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Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure

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COMPETENCE CENTRE FOR ROADS & STRUCTURES

Monday, October 17, 2016 **Parallel Session 3** 17.30-18.30

	Auditorium	Senaatzaal	Frans van Hasseltzaal
	MS5: Building Information Models (BIM) for the Life-Cycle *Chairs: J. Bakker & A. Adriaanse*	GS3: Service Life Prediction *Chairs: C. Andrade & A. Miyamoto*	SS6: Dynamic Contracting: Optimal performance over the life cycle due to better cooperation between contact partners *Chairs: M. Hertogh & W. Leendertse*
17.30	Current situation and perspectives of the technique for the next decade ***E. Kortstee*** *& L. van der Geest*	Remaining life prediction of an aged bridge based on carbonation tests for cross-section cutting-off girders ***A. Miyamoto*** *& R. Kiviluoma*	Planning and contracting of transport infrastructure in a dynamic environment ***W. Leendertse****, T. Busscer, J. Arts & F. Verhees*
17.45	TRIMS: A risk-based information model to manage object data ***M. Bakx-Leenheer*** *& A. Lutterop*	Corrosion modelling and performance Indicators ***C. Andrade****, N. Rebolledo & F. Tavares*	In search for contract flexibility in a dynamic environment: A theoretical framework ***H.C. Demirel****, L. Volker, M. Hertogh & W. Leendertse*
18.00	Government's perspective on BIM and sustainability in transport infrastructure in Europe and China ***Y. Liu****, S. van Nederveen & M. Hertogh*	Determining the remaining lifespan of concrete structures *T.W. Groeneweg, J.G.A. van Hulst &* ***J.G.A.M. Reinders***	Life-cycle performance as results of basic design considerations ***S. Zmigrodzki***
18.15	BIM supporting economic optimization of seismic retrofit of existing structures ***U. Vitiello****, A. Salzano, D. Asprone & A. Prota*	About the economic life prediction for existing RC buildings ***M. Vona****, P. Harabaglia, M. Mastroberti & B. Manganelli*	

Corrosion modelling and performance Indicators

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Institute of Construction Sciences Eduardo Torroja

ABSTRACT: Reinforcement corrosion is recognized to be the most detrimental damage for concrete structures due to its economic consequences and cost of preventive measures. This situation has promoted the modelling of the corrosion process initiation and the use of Indicators to define concrete quality for new structures, such as the Rapid Chloride Permeability test. In present work, it is analyzed the models used for corrosion initiation prediction and their limitations, as well as the performance indicators that have being proposed to qualify the concrete resistance against the progress of chlorides and carbonation. Among these indicators particular attention is paid to the use of the electrical resistivity to characterize both the initiation and propagation phases of corrosion. Finally is proposed the definition of Performance Indicator to such property which could inform on the degree of damage or anomalous performance and that could be monitored through sensors placed on the structure in order that these measurements could save the need of visual periodic inspections.

1 INTRODUCTION

Concrete durability Codes and Standards in general contain provisions related to: the concrete materials, the limit of dangerous substances, such as chlorides or sulphates, limitations to the crack width transversal to the reinforcement and 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. In this respect, first Collepardi et al. (1970) and Bazant (1979) and later Tuutti's (1982) proposal on the definition of service life by dividing it into the initiation period, t_i, and propagation period, t_p, have marked an important milestones.

$$t_{life} = t + t_p \qquad (1)$$

Numerous further attempts trying to quantify both t_i and t_p have been later 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. Another recent trend to avoid the uncertainties related to models is the use of "durability indicators" (Baroghel-Bouny 2002) based in the so called "performance" concept. 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.

1.1 *Multilevel Verification of Durability*

The consideration of the several approaches to durability calls to propose their classification in categories. The classification can be made in different manners (Andrade et al. 2000). In this paper three categories are identified (table 1). Regarding the design level they are: deterministic, semi- or full probabilistic and with respect to the verification method also three levels are used today: I) Deemed to satisfy rules contained in present standards II) Performance Indicators that are concrete properties or performance results and III) the models in which the time is explicit in the formula. The main aspect to be considered regarding table 1 is that all the results should be coherent between themselves which means that all levels shoud classify similarly which is not an easy task because different concrete mixes can lead into similar durability.

Table 1. Verification of Durability by three categories (Andrade et al. 2000).

DURABILITY DESIGN LEVEL		I	II	III
Reliability level		Deterministic	Semi-probabilistic	Probabilistic
Durability Verification level	I	Code rules	Code rules	
	II	Performance Indicators	Performance Indicators	Performance Indicators
	III	Models using Time	Models using Time	Models using Time

1.2 *Performance approach and modelling*

This modern development supposes to design durability, not by specifications but by defining a "performance". With regard to the durability.until present there were two basic different manners to specify a performance approach: 1) by methods indirectly related to durability which characterize a particular concrete property, as can be: porosity, permeability, resistivity or diffusivity, and 2) or by methods directly related to durability which characterize the response of the concrete to a particular aggressivity, as is the case of testing sulphate resistance by measuring the expansion or the loss in mechanical strength. In both cases the concrete property is ranked assuming a certain not specified service life. This trend of defining a performance 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 (Whiting 1981) and that is used by defining a target value of 1000 coulombs to be fulfilled by the concrete.

More recently, models with the time explicit in the mathematical formula are focussing the interest and service lives of 100 years is now a somehow common specification for special structures (Maage 1996, Mangat & Molloy 1994, Bamforth & Chapman-Andrews 1994). Thus, models based in Fick's second law of diffusion are proposed and introduced in analytical and numerical models that are available through internet or can be developed by the user. The Model Code 2010 (2012) has incorporated models for chloride penetration, carbonation and other deterioration mechanims. Although to specify a target service life and a mechanism of attack seems and advance with respect to the classical approach of deemed-to-satisfy rules for concrete mix, the situation from a practical point of view is however complex, because there are still several undetermined parameters in the application of chloride or carbonation models which being assumed introduce uncertainties (Gulikers 2006, Andrade et al. 2006). Additionally, as the models are relatively new, they are not calibrated in the same concrete with long term records, which means that there are not cases in which short term tests were performed time ago and verification now could confirm the adequacy of the prediction. The longest timeframe for the calibration of models is around of 20-30 years.

One of the problems in the models is related to that the initial and boundary conditions of the solution of the diffusion law (Gulikers 2006, Andrade et al. 2006) are not fulfilled in the real structures. This is due to both, the surface concentration, C_s, and the diffusion coefficient, D_{ap}, are not constant along the structure's life. This lack of constancy depends on the environmental conditions and of the cement type. Another key aspect of the calculation of service life in chloride bearing environments is the selection of a chloride threshold, Cl_{th}, which is not a fixed value together with the definition of full absence of corrosion as limit state. In the MC 2010 is proposed for steel corrosion, a probability of 10% (a reliability index β = 1.3) typical of serviceability limit states, SLS. The meaning of the probability percentage of depassivation has not been justified in terms of real structural performance. Finally the MC 2010 does not propose any model for the propagation stage of corrosion. The evolution of corrosion depends on the concrete porosity and its moisture state and models have been defined time ago.

Another present trend is related to the application of structural reliability principles to service life as incorporated in Model Code 2010 (2012). The structural design is made through the identification of limit states which are defined through Limit States Functions. The difficulty of this approach is the lack of data on the statistical distributions of the input parameters. As mentioned, the surface concentration and the D_{ap} value evolve with time and additionally they have a scatter which is unknown because no records exit. On the concrete cover there are more studies showing that a coefficient of variation from 15% to 30% can be reasonable. The same uncertainty exists on the critical chloride content that it is not a fixed quantity as it is influenced by several variables, Then, as in the other input parameters the designer has no clear indication on which value and which statistical distribution to adopt. This makes the design very expert-dependent. Results are always obtained, but how them will be certain in 100 years is challenge.

In present paper is presented a model for servie life of the reinforcement based in the electrical resistivity of the concrete which tries to overcome some of the diffisculties of the traditional models. It has two main advantages: the measurement methhod is non-destructive and can be repeated in the same specimen or can be applied on site in the real structure and it takes into account the propagation period as the resistviity is proportional to the corrosion rate.

1.3 *Electrical resistivity as unique parameter for initiation and propagation periods modelling*

Responding to the interest of finding performance parameters or durability indicators that, being suitable for quality control, could also be applicable for modeling service life, the electrical resistivity of concrete appears as a very promising selection (Andrade 1993). 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 Ω.m), inverse of the conductivity, is the property of the material that reflects the ability to transport electrical charges. It is a volumetric standarization of the electrical resistance (R_e), which by Ohm's Law is expressed as the ratio of voltage and current applied ($R_e = V/I$) (figure 1). The current applied by means of two electrodes is transported through the aqueous phase of concrete pore network by the electrical carriers (ions), because the solid cement phases are not able to conduct electrical charges.

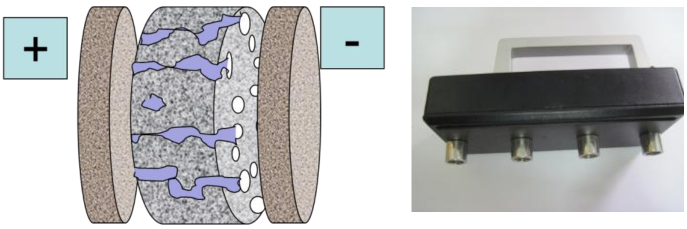

Figure 1. Left: direct, the electrical resistivity is the ratio between voltage applied with two electrodes and circulating current standariez to a regular geometry. Right: four points or Wenner method.

1.4 *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) (see figure 2) due to 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 time power exponents for OPC than for blended cements and should to be taken into account for estimating resistivity at different ages.

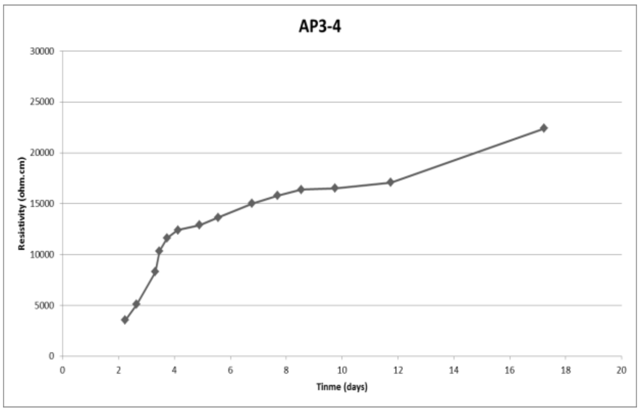

Figure 2. Evolution of resistivity of a concrete in saturated conditions during hardening

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. 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. An increase in temperature should increase diffusivity, D, and corrosion rate, V_{corr}, however this increase in temperature may at the same time produce an evaporation, which in turn would effect on the opposite in both, D and V_{corr}. Therefore, the calibration by the models of the real effect of temperature on the prediction is, by large, still very seldom and uncertain.

1.5 *Resistivity and Diffusivity*

The relation between resistivity and Ficks law on diffusion is based in one of the Einstein laws (see figure 3) which relates the movement of electrical charges to the conductivity of the medium (Andrade 1993), where D_s= effective or steady-state diffusion coefficient, $F_{Cl,CO2}$ is a factor, which is dependent to the external aggressive concentration, ρ_e 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 3.

$$D_e = \frac{k_{Cl,CO2}}{\rho_e} = F_{Cl,CO2}\,\sigma \quad (2)$$

In consequence, if $F_{Cl,CO2}$ is established, the diffusion coefficient of the chloride ion or carbonation in concrete can be calculated providing that there is not interaction between aggressive substance 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”).

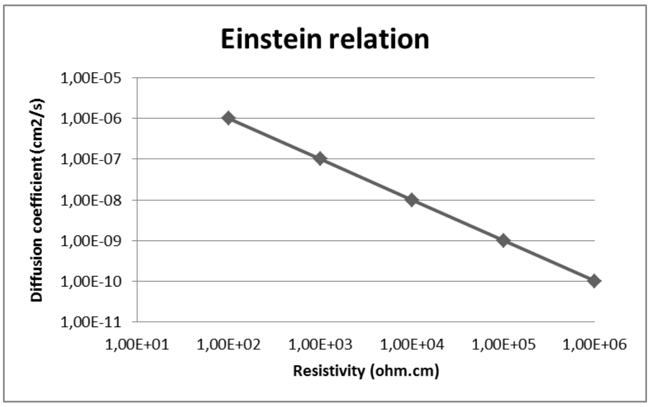

Figure 3. Relation between resistivity and diffusivity as (effective without binding effects) calculated from Einstein law

2 SERVICE LIFE MODEL BASED IN THE RESISTIVITY MEASUREMENTS

2.1 *Modification of Einstein law*

As mentioned, the above expression 2 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 1 (Andrade 2004) to account for these effects together with the value of the $F_{Cl,CO2}$ factor which takes into account the concentration of the chloride ions or aggressive substance.
The factors then introduced in the equation 1 in order to apply it to concrete have been:

- $F_{Cl,CO2}$ has been named "environmental factor". It depends on chloride concentration and in the case of carbonation, on the concrete moisture content
- r_b "retarder or reaction factor" which multiplies the resistivity to account for the "retarder" effect of chloride binding during penetration of chlorides or of the carbonation (the carbonation progresses when the concrete is partially saturated by the empty ore voids). That is, as higher is the porosity or the empty pores due to dry conditions, higher the carbonation depth will be but however, a certain moisture level is necessary for the carbonation reaction to proceed.
- Finally, the "aging factor" *q* (Andrade 2011) which accounts for the evolution with time of the porous microstructure.

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

2.1.1 *Environmental factor F*

The environmental factors F_{Cl} and F_{CO2} depend on the exposure conditions (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, k_{Cl} and k_{CO2}, following the exposure classification of EN206

Exposure class	F ($cm^3\Omega$/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 sumerged	17000
XS3 tidal	25000

2.1.2 *Retard factor r_b*

The retard or reaction factors r_{Cl} and r_{CO2} (Andrade 2004) depend on the type and amount of cement and therefore on the reaction of the penetrating substance with the cement phases. Equation 2 can be now expressed as:

$$D_{CO2} = \frac{F_{Cl,CO2}}{\rho_{ef} \cdot r_{Cl,CO2}} \qquad (3)$$

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

2.1.3 *Aging Factor q*

It accounts for the refinement of the concrete pore system results in an increase of resistivity with time (Andrade 2011). The resistivity evolves with time due to the progression of hydration and by the combination of the cement phases with the chlorides or carbon dioxide. It can be calculated through the expression 4:

$$\rho_t = \rho_0 \left(\frac{t}{t_0} \right)^q \qquad (4)$$

Where: ρ_t = resistivity at any age t and ρ_0 = resistivity at the age of the first measurement t_0.

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

2.2 *Service Life Model*

The model proposed (Andrade 2004) is based on the measuring of electrical resistivity for its use as the main parameter for determining both t_i and t_p periods. For the initiation period, the estimation of the penetration of an aggressive front can be modelled by the simplest equation of the "square root of time", or "time lag" expression.

$$x_i = V_{CO2,Cl} \cdot \sqrt{t} \qquad (5)$$

The propagation period is directly proportional to the corrosion rate taking into account the loss in rebar diameter, or pit depth, (P_{corr}) as the limit corrosion attack, (Andrade et al. 1990):

$$I_{corr}\left(\frac{\mu A}{cm^2}\right) = \frac{K_{corr}}{\rho ef\,(Kohm \bullet cm)} \qquad (6)$$

Then, the general expression of service life can be formulated as follows:

$$t_l = t_i + t_p = \frac{x_i^2}{V_{CO_2,Cl}} + \frac{P_{corr}}{V_{corr}} \qquad (7)$$

A model based in the resistivity as unique controlling parameter of both periods calls for expressions having this parameter in both terms. For the initiation period, $V_{CO2,\,Cl}$ is proportional to the square root of the diffusivity and is then the inverse of the resistivity:

$$V_{Cl,CO2} = \sqrt{D = \sqrt{F_{Cl,CO2} / \rho \cdot r_{Cl,CO2}}} \text{ (6)} \qquad (8)$$

In the case of the propagation period, expression 6 can be written in function of the resistivity:

$$t_l = \frac{P_{corr} \cdot \left(\rho_{ef}\left(\frac{t}{t_0}\right)^q \cdot W_s\right)}{K_{corr} \cdot 0.00116} \qquad (9)$$

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, W_s = 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 $\mu A/cm^2 \cdot k\Omega \cdot cm$= to 26 mV/cm relating the resistivity and the corrosion rate I_{corr}.

Then, the final expression of the service life model based on resistivity is:

$$t_l = \frac{x^2 . \rho_{ef}\left(\frac{t}{t_0}\right)^q}{F_{Cl,CO_2}} \cdot r_{Cl,CO2} + \frac{P_{corr} \cdot \left(\rho_{ef} \cdot \left(\frac{t}{t_0}\right)^q \cdot W_s\right)}{K_{corr} \cdot 0.00116} \qquad (10)$$

3 APPLICATION OF RESISTIVITY MODEL TO THE NEW LOCKS OF PANAMA CANAL

The works of the new locks of Panama Canal started in 2011 being built by a Consortium named GUPC: Grupo Unidos por el Canal. In the concrete Technical specification it was prescribed to fulfil 1000 coulombs with no definition of the age and to use a service life model to demonstrate compliance with 100 years of service life. These prescriptions were considered not fulfilled in the initial trials of concrete mixes by the Authority of Panama Canal (ACP). After being invited to collaborate the authors of this communication suggested: a) different prime materials and batching to manufacture a series of alternative concrete mixes; b) the testing of natural chloride diffusion (ponding tests) and continuous monitoring by measuring electrical resistivity over time; and c) the use of LIFEPRED, a numerical model based on Fick's law for calculating service life.

The results indicated that the resistivity was equivalent to the rapid Chloride Permeability test (figure 4) and in addition provided the values (see table 5 of some mixes and) of the aging factors in a non-destructive manner. Table 5 gives the age factors obtained from 38- and 120-day data, the 38- and 120-day. Diffusion coefficients obtaining from natural diffusion tests are shown in Figure 6 for all the mixes except A3 and P3, whose tests were conducted on the 14-month materials only.

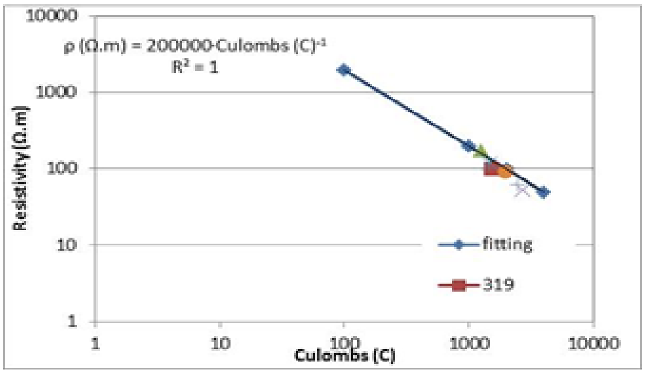

Figure 4. Relationship between electrical charge in coulombs and resistivity.

Table 5. Age factor values found from variations in resistivity over time

38/120-DAY RESISTIVITY AGE FACTOR						
mixes	SMC-A11	SMC-P11	SMC-A50	SMC-P50	SMC-A56	SMC-P56
Age factor	0.492	0.584	0.349	0.609	0.629	0.718

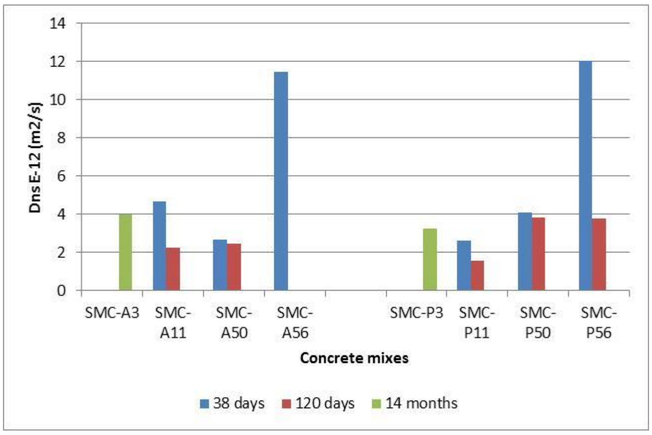

Figure 6. Diffusion coefficients at 38- and 120-day for all mixes except A3 and P3 (tested after 14 months only).

Figure 7 gives the values of resistivity and their evolution with time. The dashed horizontal line shows the equivalence to 1000 coulombs, which is overpassed with time by all mixes.

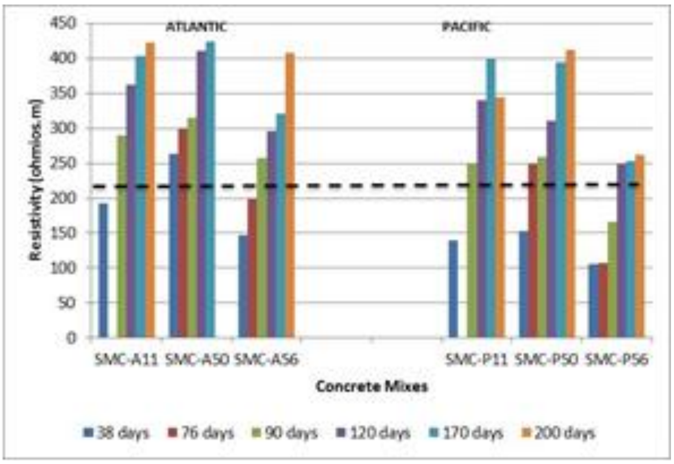

Figure 7. Relationship between electrical charge in coulombs and resistivity.

Finally, figure 8 shows the comparison between the results of calculation of service life through LIFEPRED program and the resistivity model of equation 2 for the mixes studied with three cover depths: 100, 125 and 150 mm. Both methods give very similar values of the expected service life.

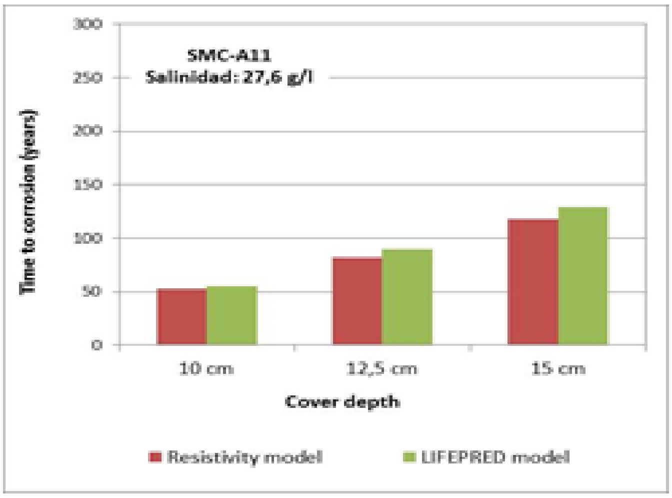

Figure 8. Service lives found with the LIFEPRED program and the resistivity model of equation 2 for high and extra-high salinity and three cover depths

4 SUMMARY COMMENTS

The prediction of service life of concrete reinforcement is still a subject of research because the methods of calculation and the tests have not been yet validated at long term. All the results should be taken with precaution and used more as a rational and expert engineering assessment, than a mathematical precise calculation. Comparison of real and laboratory results and validation of the prediction models is very necessary.

In present paper is presented a model based in the electrical resistivity which has been applied to the calculation of the service life of concrete mixes used in the new locks of Panama Canal together with the traditional models based in Fick's law. Its main advantage was its non-destructive character.

ACKNOWLEDGEMENTS

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