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Types of Models of Service Life of Reinforcement: The Case of the Resistivity

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Abstract

The design of concrete structures is usually made by means of a performance approach based on strength tests carried out following testing conditions agreed by convention. A similar approach should also be followed in the case of durability design regarding reinforcement corrosion. This type of consideration enables the definition of a four level methodology for design against reinforcement corrosion in parallel with that followed for strength design. Levels from I to IV are proposed: a] level I would be the prescriptive method already given in present codes based on "deemed-to-satisfy" rules, b] level I is that where still not quantification of the time to reach a limit state is explicit but the minimum life time is assured through performance based tests, c] level III would be the level in which the calculation of aggressive ingress through models having explicit the time is made and d] level IV includes the verification that the resistance of the cover thickness against the penetration of aggressive substances is higher than the environmental action effect including probabilistic treatments.

For level II and III the measurement of the electrical resistivity results a very suitable proposal due to this parameter can be measured in a non destructive test and serves to quality control. It is not only a performance test [level II] but it can be included in models of both the initiation and propagation periods. For the time to corrosion onset, the electrical resistivity represents the porosity and its connectivity and therefore can be used to model transport processes. It also results very suitable for measuring concrete aging and then accounting for the reduction of the diffusion coefficient with time. 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.

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In this respect, Tuutti's proposal [1] on the definition of service life by dividing it into the initiation period, t_i, and propagation period, t_p, has marked an important milestone. Numerous further attempts trying to quantify both t_i and t_p [2-4] have been published. These models based in Fick's Second Law are now very popular in the scientific community. However, in spite of the possible potential higher accuracy of the models more complex than the based in Fick's Law, design engineers show reluctance to use this kind of models and even less prone to introduce them into national Codes or Standards.

Several proposals exist based in modelling the mechanisms of attack [1-5] or in the so called "performance" concepts [3] or in the use of "durability indicators" [6-7]. 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. This situation demands the calibration of the new proposals and the need to make coherent the new models with long term experience. It demands as well not to decide at present which of the proposals is better but to consider all possibilities until the calibration could be ample enough.

The consideration of the several approaches to durability design is the basis to propose a "multilevel" methodology, which could classify them and enable benchmarking in order to select in the future those being the better predictors of real behaviour. The methodology described in present paper, classify the approaches in four levels assuming that the concrete's resistance (durability) has to be greater than the effect of environmental actions sustained by the structure. The levels selected differ in the type of relation considered to express the concrete's resistance (durability). Present Codes for calculating concrete's resistance to fire, were taken as examples.

2. Proposed Multilevel Methodology

In addition to the deemed to satisfy rules contained in present standards, the most popular manner to design for certain durability is the modelling based in the assumption that the penetration of aggressive substances is controlled by diffusion. This approach can be mainly applied to reinforcement corrosion but results less applicable to other types of attack as alkali-aggregate reaction, AAR, or sulphate attack where the reaction step may be more controlling than the diffusion one.

Apart from the use of concrete mix or the modern models there have to be considered the use of the testing of parameters that could indirectly related to the durability but that cannot be introduced in models. This can be the case in the past of water or air permeability that was thought to represent the concrete resistance against aggressive substances, or capillary suction. In the case of penetration of sulphates or the AAR, there are a set of different tests that are proposed to classify the resistance of the concrete. All of them constitute like a group of parametric testing that are also named "performance based tests". This concept of measuring the performance [7] attracts the interest of designers as, in general, the tests are accelerated and in many occasions are cheap and can be used to rank concrete qualities. A typical example is the Rapid chloride permeability test proposed by Whiting in the 80's [8-10].

It has been recently introduced the importance of the so called "probabilitic approach" for durability design. The main offer comes after the development of the European project Duracrete [11-14], were several examples were made on the reinforcement corrosion. The main differential fact of the probabilistic approach is the use of statistical distributions that, unfortunately, at present are not enough good to assure that this approach is more accurate than the other ones.

Taking into account this panorama the proposal is to consider 4 levels [15] for durability design as is shown in Table 1.

TABLE 1: METHODOLOGY OF FOUR LEVELS FOR DURABILITY DESIGN

Design Level	Calculation Method of Durability
I	Deemed-to-satisfy-rules: concrete composition
II	Performance based tests
III	Analytical or numerical Models
IV	Probabilistic treatments

One important remark is that levels I and II are time implicit procedures and levels iii and IV have explicit the time calculation. This differentiation helps to separate the use of “performance or durability Indicators” as concrete properties whose values are used to delimitate concrete qualities fitting in an implicit service life of 50 or 100 years. However the use of models in which the property is incorporated in an expression in which the time is explicitly introduced in such a manner that the threshold values of the property varies with the time life.

If this proposal of classification in different levels is adopted, what will be necessary in the future is that all the results are coherent. The definition of coherence regarding durability is not an easy task because different concrete mixes can lead into similar durability and therefore it might happen that the application of the different levels to the same structure can lead into different suggestions of concrete mixes. Therefore, it has to be recognized that, in spite the long experience in testing durability, the proposition of a set of levels all of them giving reliable and comparative results cannot be found immediately.

3. Use of Resistivity for Levels II and III

Responding to the interest of finding performance parameters or durability indicators that being suitable for quality control could also be applicable for modelling for predicting service life, the electrical resistivity of concrete appears as a very promising selection [15-16]. It can be used as performance indicator in a similar manner than the mechanical strength and it can be introduced in a square root law in order to adapt its values to the calculation of service life.

The electrical resistivity [ρ, units Ω̃m], 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 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 [17], 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. 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.

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

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.

3.1. 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 [16], 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].

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:

$$D_{ns} = \frac{k_{Cl,CO2}}{\rho_{es} \cdot r_{Cl,CO2}} = \frac{k_{Cl,CO2}}{\rho_{app}} \qquad (2)$$

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.

3.2. 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 [15] established the direct relationship between the resistivity and the intensity of corrosion and can be expressed by the equation (3), 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.

$$I_{corr} = \frac{k_{corr}}{\rho_{ef}} \qquad (3)$$

The same equation can be used for other states of the corrosion or progation stage [19,20].

3.3. Aging factor

As the resistivity evolves with time as has been mentioned and shown in figure 1 [24], and "aging" factor should be considered. The factor should be applied longer than 10 years as the continuation of hydration or changes induced by the environment may not last longer.

This factor cannot be the same that that identified for the diffusion coefficient [19-21] and therefore if n is the aging factor of the diffusion coefficient and q that of the resistivity it has been found that q=0,8n. The representation of the

$$D = D_0 \cdot \left(\frac{t_e}{t_0}\right)^{-n} \quad (4)$$

$$\rho = \rho_0 \cdot \left(\frac{t_e}{t_0}\right)^{q} \quad (5)$$

which leads into

$$X_{Cl} = \sqrt{\frac{K}{\rho_0 \cdot \left(\frac{t_e}{t_0}\right)^{q} \cdot r_{Cl}}} \cdot \sqrt{t} \quad (6)$$

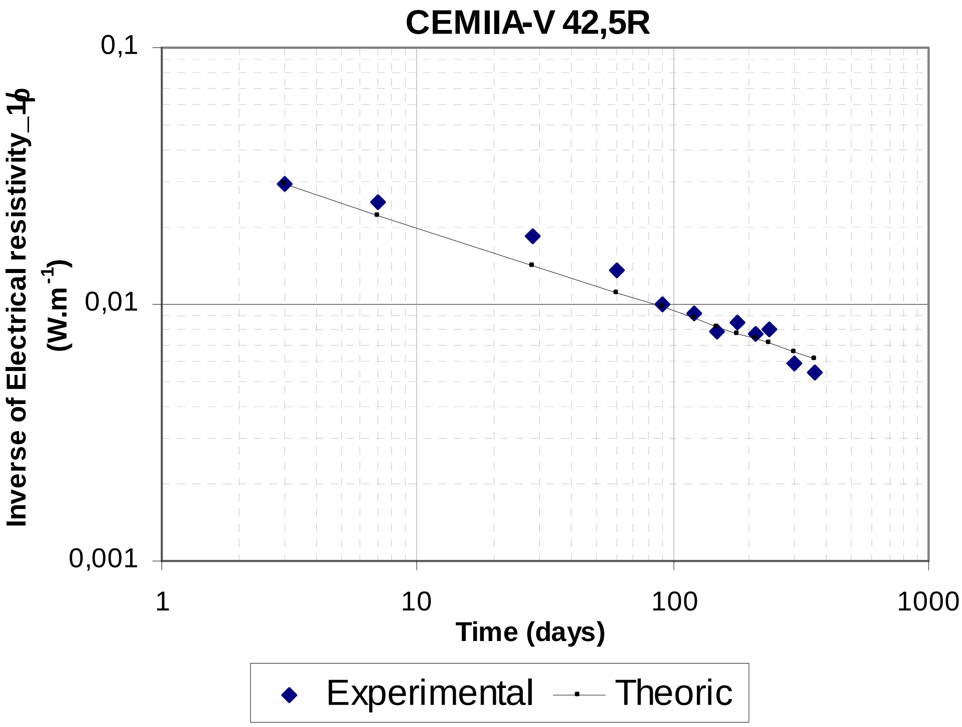

Figure 1. Decrease of resistivity with time and fitting of equation (5)

4. Service Life Model Based on Concrete Resistivity

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 [1] 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. The model proposed based in the measuring of electrical resistivity makes use of this parameter as the main one determining both t_i and t_p periods. 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 model proposed is based on the measuring of electrical resistivity for its use as the main parameter for determining both t_i and t_p periods. 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= $V_{CO2,Cl}$*√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 expression:

$$t_l = t_i + t_p = \frac{x_i^2}{V_{CO_2,Cl}} + \frac{P_x}{V_{corr}} \tag{7}$$

4.1 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 = √[D.t] which indicates that $V_{Cl,CO2}$=[D and therefore equal to [[kCl,CO2 /[es*rCl,CO2]. Rearranging this expression it results for the initiation period the equation (8).

$$t_i = \frac{x_i^{\,2} \cdot \rho_{\text{app}}}{2 \cdot k_{Cl,CO2}} = \frac{x_i^{\,2} \cdot \rho_{es} \cdot r_{Cl,CO2}}{2 \cdot k_{Cl,CO2}} \tag{8}$$

4.2. 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].

$$t_p = \frac{P_x \cdot \rho_{ef}}{k_{corr}} \qquad [9]$$

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 [*q*], and considering an environment factor [ξ] which represents the concrete moisture condition, that is ρ_{ef}: $f[t,q,\xi]$.

The final expression is written as :

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

4.3 Production of concrete for a specified apparent resistivity

It remains to describe how the concrete producer can design a mix to fulfil the service life specification. This can be done by considering Archie’s law [18] linking resistivity and porosity. From the specified resistivity the paste porosity can be obtained and through Power’s relation on porosity and w/c ratio it is feasible to prepare a mix with the needed effective resistivity at 28 days, providing the consideration of the type of cement and its retarder factor.

The concrete producer should verify by testing the reaching of the specified resistivity while the cement producer should give the retarder factor of each cement.

5. Conclusions

Resistivity is a comprehensive indication of concrete microstructure and as such it can be used as a Durability Indicator or introduced in the corresponding simple models having explicit the time.

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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