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Model for Prediction ff Reinforced Concrete Service Life Based on Electrical Resistivity

C. ANDRADE [a]

Abstract

Reinforcement corrosion is attracting research interest in many areas due to the economical consequences of the damage generated by the process. Several proposals can be found on prediction of the time to reinforcement corrosion and service life duration. In this paper a proposal is made for using the electrical resistivity to calculate both the initiation and propagation periods. For the time period to corrosion onset, the electrical resistivity serves to model the porosity and its connectivity and therefore can be used to calculate transport processes. Due to the reaction of chlorides and carbon dioxide with cement phases, the resistivity has to be factorised by a "reaction factor", r, accounting for it. Concerning the propagation period, the electrical resistivity is an indication of the moisture content of concrete and therefore, it has a relationship with the corrosion current.

An equation is presented to predict service life. Using this equation, minimum resistivity values can be established according to cover thickness and in function of exposure classes.

The model is under calibration with real data of carbonation and chloride penetration in specimens an in cores drilled from real structures.

Keywords: Concrete resistivity; reaction factor; service life.

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[a] Dr. Carmen Andrade is a Research Professor at Institute of Construction Science "Eduardo Torroja", CSIC, Madrid, Spain.

1 Introduction

For concrete durability codes and standards in general contain provisions related to: a) the concrete materials: cement, water, steel and aggregate types, concrete mixture 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, because of 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 (3) or in the use of “durability indicators” (4)(5). Nevertheless, their effective incorporation into the standards seems to be slow and a worldwide controversy exists on which is the best approach, because of the lack of experience with these new proposals.

The present paper presents a proposal that tries to be comprehensive by responding to the demand related to the introduction of performance parameters or durability indicators and, at the same time, is applicable for predicting service life. The chosen durability parameter is the electrical resistivity of concrete. The basis and development of the model is presented briefly.

2 Reinforcement Service Life Modelling

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 material duration of t_l is usually undertaken by considering that the aggressive penetrates material through concrete cover by diffusion and therefore, Ficks law’s is used to calculate a diffusion coefficient used to predict the concentration of the aggressive material at a certain depth and 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 t_i indicates the initiation of t_p.

The propagation period, t_p, is calculated by assuming a constant or averaged corrosion rate, V_{corr}. 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 this period.

3 Meaning of Concrete Resistivity

The model proposed here based in the measuring of electrical resistivity makes use of this parameter for determining both ti and t_p periods (6). This is possible because of 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 electrical potential difference or the current applied by means of two external electrodes to a concrete specimen is carried through concrete pore network by the electrical carriers (ions). As the porosity increases, the resistivity is reduced due the higher volumetric fraction of pores. 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 Ohm.cm, which is comparatively very small taking into account that the concrete resistivity after several days of hardening is in the range of several hundreds ohm centimeters. However, 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. In chloride contaminated concrete, the chlorides lowers the concrete resistivity, but not too much because the resistivity of an alkaline solution is not lowered very much by the presence of chlorides.

In summary, the electrical resistivity 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.

4 Calculation Of The Initiation Period

In *chloride environment* resistivity is directly related to ionic diffusivity in saturated concrete through Einstein law:

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

Where

D_e = effective diffusion coefficient;
k_{Cl} = a factor which depends on the external ionic concentration;
ρ_{es} = the resistivity (in this case of concrete saturated with water);
σ = the conductivity (inverse of resistivity).

If k_{Cl} is established, the diffusion coefficient of the chloride ion can be calculated providing that no reaction of chlorides exists with the cement phases, because the De of Einstein law does not account for binding (that is why it usually is named as “effective”). However, the chloride binding has to be taken into account. This is done 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.

An “apparent” electrical resisvity, ρap, in saturated conditions can be then defined as $\rho ap = \rho_{es}\cdot r_{cl}$.

Equation [1] can be now written:

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

In the case of carbonation, it progresses when the concrete is partially dry. The higher is the porosity, the higher will be the carbonation depth. As said, porosity is appraised by measuring the electrical resistivity. Therefore, equation [1] can be also applied to carbonation providing another constant k_{CO2} is considered for the atmospheric exposure. In addition, in a similar manner as for chlorides a reaction factor, r_{CO2}, taking into account the amount of alkaline material able to bind CO_2, has to be introduced:

$$D_{CO2} = \frac{k_{CO2}}{\rho_{es} \cdot r_{CO2}} \quad (2')$$

Thus, expressions of the diffusion coefficients of chlorides and carbon dioxide in terms of the apparent electrical resistivity, $\rho_{ap} = \rho_{es} \cdot r_{co2.}$, in saturated concrete have been deduced.

4.1 Calculation of reaction factor

A key aspect of the proposed method is related to the so called "reaction factor" that accounts for the amount of penetrating substance not really moving inwards, but being immobilized by the cement phases. It represents the proportion of CO_2 reacting with the alkaline compounds of hydrated cement or the proportion of chlorides being bound.

The reaction factor is proposed to be taken into account in the expression: $\rho_{ap} = \rho_{es} \cdot r$, it represents the number of times the effective resistivity ρ_{es} is apparently increased. Therefore, r can be formulated as a retarder factor varying from 1 to 5 or 10 times. It can be calculated from specific experiments, for instance, comparing the diffusion coefficients in steady and in non-steady state conditions.

The r factor might be as well derived from experiments in mortar, whose translation into values for concrete can be made taking into account the differences in w/cm and in cement content, through the equation:

$$r_c = r_m \cdot f\ (w/cm).f\ (cement \cdot content) \quad (3)$$

Where

r_c = reaction factor in concrete;
r_m = reaction factor in mortar;
w/cm = water/cement ratios of concrete and mortar.

For the sake of simplicity of design, the characteristic value of r_m might be provided by the cement producers in the same manner they provide the cement grading. In this assumption, the concrete producer does not need to test for r_{Cl} and r_{CO2}, but simply apply equation [3] for each particular concrete proportioning.

4.2 Influence of age and temperature in the resistivity

For the formulation of the model it is not necessary to do more than develop the value of the resistivity after 28 days of wet curing to obtain $\rho_{es,\ 28d}$, as the reference parameter as in the case of mechanical strength. However, for the sake of a comprehensive presentation, it is worth mentioning 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 to the refinement of the pore structure. This evolution is very similar to that of the increase of mechanical strength. The decrease in porosity with the advance of hydration leads to a lowering in porosity which is reflected in both mechanical strength and resistivity. The time law that can be applied for this evolution of ρ_{es} with age is of the type:

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

Where

$\rho_{es,28d}$ = resistivity at 28 days;
$\rho_{es,t}$ = at any testing time;

M = a function of time evolution.

This law may have different power exponents for normal portland cement than for blended cements. There are values in the literature (7)(8) and work is being done for its quantification.

Temperature has an important effect on resistivity, which only can be generalized if the ρ values are standarized to a reference temperature, that which is proposed to be 25ºC (9). An increase in temperature should increase diffusivity, D, and corrosion rate, V_{corr},. However, this increase in temperature may at the same time produce evaporation, which in turn would effect on the opposite in both, D and V_{corr}. Therefore, the incorporation of temperature effects on models is done still very seldom. In present case, it is incorporated by suggesting to measure $\rho_{es,\ 28d}$ at 25ºC. The standardization of resistivity from other temperatures has been explained in (9).

5 Calculation of the Propagation Period

When reinforcement corrodes, there is a relationship between corrosion rate and electrical resistivity of the type (10):

$$I_{corr} = \frac{k_{corr}}{\rho_{ef}} \quad (5)$$

Where

k_{corr} = constant with a value of 3x104µA/cm2·kΩ·cm;
ρ_{ef} = averaged value of resistivity variations during exposure time.

The resistivity, ρ_{ef}, 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 t_p, it can be assumed an annual average concrete moisture content in each exposure class. Averaged I_{corr} and ρ values can be attributed for each exposure class (considering both moisture and temperature).

6 Service Life Model Based on Concrete Resistivity

Assuming a square root relation between penetration of the aggressive front and time $x_i = V_{CO2},\ C_l\ \sqrt{t}$, the factor of relation V represents the ease or velocity of penetration, $V_{Cl,\ CO2}$ and therefore, the service life can be written in the form:

$$t_l = \frac{x_i^2}{V_{CO_2,Cl}} + \frac{P_x}{V_{corr}} \quad (6)$$

Where

P_x = limit for corrosion attack depth (loss in rebar diameter or pit depth);
V_{corr} = corrosion rate;
X_i = cover thickness;
$V_{co2,cl}$ = rate of penetration of carbonation or chlorides.

Based on these considerations, the model can now be expressed in the following manner:

1) Initiation period – Assuming the mentioned square root relation between diffusivity and penetration depth of the aggressive material, Einstein relation enables to write:

$$x_i = k_{Cl,CO_2}\sqrt{D_a\, t} \qquad (7)$$

Where

$k_{Cl,CO2}$ = factor of aggressive penetration;
D_a = apparent or non steady state diffusion coefficient taking into account binding and x_i= penetration depth of the aggressive.

Substituting in [2] and [2´] in [6] assuming D_a= D_{Cl}, CO_2:

$$t_i = \frac{x_i^2 \cdot \rho_{es} \cdot r_{Cl,CO2}}{2 \cdot k_{Cl,CO2}} \qquad (8)$$

2) Propagation period – substituting [5] in [6] results.

$$t_p = \frac{P_x \cdot \rho_{ef}}{k_{corr}} \qquad (9)$$

Finally the addition of t_i+t_p gives the total service life of reinforcement

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

The main parameter is the concrete resistivity measured in saturated conditions, at 25ºC and, at 28 days of life, and ρ_{ef} given as an annual average value for certain exposure conditions.

This equation considers both initiation and propagation periods which, means that the limit state assumed when a certain degree of corrosion in the reinforcement is reached. However, it can also be used by considering the depassivation as the limit state, in which case only the first term of the equation serves.

$$t_l = t_i = \frac{x^2 \cdot \rho_{es} \cdot r_{Cl,CO_2}}{k_{Cl,CO_2}} \qquad (10')$$

With regard to the other parameters r and k, r 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* values are factors which should account for the environmental concentration of aggressive material (exposure class).

7 Practical Application to Standards

Equations 10 and 10' enable the calculation of the characteristic resistivity as a function of the target service life and the cover thickness. 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, and assuming a limit state of depassivation (equation [10']) in 50 years.

Table 1. Apparent Resistivity values for a t_l= 50 years assuming the depassivation as the limit state, t_l= t_i.

Apparent Resistivity (Ohm.·m) in saturated conditions at 28 days of curing		
Cover (mm)	**Carbonation**	**Chlorides**
20	250	2500
30	120	1110
40	63	625
80	15	160

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

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 thicknesses according to exposure aggressivity through certain equations as a manner of a model. It results a promising possibility as being resistivity a non destructive measurement it can be used for routine on-site quality control.

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 values, 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 V_{corr}.

3) The establishment of the r_{Cl} and r_{CO2} for the particular cement and concrete (tested by the cement or concrete manufacturer).

4) The measurement of ρ_{es} at 28 days in the same concrete specimens used for mechanical strength.

5) The calculation of ρ_{as}=$\rho_{es} \cdot r_{Cl,CO2}$

6) The comparison of the ρ_{as} obtained with the table of characteristic values such as Table 1 or the calculation of expected service life through equation 10 or 10´.

8 Final Comments and Conclusions

The need to provide concrete with a target durability has stimulated the development of models to predict service life. These models are based on concrete permeation or resistance to penetration. In general, diffusion coefficients derived from analytical solutions to differential equations are used. This approach has several limitations because the reproduction of real boundary and initial conditions by 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 progress. The general expression of service life results:

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

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

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