusion of Chloride Ions In Hardened Cement Pastes" Cement and Concrete Research. Vol. 1 1, No. 3, pp. 395-406

[3] Baroghel-Bouny, V. 2002, "Which toolkit for durability evaluation as regards chloride ingress into concrete? Part II: Development of a performance approach based on durability indicators and monitoring parameters". Proceedings of the 3rd International Workshop "Testing and modelling chloride ingress into concrete" Madrid Spain. C. Andrade and J. Kropp editors.

[4] Andrade, C. & Alonso, C. 1997, "A simplified application to carbonation and chloride penetration rates of the performance concept". International ECSN Symposium on "European Concrete Standars in Practice". Copenhaguen (Denmark)Alonso, C.,

[5] Andrade, C., Alonso, C., Arteaga, A. & Tanner, P. 2000, "Methodology based on the electrical resistivity for the calculation of reinforcement service life" 5th Canmet/ACI

Int. Conference on Durability of concrete – Supplementary papers volume. Barcelona, Spain. pp.899-915.

[6] Andrade, C. & González, J.A. 1988, 'Relation between concrete resistivity and corrosion rate of the reinforcements in carbonated mortar made with several cement types', Cement and Concrete Res. Vol. 18, pp. 687-698.

[7] A.J. Bard, L.R. Faulkner - Electrochemical Methods. Fundamentals and Applications - Jon

[8] Wiley & Sons Ed., (1980).

[9] C. Andrade "Calculation of chloride diffusion coefficients in concrete from ionic migration measurements", Cement and Concrete Res., 23, 724-742 (1993).

[10] Andrade, C; Castillo, A; Río, = & d'Andrea, R. "Empirical relation between electrical resistivity and compression strength of cilindrical specimens of concrete made with different cement types". 47º Congreso Brasilero do Concreto. CBC-2005, September 2005.

[11] Castellote, M., Andrade C. & Alonso, C. "Standardization, to a reference of 25 C, of the electrical resistivity values measured at any temperature for mortars and concrete in saturated conditions". ACI Materials Journal.

[12] Whiting, D. 1981, "Rapid determination of the chloride permeability of concrete" – Federal Highway Administration – Report FHWA/RD-81/119.