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Diseño y evaluación de la vida útil a través de resistividad eléctrica concreta

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RESUMEN
Este artículo describe el uso de la resistividad eléctrica del concreto como parámetro de desempeño de durabilidad y la información complementaria que puede proporcionar la resistividad, como: período de fraguado, resistencia mecánica y grado de curado. Además, se explica cómo diseñar la mezcla de concreto para obtener una resistividad objetivo. Los códigos actuales aún tienen requisitos prescriptivos para el diseño por durabilidad del concreto y para la corrosión del refuerzo. Sin embargo, las tendencias modernas especifican el desempeño más que las características del concreto. Este enfoque de desempeño exige definir un parámetro de control de la durabilidad, como el coeficiente de difusión del cloruro, con su prueba correspondiente y el modelo para predecir el tiempo de corrosión del acero.
Palabras clave: resistividad eléctrica concreta; desempeño de durabilidad; coeficiente de difusión de cloruro.

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Design and evaluation of service life through concrete electrical resistivity

ABSTRACT

This paper describes the use of concrete electrical resistivity as durability performance parameter and the complementary information that resistivity can provide like: setting period, mechanical strength and degree of curing. Also, it is explained how to design the concrete mix to obtain a target resistivity. Current codes have prescriptive requirements for the durability of concrete and reinforcement corrosion. However, modern trends specify the performance rather than the concrete characteristics. This performance approach demands to define a durability controlling parameter, such as the chloride diffusion coefficient, with its corresponding test and the model to predict the time to steel corrosion.

Keywords: concrete electrical resistivity; durability performance; chloride diffusion coefficient.

Projeto e avaliação da vida útil através da resistividade elétrica do concreto

RESUMO

As normas atuais têm requisitos para o projeto de durabilidade do concreto com base na resistência à compressão e provisões relacionadas ao teor de cimento e à relação água-cimento. Para corrosão da armadura, os códigos também especificam as larguras máximas das fissuras de flexão. No entanto, as tendências modernas preferem especificar o desempenho em vez das características do concreto. Essa abordagem de desempenho exige definir um parâmetro de controle de durabilidade, como o coeficiente de difusão de cloreto, com seu teste correspondente e o modelo para prever o tempo de corrosão do aço. Este artigo descreve o uso da resistividade elétrica do concreto a ser usada como parâmetro de desempenho de durabilidade e as informações complementares que a resistividade pode fornecer como é: o período de ajuste, a resistência mecânica e o grau de cura. Além disso, é explicado como projetar a mistura de concreto para obter uma resistividade alvo.

Palavras-chave: resistividade elétrica do concreto; desempenho em durabilidade; coeficiente de difusão de cloretos.

1. INTRODUCCIÓN

La resistividad eléctrica concreta se midió comparativamente temprano con respecto a la aplicación de otras técnicas electroquímicas en concreto porque se informan estudios de los años 40-50 (Hammond y Robson, 1955; Monfore, 1968) relacionados con la caracterización del concreto como aislante eléctrico. utilizado en durmientes de tren y porque se aplicó a la medición no destructiva de la configuración del cemento (Calleja, 1953). Es en la década de los 60 cuando comenzó a aparecer la corrosión por armadura como una posible angustia potencial y comenzaron a aplicarse técnicas electroquímicas, en particular curvas de polarización (Gjorv et al., 1986; Gouda y Monfore, 1965).
Sin embargo, su papel en estos experimentos electroquímicos no se evaluó hasta que la técnica de resistencia a la polarización, Rp, se usó para medir la velocidad de corrosión instantánea (Andrade y González 1978, González et al. 1980), porque sus valores podrían verse muy afectados por el óhmico descartar si no elimina el componente resistivo del valor registrado. La medición sistemática de la caída óhmica que afecta las mediciones Rp permitió evidenciar que la resistividad del concreto es una función directa de la porosidad del concreto y su grado de saturación de agua (Andrade et al., 2000a; McCarter y Garvin 1989) y luego, la tasa de corrosión función directa de la resistividad con la consecuencia de que el control óhmico es el mecanismo clave de control de la velocidad de la corrosión del refuerzo.

Es en la década de los 90 cuando surge el interés por la resistividad cuando se demuestra la relación entre la difusión del cloruro y la resistividad del concreto (Andrade et al, 2000b). No se apreció explorar esta relación y, en su lugar, la mayoría de los investigadores se enfocaron en desarrollar modelos y pruebas sobre la migración de cloro (Andrade, 1993; Tang, 1996). Sin embargo, el autor de esta comunicación se ha sentido atraído por las numerosas aplicaciones potenciales de la resistividad del hormigón y, en particular, ha identificado que es el parámetro clave que vincula la microestructura con la capacidad de transporte del hormigón y ha estudiado en profundidad los fundamentos de la resistividad, en particular, la predecir la vida útil del refuerzo a partir de su caracterización (Andrade et al, 1993; Andrade, 2004). En el presente trabajo se describen algunas de las bases microestructurales de la resistividad como parámetro universal que controla los procesos de transporte en hormigón como medio poroso, así como la relación entre la corrosión de refuerzo y el grado de saturación que hace variar la resistividad del hormigón.

2. FUNDAMENTOS DE RESISTIVIDAD DEL CONCRETO

La resistencia eléctrica del concreto, R, es la relación entre la caída de tensión, V, aplicada a un cuerpo conductor y la corriente, I, inducida por él.

$$R = \frac{V}{I} = \rho \frac{l}{A} \quad (1)$$

Esta resistencia, si está estandarizada a una geometría regular, permite conocer la resistividad a través de la ley de Ohm que se da en la ecuación 1 (l = la distancia entre los electrodos y A es el área de la sección transversal en la figura 1).

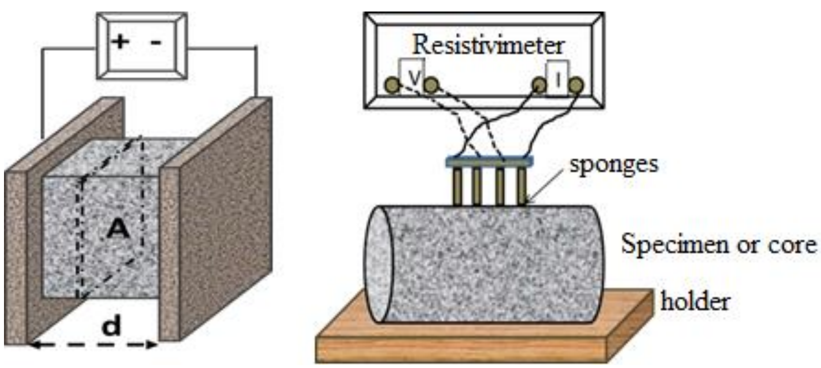

Figura 1. Izquierda: directa, método para medir la resistividad (la red de poros se hace evidente por el bien de la representación). Derecha: cuatro puntos o método Wenner. La resistividad del concreto es una indicación de la porosidad del concreto y el grado de saturación del agua.

El método más común de medición de resistividad es el método "directo" o "a granel" (figura 1-izquierda). Se aplican dos electrodos colocados en dos caras paralelas de un espécimen o disco de concreto y voltaje. El otro método común es el conocido como "cuatro puntos o método Wenner" que se muestra en la misma figura.

2.1 Evolution of resistivity during setting and hardening

When water is mixed with the cement powder the paste formed is very fluid and then the resistivity is very low (figure 2), however as soon as the paste is setting, the resistivity increases following cement hydration (Calleja, 1953). The increase continues during hardening as porosity evolves with cement hydration. This increase with time serves to monitor the "aging factor of hydration" which will be addressed later.

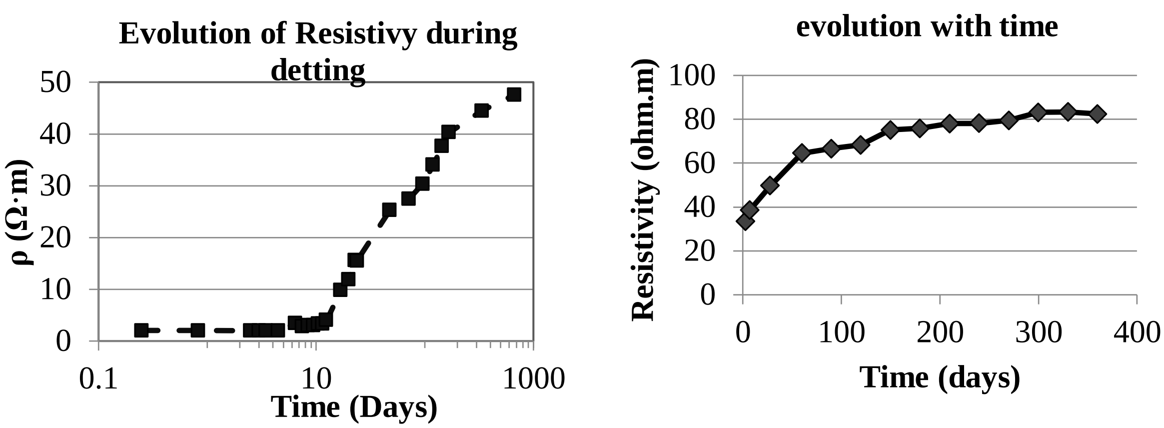

Figure 2. Left: Evolution of resistivity of mortar with w/c ratio of 0.65 during cement setting. Right: example of evolution of concrete resistivity during hardening

2.2 Relation resistivity and mechanical strength

The increase of resistivity with time is parallel to that of mechanical strength due both parameters depend on concrete porosity. In figure 3 is shown their relation for numerous concretes which indicates that the resistivity may be used to predict mechanical strength when the specimens are of the same cement type and cured in standardized conditions.

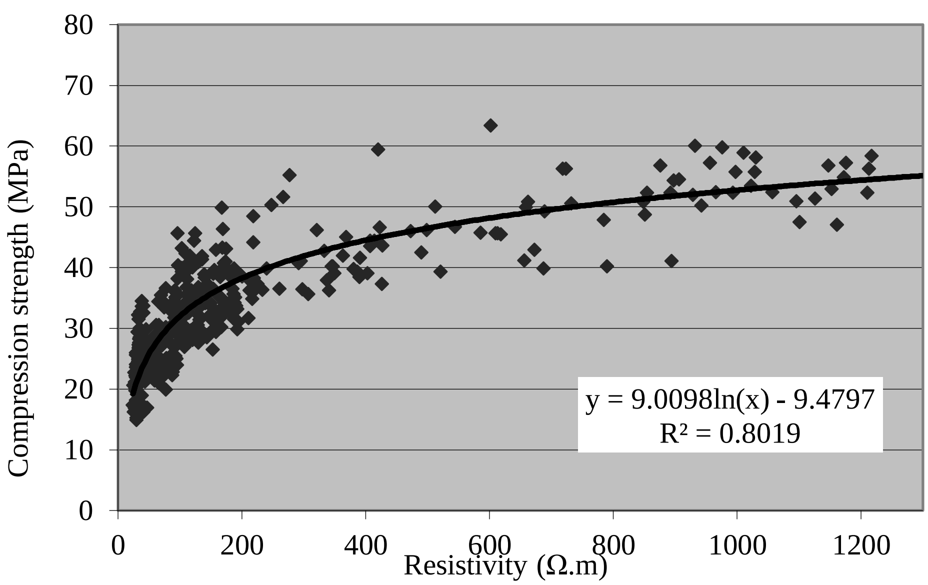

Figure 3. Relation of compressive strength of concretes at different ages and resistivity.

2.3 Relation of Resistivity with pore microstructure and water saturation

Concrete is a porous body in which the solid phases are non-conductive being the pores filled with a solution which is the conductive phase. Then the resistivity/conductivity of the concrete will depend on the total pore volume and on its pore size distribution. As higher is the porosity, lower is the resistivity providing the concrete is water saturated. If the concrete is not saturated then, the resistivity is an indication of concrete degree of saturation (McCarter and Garvin, 1989; Andrade et. al, 2000b). This relation can be expressed through a modification of Archie's law (Archie, 1942), where ρ_0= the resistivity of the pore solution (average value from 10 to 50 Ω.cm), W is the volumetric fraction of water and τ is the tortuosity factor, τ:

$$\rho = \rho_0 \cdot W^{-\tau} \qquad (2)$$

Regarding the influence of the chemical composition of pore solution, ρ_0, its impact in the total resistivity following equation 2 is small providing the concrete remains alkaline. If concrete is carbonated then, the value of ρ_0 is much higher.

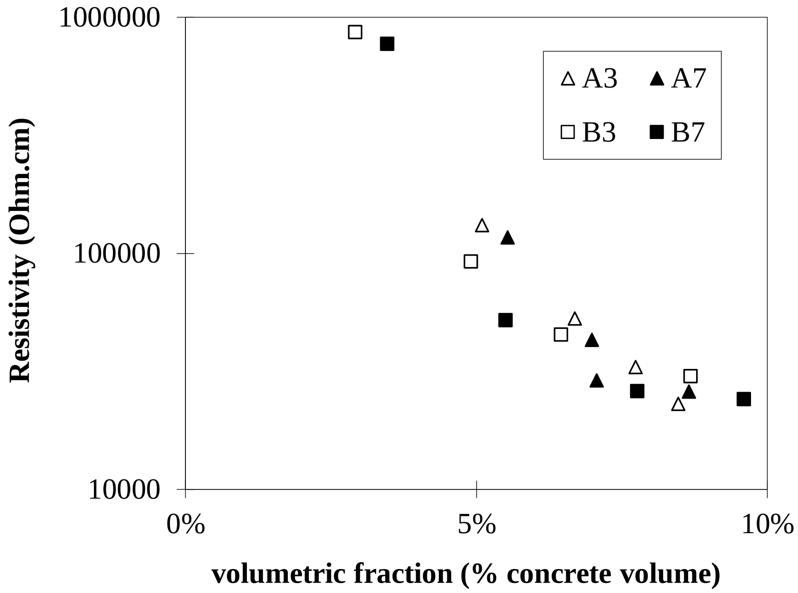

Figure 4. Relation between volumetric fractions of porosity saturated with water and resistivity of four different mixes. The value of τ of equation 2 is 2.52 in the figure (Andrade, Bolzoni, Fullea, 2011)

An illustration of this empirical relation is given in figure 4 (Andrade, Bolzoni, Fullea, 2011) where four concrete mixes have been conditioned to several relative humidities in which the resistivity was measured together with the weight. It indicates that below a RH of 65% the resistivity rises exponentially while it is above 85-90% RH when it reaches the minimum values due to the capillary pores that are starting to be filled with evaporable water.

2.4 Influence of temperature in the Resistivity

With respect to the influence of temperature, it has an important effect on resistivity: resistivity increases when temperature decreases. This effect only can be generalized if the ρ values are standardized to a reference temperature that it is proposed to be 25ºC. Other possibility is the use of Arrhenius law; however, it has been detected that the Activation energy depends on the degree of saturation and a single value seems not exiting (Andrade, Zuloaga, et. al, 2011). For practical applications, however the effect can be neglected if the temperature is varying from 18 to 22ºC. Larger variations may need standardization.

On the other hand, an increase in temperature usually means evaporation of pore water, which in turn means increase of resistivity. That is, the final effect of temperature in the corrosion is counter-influencing as an increase in temperature may produce a slowing of the Diffusion coefficient and the corrosion rate due to the drying. Therefore, the incorporation of temperature effects on models is very premature and more results are needed.

3. RELATION BETWEEN RESISTIVITY, DIFFUSIVITY AND CORROSION RATE

3.1 Resistivity-Diffusivity

Being concrete a porous material, Resistivity is related to its ionic transport ability by applying Einstein law on conductivity-diffusivity which relates the movement of electrical charges to the conductivity of the medium (Andrade, 1993) as represented in figure 5 in a log-log graph:

$$D_e = \frac{F}{\rho_{ef}} = F \cdot \sigma = \frac{2E-4}{\rho_{ef}} \quad (3)$$

Where:
De = effective diffusion coefficient
F = a factor, which depends on the external ionic concentration
ρ_{ef} = “effective” resistivity (in this case of concrete saturated with water)
σ = conductivity (inverse of resistivity)
A value of kCl of 20x10-5 can be used for external chloride concentrations of 0.5 to 1 M.

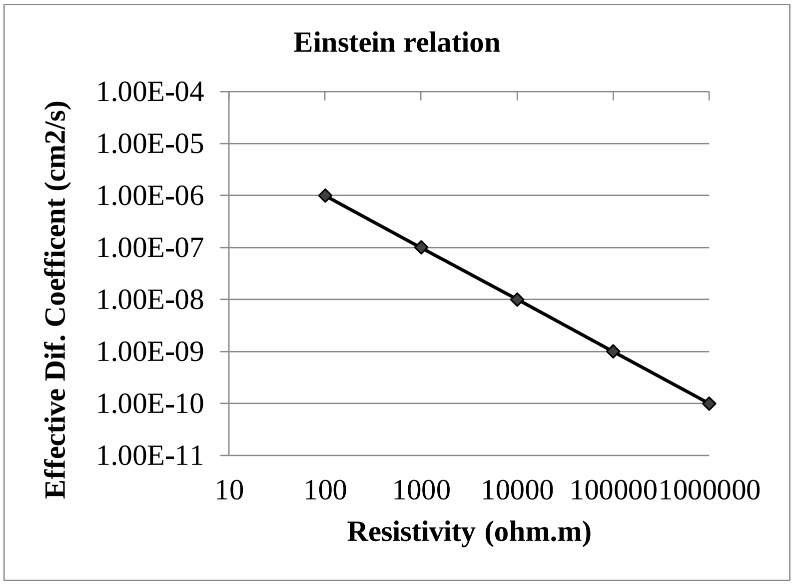

Figure 5. Relation between resistivity and diffusivity as calculated from Einstein law.

3.2 Resistivity- Corrosion Rate

It is the dependence with moisture of the resistivity which explains the relation between it and the reinforcement corrosion rate which is illustrated with the graph I_{corr}-resistivity (Andrade et. al. 2000a; Lambert et. al., 1991) of figure 6, in which it is illustrated the average relation and some values of a particular test. The inclined line in the figure 6 represents the expression:

$$I_{corr}\left(\frac{\mu A}{cm2}\right) = \frac{26}{\rho\ (K\Omega \cdot cm)} \quad (4)$$

If the Icorr is given as Vvorr in mm/year this expression 3 results in expression 4:

$$V_{corr} = \frac{0.0116 \cdot 26000}{\rho} = \frac{301.6}{\rho} \quad (5)$$

Where Vcorr = (mm/year), 0.0116 = conversion factor between V_{corr} and I_{corr} and ρ = concrete resistivity (ohm·cm).
This relation has opened the door to derive the corrosion rate from resistivity providing the corrosion is in active state, because when the steel is passive the resistivity cannot be used to forecast corrosion rates.

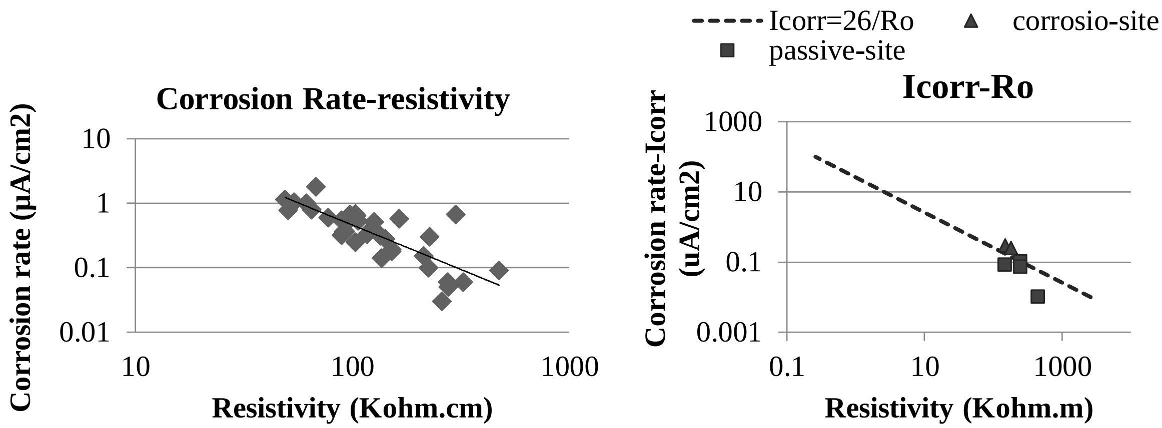

Figure 6. Two examples of the Graph I_{corr}- ρ_{ef} which indicates the relation between the I_{corr} and the degree of concrete saturation.

3.3 Diffusion Coefficient-Corrosion Rate

It is apparent that equation 3 and equation 4 are very similar in spite that one (that of the diffusivity) is based in the well based theory of movement of electrical charges and the other (that of the I_{corr}) is empirical and developed for concrete (perhaps it could be applied to some porous materials as corrosion of metals in soils). What is the physical meaning of that similarity?. The explanation found with respect to the equation of the I_{corr}-ρ was the well-known "resistance control" of the corrosion activity of the micro- and macro-galvanic cells. That is, the resistivity of the electrolyte controls the maximum rate of corrosion (either the movement of the produced iron ions and that of the hydroxides produced in the cathode) while in solution the corrosion activity rate is more controlled by the energy of activation (activation control) or the concentration of the ions oxidized in the anodic areas or reduced in the cathodic ones (concentration control). This resistance control is what expresses the equation 4 of the diffusivity: the ions cannot move faster that the resistivity of the solution allows. Being the movement of electrical charges (ions) involved in the corrosion and in the diffusion, both are controlled by the resistivity of the electrolyte.
Apart from the physical meaning, it has also to be considered the mathematical similarity. This is very interesting from a practical point of view because, in addition to make possible the calculation of the diffusion coefficient and the corrosion rate from the resistivity of the concrete, it also enables the calculation of the maximum corrosion rate to be produced in a concrete if the coefficient of diffusion is known and vice versa, the deduction of the coefficient of diffusion from a measurement of maximum corrosion rate.
Operating mathematically by equalizing both expression 3 and 4 and assuming that for the sake of simplification in equation 4 the value of k= $2.6\cdot10^{-5}$ instead of k= $2.3\cdot10^{-5}$, it can be deduced that:

$$\rho = \frac{26\cdot10^{-5}}{D_e} = \frac{26000}{I_{corr}} \qquad (6)$$

which aims into:

$$I_{corr} = \frac{26000}{26 \cdot 10^{-5}} \cdot D_e = D_e \cdot 10^8 \qquad (7)$$

And

$$D_e = I_{corr} \cdot 10^{-8} \qquad (8)$$

Table 1 gives some calculations for different values of I_{corr} and D_{ef}.

Table 1. Equivalence between Def and I_{corr} for the value of k=2.6E-5

D_{ef} (cm²/s)	0.1E-8	1E-8	10E-8
I_{corr} (µm/year)	0.1	1	10

It must be stressed that such relations are based in the so called "effective diffusion coefficient", De which is a steady-state value and not in the Apparent D_{ap} that averages the evolution of the coefficient along the testing time and it is the result of a non-steady-state regime.

3.4 Relation between resistivity and water saturation

Following with analogies, it is possible to calculate the corrosion rate from the water saturation, as this one depends on the resistivity. Substituting equation 2 and 3 in 4 results in equation 6:

$$V_{corr}\ (\frac{mm}{year}) = 6 \cdot W^2 \qquad (9)$$

Being: W= $S_w \cdot \varepsilon$, S_w = concrete water saturation degree, % and ε= porosity in volume, % This equation enables to deduce the maximum velocity of corrosion in a concrete in function of its volumetric fraction of pores saturated with water. Thus, as an example, for a W = 0.05 (50% of saturation degree in a concrete with 10% of porosity in volume), the maximum corrosion rate would be of 15 µm/year.

Then, in figure 7, all the concordances and analogies are summarized.

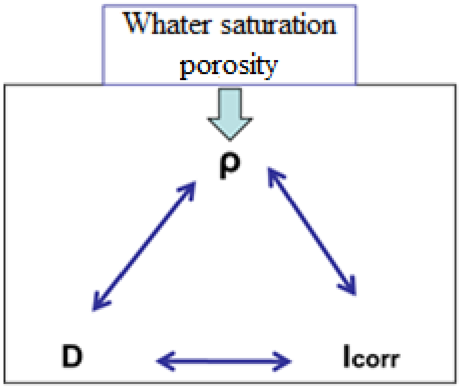

Figure 7. Relations between Resistivity-Diffusivity and Corrosion rate

4. SERVICE LIFE MODEL BASED IN THE RESISTIVITY MEASUREMENTS

Two main aspects must be taken into account when trying to calculate the service life from the resistivity (Andrade, 2004).

- It is necessary to introduce the relation of ρ with time
- The ρ is proportional to the effective diffusion coefficient, that is the reaction of chlorides with the hydrated cement phases has to be incorporated.

4.1 Relation with time

The resistivity can be introduced in a "square root law" enabling the relation between time and the resistivity. Thus, if using the standard square root law:

$$x = V_{CO2,Cl} \cdot \sqrt{t} = \sqrt{2 \cdot \mathrm{D} \cdot t} \qquad (10)$$

Where x= depth of carbonation or chloride threshold penetration and t= time life. The model based in the resistivity was proposed (Calleja, 1953) by substituting the value of D by expression 7 which gives:

$$x = \sqrt{2 \cdot \frac{k}{\rho} \cdot t} \qquad (11)$$

Based in this relation, a complete model has been developed (Calleja, 1953). For the sake of summarizing it is presented in equation 12 and equation 13:

$$t_l = t_i + t_p = \frac{x_i^2}{V_{CO_2,Cl}} \qquad (12)$$

$$t_l = \frac{x^2 . \rho_{ef}}{k_{Cl,CO_2}} \qquad (13)$$

Where:

t_i= initiation period

t_p= propagation period

ρ_{ef} = effective resistivity (at 28 days of wet curing)

$k_{CO2,\,Cl}$ = environmental factor depending on exposure class

Knowing the value of the resistivity in the same specimen than that used for mechanical strength at 28 days, this model enables the calculation of the time to corrosion and the corrosion propagation period, if some information on the reaction ability of the cement phases and the aging factor are known.

4.2 Consideration of chloride reaction and other factors

As has been mentioned, 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 (Andrade, 1993; Andrade et al, 1993; Andrade, 2004; Garboczi, 1990) (see equation 3). This expression only accounts for the transport of the chloride ions through the pore network which is insufficient to characterize the transport through concrete where reaction of chlorides takes place and this reaction and the hydration make to evolve the porosity. Then some factors have to be

applied to equation 3 to account for these effects together with the value of the k factor which takes into account the concentration of the chloride or aggressive substance.
The factors introduced in the equation 3 have been:

- ***k*** has been named "environmental factor". It depends on chloride concentration and in the case of carbonation, on the concrete moisture content (Andrade, 1993; Andrade, 2004)
- r_b "retarder or reaction factor" (Andrade et al, 2014) which multiplies the resistivity to account for the "retarder" effect of chloride binding during penetration of chlorides. It can also be applied to the case of carbonation. This is due to carbonation progresses when the concrete is partially saturated. That is, as higher is the porosity or the empty pores due to dry conditions, higher the carbonation depth will be but a certain moisture level is necessary for the carbonation reaction to proceed.
- Finally, the "aging factor" q (Andrade, Castellote, D'Andrea, 2011) which accounts for the evolution with time of the porous microstructure.

These factors have been quantified to introduce them in an expression linking resistivity with time that will be described later.

Environmental factor F

The environmental factors F_{Cl} and F_{CO2} depend on the exposure conditions (Andrade, 1993; Andrade, 2004). Table 2 presents values that were calculated by inverse analysis of test results obtained on real structures.

Table 2. Values of environmental factors, kCl and kCO2, following the exposure classification of EN206

Exposure class	F (cm³Ω/year)
X0,XC1,XC2	200
XC3 moderate humidity	1000
XC4 cycles wet and dry	3000
XS1 (d > 500 m distance to the coast line)	5000
XS1 (d < 500 m distance to the coast line)	10000
XS2 submerged	17000
XS3 tidal	25000

Reaction factor r_b

The reaction factors r_{Cl} and r_{CO2} (Andrade et al, 2014) depend on the type and amount of cement and therefore on the reaction of the penetrating substance with the cement phases. Equation 3 can be expressed as:

$$D_{CO2} = \frac{F_{Cl,CO2}}{\rho_{ef} \cdot r_{Cl,CO2}} \tag{14}$$

The values can be calculated either by direct measurement, or indirectly by measuring the relation between the effective and apparent diffusion coefficients, or by calculation based on the cement composition. Table 3 presents examples of r_{Cl} values that were calculated based on test results obtained by comparing steady and non-steady diffusion coefficients.

Table 3. Examples of values of the reaction factor of chlorides, r_{Cl}, for 3 types of cement

Cement	r_{Cl}	Standard Deviation
CEM I	1.9	1.3

CEM I + silica fume	1.5	0.5
CEM IIA (with pozzolan and fly ash, in ≤ 20%)	3.0	2.1

Aging Factor q
It accounts for the refinement of the concrete pore system results in an increase of resistivity with time (Andrade, Castellote, D'Andrea, 2011). The resistivity evolves with time due to the progression of hydration, the combination of the cement phases with the chlorides or carbon dioxide which usually decreases the porosity and by the concrete drying out (depending on the environment. It can be calculated through the expression 15.

$$\rho_t = \rho_0 \left(\frac{t}{t_0} \right)^q \tag{15}$$

Where:
ρ_t = resistivity at any age t
ρ_0 = resistivity at the age of the first measurement t0
Values of q found for different cement types are given in table 4.

Table 4. Values of the ageing factor

Cement	***q***	**Standard Deviation**
I	0.22	0.01
II/A -P	0.37	0.06
II/A-V	0.57	0.08

The relation between q and the aging factor n of the diffusion coefficient gives the expression 23:

$$q = 0.8\, n \tag{16}$$

4.3 Propagation period
In the case of considering the propagation of corrosion (t_p), considering the loss in rebar diameter, or pit depth, (P_{corr}) as the limit corrosion attack, the service life of structure can be written by the expression 9:

$$I_{corr}\, (\frac{\mu A}{cm^2}) = \frac{Kcorr}{\rho_{ef}\,(Kohm.cm)} \tag{17}$$

The relation for the service life prediction can be then formulated as follows (16):

$$t_l = \frac{P_{corr} \cdot \left(\rho_{ef} \left(\frac{t}{t_0} \right)^q \cdot W_s \right)}{K_{corr} \cdot 0.00116} \tag{18}$$

Where:
P_{corr} = steel cross section reached at the time t_p
ρ_{ef} = resistivity at 28 days in saturated conditions

q = aging factor of the resistivity (Table 4)
ξ = environmental factor of the corrosion rate (it can be of 10±2 for carbonation and 30±5 for chlorides)
K_{corr} = constant with a value of 26 μA/cm²·kΩ·cm= to 26 mV/cm relating the resistivity and the corrosion rate I_{corr}
Complete expression of the service life model based in the resistivity.
Then, the final expression of the service life model based on resistivity is:

$$t_l = t_i + t_p = \frac{x_i^2}{V_{CO_2,Cl}} + \frac{P_{corr}}{V_{corr}} \tag{19}$$

$$t_l = \frac{x^2 \cdot \rho_{ef} \left(\frac{t}{t_0}\right)^q}{F_{Cl,CO_2}} \cdot r_{Cl,CO2} + \frac{P_{corr} \cdot \left(\rho_{ef} \cdot \left(\frac{t}{t_0}\right)^q \cdot W_s\right)}{K_{corr} \cdot 0.00116} \tag{20}$$

Example of application

For the initiation period the application of the above theory can be shown by way of example, assuming a concrete with a cover depth of 4 cm made with cement type I with silica fume (reaction factor = 1.5 and aging factor = 0,22) to be placed in exposure class XS3 (tidal and splash conditions). Considering a service life of 100 years, the values of the reaction, as well as the environmental and aging factors are presented in Table 5. The calculations indicate that the resistivity needed at 28 days of age, measured in saturated conditions, is 215 Ω-m.

Table 5. Input data for a calculation of the concrete resistivity

Cement type I with silica fume	r_{Cl} = 1,85
Exposure class (XS3)	F (cm³Ω/year) = 25000
Service life	t (years) = 100
Cover depth	X_{Cl} (cm) = 4
Ageing factor during 10 years	q = 0.22

$$4 = \sqrt{\frac{25000}{\rho_0 (\frac{100}{0.0767})^{0.22} \cdot 1.5} \cdot 100} \; \{ \; \rho_0(\Omega \cdot cm) = 21497 \rightarrow \boxed{\rho_0(\Omega \cdot m) = 215}$$

With this resistivity the length of the propagation period following Table 6 is:

Table 6. Input data for the propagation period

Limit Diameter loss, P_{corr}	100 μm = 0.01 cm
ρ_{ef} at 28 days	21.5 Kohm.cm
***q* applied during 100 years**	0.22
W_s in saturated conditions	1

$$t_l = \frac{0.01 \cdot \left(21.5 \cdot \left(\frac{100}{0.0767} \right)^{0.22} \cdot 1 \right)}{26 \cdot 0.00116} = 34.54 \text{ years}$$

This propagation period may be included in the 100 years or considered apart as an additional safe time until cracking is produced.

5. PRODUCTION OF CONCRETE FOR A SPECIFIED APPARENT RESISTIVITY

Once known the resistivity which is needed to reach a nominal service life, it remains to describe how the concrete producer can design a mix to fulfil the service life specification. This can be done (Andrade and D'Andrade, 2010) by considering a modification of Archie's law linking resistivity and porosity:

$$\rho_{28d} = \rho_o \cdot \varepsilon^{-\tau} \tag{21}$$

where ρ_{28d} is the resistivity of concrete under saturated condition at 28 days, τ is the tortuosity coefficient which is estimated by fit to the experimental data, and ε is the total porosity.
The coefficient τ depends on the concrete composition which is identified to the tortuosity, and could be determined from type or family of cement type by means of measuring the porosity and the resistivity. The values found in present research are. For type I cement τ= 1.9, for type II-AV τ= 2.3 and for type II AP τ= 1.6.
From the specified resistivity the paste porosity can be obtained and through Power's relation on porosity and w/c ratio

$$\varepsilon_p(\%volumen) \approx \frac{\left(w/c \right) - 0{,}36\alpha}{\left(w/c \right) + 0{,}32} \times 100 \tag{22}$$

To use ρ_p in the model based on Archie's law, it must convert the porosity of the paste (ρ_p) to porosity of the concrete (ρ). For this, it is applied a simple method based on multiplying the percentage of capillary porosity of the paste by the volume of paste (γ) in the concrete.

$$\varepsilon = \varepsilon_p \cdot \gamma \tag{23}$$

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 his cements.
So, the following concrete design methodology based on Archie's law model is proposed to achieve the prescribed value ρ_{28d}:

1. Select a type of cement. It fixes the values of reaction factor (r) and tortuosity (τ) are defined.

2. Select a w/c ratio and calculate porosity of the paste following Powers' model
3. Then calculate the expected resistivity through $\rho = \rho_o \cdot \left(\varepsilon_p \cdot \gamma\right)^{-\tau}$.

6. FINAL COMMENTS

Concrete is a very complex material but which is placed on site in many manners by relatively simple practices. It needs to be modelled by sophisticated models, but also by simple ones which could help to improve the quality and spread the tools for it. The electrical resistivity, being a non-destructive method simplifies very much the control of the durability. On the other hand, it enables multiple applications in concrete technology and the quantification of the expected life. It has been summarized some of the possible applications of the concrete electrical resistivity values. Its main advantage is that the measurement is non-destructive and the concrete can be monitored. Concrete resistivity is able to inform on:

- Porosity
- Degree of water saturation
- Degree of curing
- Cement setting time
- Concrete mechanical strength
- Reinforcement corrosion rate
- Gas and water permeability

In present paper is shown the fundamental relations of resistivity with diffusivity and with the reinforcement corrosion rate. Resistivity is the parameter enabling to link microstructure with the macro-performance Also has been summarized the model for service life prediction based in Einstein law relating electrical resistance or conductance with the diffusion coefficient. Making certain assumptions this basic law can be applied to the advance of carbonation front or chloride threshold, and to the representation of steel corrosion propagation. This model can be used for calculating cover thicknesses from actual resistivity values or the minimum resistivity for a certain cover thickness.

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