Concrete Mixture Design Based on Electrical Resistivity

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ABSTRACT

Current codes have requirements for the durability design of concrete based on compressive strength and provisions related to cement content and water – cement ratio. However, such requirements do not take into account important parameters related to the behaviour of concrete against to aggressive attack. The electrical resistivity of the hardened concrete is related to connectivity of pores network under saturated condition.. This paper proposes a methodology of design based on the Archie law, which is originated from the concept of diffusion and provides properties such as electrical resistivity, porosity, and tortuosity, for estimating the ideal mix of concrete (maximum water cement, the minimum content of cement and cement type) for a specific environmental class and service life. It also considers the chemical reaction of chloride and carbonation with the phases of cement, so called factor of reaction (r) which depends on the type of cement and indicates the delay on the agressive penetration.

INTRODUCTION

Due the need to assess the durability of reinforced concrete structure, mainly in terms of corrosion process of the reinforcement, there is a trend of incorporating more advanced concepts of sustainability in rules of project. There are many proposals of models based on mechanisms of attack for the prediction of service life [Page, 1981; Tuutti, 1982]. However, despite the obvious importance of taking into account the real behaviour of concrete for calculating the service life, only some of these models are based on the properties of concrete obtained experimentaly by means the consideration of durability indicators [Andrade and Alonso, 1997; Baroguel-Bouny et al., 2004].

At the present communication it is proposed a design methodology of concrete mix based on the use of indicator of durability obtained from a simple test method used in production quality control. The durability indicator chosen for the proposal has been the electrical resistivity [Monfore, 1969, Alonso et al., 1988, Andrade et al., 2000]. The classical Archie's law model is also referred is this proposal.

The Archie's law comes from the concept of diffusion of substances in saturated rocks, and includes properties such as electrical resistivity, porosity, and tortuosity of the porous network. Therefore, the present proposal raises the use of this model to estimate the appropriated concrete mix (maximum water-cement ratio, minimum cement content and type of cement) for achieving the prescribed resistivity for garantee the durability of structure exposed to a aggressive environmental class and specific service life.

The prescribed electrical resistivity will be the "apparent resistivity", which is expressed by means $p_{ap}=\rho * r$), where ρ is the resistivity obtained from experimental test and r is the reaction factor (r) that takes into account the interaction of the phases of the cement with the aggressive. The prescription of the resistivity ρ_{ap} values is based on the service life model to assess the reinforcement corrosion proposed in another publication [Andrade et al., 2006], which is not discussed in this paper.

EXPERIMENTAL PROCEDURE

It has studied 22 different dosages, where 9 of them were prepared using cement type I and others one using type II cement with 6 to 20% of fly ash (V) or natural pozzolana (P).

These concretes were tested using the Wenner method to assess the electrical resistivity [Polder et al., 2000)] and the method of mercury intrusion porosimetry for (MIP) for determining the total porosity. The Table 1 shows the concrete mixes studied and the results of tests.

THE RESISTIVITY AND THE MICROSTRUCTURE

The electrical resistivity (ρ in unit Ω.m), inverse of conductivity, it is a volumetric measurement of electrical resistance (Re in Ω unit), which is expressed by Ohm's law as the relation between voltage and current (Re = V / I). It was developed initially in the field of geophysics [Wenner, 1915] and reflects the ability of the porous medium for the transport of electric charge in a volume semi-infinite [McCarter and Garvin, 1989]. The electric current is conducted through the network of interconnected pores for the movement of ions (I), which generates a potential difference (V) between the electrodes.

In a porous medium such as concrete, the resistivity reflects the ability to transport electrical charge on the ions dissolved in the aqueous phase of a given volume, [Hansson et al., 1985], assuming the aggregates as electrically inert because their resistivity is several orders of magnitude higher than the pore solution one.

Since the solution of the pores is only a volume fraction of the total, it could be expressed as equation (1), where ρ_0 is the resistivity of pore solution (approximately 0.5 Ω. m) [Buenfeld et al., 1986; Goni and Andrade, 1990] and ϕ is the volume fraction of liquid in the pores (non-saturated, $\phi<\varepsilon$, pore volume, saturated ε , ϕ = pore volume):

$$\rho = \rho_0 \cdot \phi \qquad (1)$$

Table 1. Concrete mixes and test results

N	Cement (C)		Water	w/c	Resistivity (□.m)	Porosity (% in vol) MIP
	Type	Kg/m^3	l/m^3			
I-1	CEM I 42,5 R	275,0	165,0	0,60	62,1	6,77
I-2	CEM I 42,5 R	275,0	165,0	0,60	77,4	9,32
I-3	CEM I 52,5 R	300,0	180,0	0,60	65,9	10,07
I-4	CEM I 52,5 R	300,0	165,0	0,55	71,2	7,28
I-5	CEM I 52,5 R	300,0	150,0	0,50	87,6	7,24
I-6	CEM I 52,5 R	350,0	157,5	0,45	108,5	7,93
I-7	I 42,5 R/SR	400,0	180,0	0,45	179,5	8,94
I-8	CEM I 52,5 R	450,0	202,5	0,45	84,2	6,38
I-9	CEM I 52,5 R	450,0	166,5	0,37	107,4	6,25
II-1	CEM II/A-P 42,5 R	310,0	175,0	0,56	49,7	12,19
II-2	CEM II/A-P 42,5 R	355,0	180,0	0,51	45,3	4,67
II-3	CEM II/A-P 42,5 R	400,0	180,0	0,45	50,7	7,63
II-4	CEM II/AV 42,5 R	275,0	165,0	0,60	43,4	7,58
II-5	CEM II/AV 42,5 R	300,0	150,0	0,50	54,5	14,30
II-6	CEM II/AV 42,5 R	320,0	185,6	0,58	68,8	9,76
II-7	CEM II/A-P 42,5 R	344,0	203,0	0,59	14,1	17,37
II-8	CEM II/AV 42,5 R	300,0	165,0	0,55	76,8	8,67
II-9	CEM II/AV 42,5 R	320,0	176,0	0,55	84,8	11,18
II-10	CEM II/A-P 42,5 R	340,0	187,0	0,55	37,0	17,20
II-11	CEM II/A-P 32,5 R	350,0	182,0	0,52	28,5	11,68
II-12	CEM II/A-P 42,5 R	425,0	208,3	0,49	18,5	13,94
II-13	CEM II/A-P 42,5 R	380,0	182,4	0,48	20,3	12,31

In 1942, Archie [Archie, 1942] concluded in the study of rocks saturated with salt water that the expression (1) does not take into account the tortuosity of the pores, which makes the distance between the faces of the geometric volume be different of the apparent length. Therefore, Archie proposed the expression known as Archie's law, which is presented and applied following.

PREDICTION OF RESISTIVITY BY MEANS THE ARCHIE'S LAW

In this chapter it is estimate the electrical resistivity of hardened concrete at 28 days under saturated condition by means the model based on Archie's law (2) [Archie, 1942], which relates the value of electrical resistivity (ρ), the porosity of the material (ε) and other aspects of the microstructure (τ). Where the initial resistivity ρ_0 is approximately the resistivity of pore solution, and a is approximately equal to 1.

$$\rho = \rho_o \cdot a \cdot \varepsilon^{-\tau} \qquad (2)$$

To validate the mentioned expression, the graph in Figure 1 shows the fit of potential function form of the Archie's law model ($y = ax^b$) to the relation between the resistivity measured at 28 days of curing and total porosity by the MIP method, both obtained by concrete mixes studied.

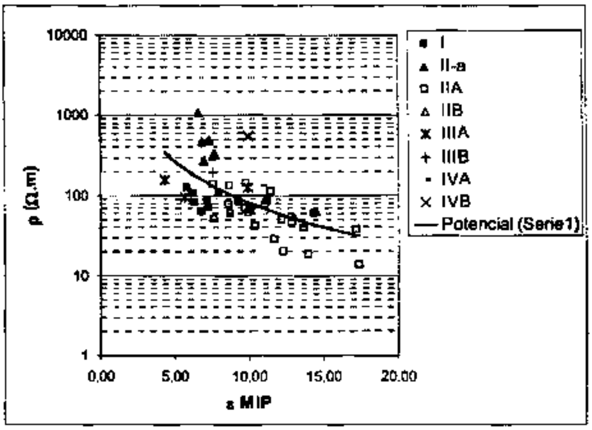

Figure 1. Relationship between parameters of electrical resistivity and total porosity of concrete studied

The coefficient τ depends on the concrete composition reflected by the tortuosity, and could be determined by adjustment to experimental results. The equation based on the law of Powers [Powers et al. 1959] is used to estimate the capillary porosity of the paste. Thus, modifying equation (2), it is obtained the following expressions (3):

$$\rho_{28d} = \rho_o \cdot \varepsilon^{-\tau} \qquad (3)$$

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.

Assessment of tortuosity coefficient ,τ

The coefficient τ represents the formation of porous network as connectivity and tortuosity, being one of the most importante factor which influences the electrical resistivity, and is estimated within the range between 1 and 2 according to [Wong et al., 1984]. Therefore, it is represent in Figures 2, 3 and 4, the adjustment of equation (3) by the method of least squares to the relationship between total porosity (ς) obtained from MIP method and resistivity at 28 days (ρ), for concretes prepared with cements I, IIA and IIA-V-P, respectively.

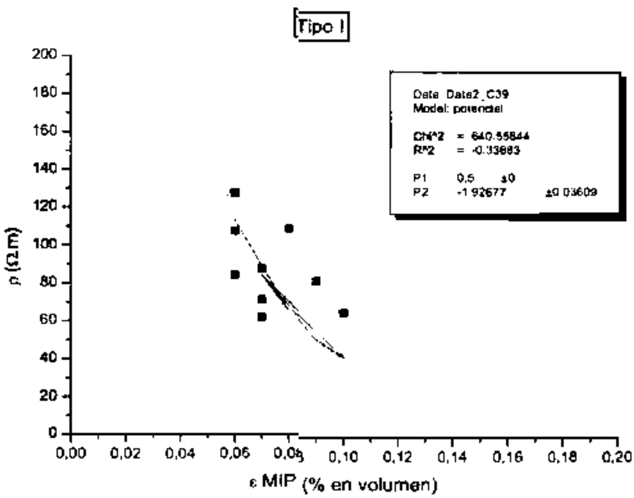

Figure 2. Relationship between electrical resistivity (axis y) and total porosity of concrete (axis x) with Type I cement.

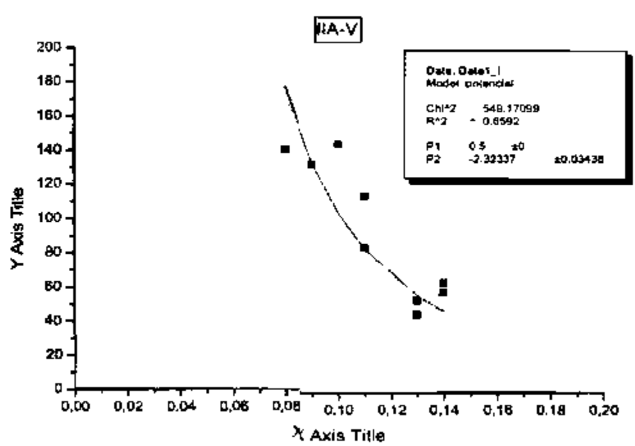

Figure 3. Relationship between electrical resistivity (axis y) and total porosity (axis x) of concrete with cement type IIA-V

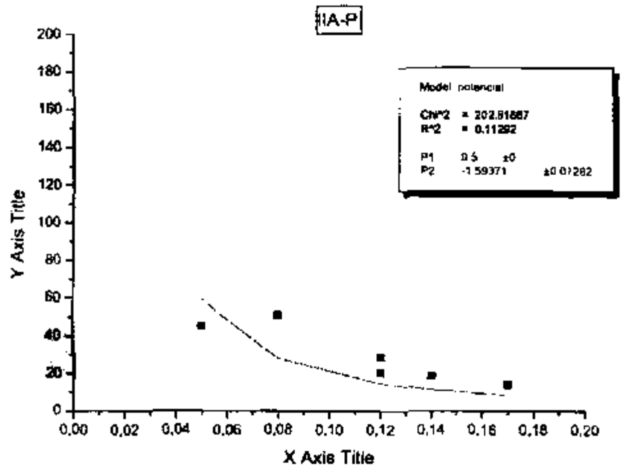

Figure 4. Relationship between electrical resistivity (axis y) and total porosity (axis x) of concrete with cement type IIA-P

Although it is not appreciated satisfactory correlation coefficients (R^2) for the presented relationships, it is observed different values for τ which are clearly dependent on the type of cement. On this basis, it is considered as estimated value of τ those obtained from adjustment of potential functions rounded to one decimal for each type of cement.

Therefore, the following τ values has been obtained:

- - For cement type I; τ = 1.9,
- - For cement type IIA-V; τ = 2.3,
- - For cement type IIA-P; τ = 1.6.

Calculation of porosity ε by means the Powers equation

Powers [Powers et al. 1959] has proposed the familiar expression for calculating the "capillary porosity" of paste, ε_p (4), where α is the degree of hydration of cement and w / c the water-cement ratio.

$$\varepsilon_p(\%volumen) \approx \frac{\left(w/c\right) - 0{,}36\alpha}{\left(w/c\right) + 0{,}32} \times 100 \qquad (4)$$

In order to use ε_p in the model based on Archie's law, it must convert the porosity of the paste (ε_p) to porosity of the concrete (ε). For this, it is applied a simple method based on multiply the percentage of capillary porosity of the paste to the volume of paste (γ) in the concrete (5).

$$\varepsilon = \varepsilon_p \cdot \gamma \qquad (5)$$

The percentage of paste in concrete (γ) is estimated using the expression (6) of the relationship between the volume of paste and concrete volume.

$$\gamma_{pasta}(\%_{vol}) = \frac{Vol_{pasta}}{Vol_{hormigon}} \approx \frac{\left(\dfrac{Cemento(Kg)}{\delta cemento\left(Kg/m^3\right)} + \dfrac{Agua(Kg)}{\delta agua\left(Kg/m^3\right)}\right)}{1000\left(m^3\right)} \qquad (6)$$

Regarding the value of α, it is assumed approximate values of the degree of hydration at 28 days as observed in some studies [Lam et al., 2000, Chen and Brouwers, 2004 , Wang et al., 2004; Pane and Hansen, 2005]. In according to the authors, α depends on not only of the type of cement, but also on the strength, w / c and curing process. However, in order to simplify the analysis, constant values of α at 28 days of curing are applied to the model of Powers (4) for different type of cement, as the following: Type I = 0.80, IIA-V = 0.65 (α values to IIA-P cement have not been found in the literature).

Validation of model

The validation of the model based on Archie's law (3) is carried on assuming the values of parameters γ, τ and ε as presented at the beginning of the document, which are shown in table 2 for the studied concretes with cement types I and IIA-V, since it is not found in the literature values for cement α IIA-P as mentioned before.

Finally, it is represent at the graphic in Figure 5 the relationship between estimated resistivity values and measured ones in the concrete at the age of 28 days. Althought it is observed some scattering, especially to cements which contain fly ash, it is appreciated an satisfactory adjustment to calculated and measured values at 28 days.

Table 2. Parameters obtained by Archie's law model

Concrete	ρ 28d (Ω.m)	Calculation of ε				m	ρcalculated (Ω.m)
		α approach	εp	γ	εcalc		
I-02	62,1	0,80	0,34	0,25	0,09	1,9	52,8
I-03	77,4	0,80	0,34	0,33	0,11	1,9	32,5
I-05	65,9	0,80	0,34	0,28	0,09	1,9	44,8
I-06	71,2	0,80	0,30	0,26	0,08	1,9	62,4
I-07	87,6	0,80	0,26	0,25	0,06	1,9	93,3
I-10	108,5	0,80	0,21	0,27	0,06	1,9	116,0
I-11	179,5	0,80	0,21	0,31	0,07	1,9	90,0
I-13	84,2	0,80	0,21	0,35	0,07	1,9	71,9
I-19	107,4	0,80	0,21	0,31	0,07	1,9	89,9
IIA-05 (V)	54,5	0,65	0,40	0,25	0,10	2,3	77,6
IIA-06 (V)	68,8	0,65	0,40	0,32	0,13	2,3	45,7
IIA-15 (V)	76,8	0,65	0,36	0,26	0,10	2,3	88,5
IIA-16 (V)	84,8	0,65	0,36	0,28	0,10	2,3	76,8
IIA-23 (V)	84,7	0,65	0,32	0,23	0,07	2,3	162,4

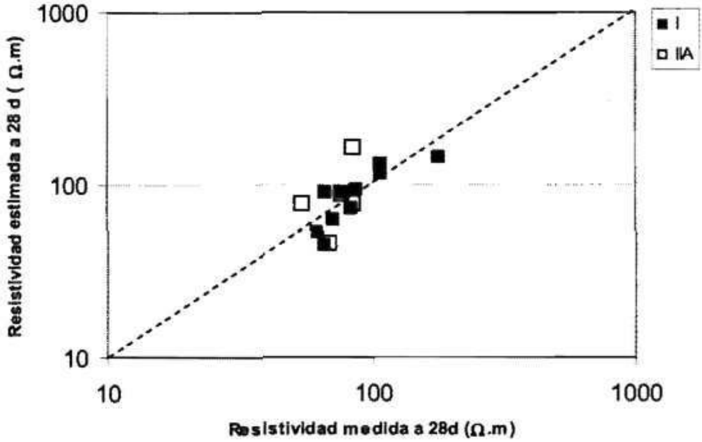

Figure 5. Relationship between the values of resistivity, measured at 28 days and estimated from the model based on Archie's law

So, the following concrete design methodology based on Archie's law model is proposed to achieve the prescribed ρ value:

1) Once chosen the type of cement, the values of reaction factor (r) and tortuosity (τ) are defined.

2) Defined at the first moment w/c ratio and cement content to th concrete of interest, both are used to estimate the porosity. The w/c ratio is applied in the Powers' model to calculate the porosity of paste ε_p (4), and, then, the cement content is used to estimate the porosity of concrete ε, where $\varepsilon = \varepsilon_p \gamma$.

3) The validation of chosen w / c ratio and cement content for achieving prescribed ρ is verified by means the application of Archie's law model $\rho = \rho_o \cdot (\varepsilon_p \cdot \gamma)^{-\tau}$. In the case of failure to achieve the goal, a complementary step should be taken, which could be by choosing another type of cement with other values of r and τ or by modifying the values of w / c and c to achieve it.

4) Finally, the real perfomance of designed concrete is checked experimentaly by the measurement of resistivity of saturated concrete at 28 days (ρ), through the expression ρ_{ap} / r.

CONCLUSIONS

The proposed design methodology is an original and unique method that is capable of guiding the designer and concrete producer on how to design the ideal mix to achieve the required electrical resistivity according to the characteristics of exposure and expected serviced life for the structure, taking into account the dosage, type of cement used, and the minimum cover required for reinforcement. Moreover, being a nondestructive method to determine the resistivity, it can be applied in the production control to assess the durability of the material quickly and cheaply, applicable on the same specimen used for the control of compressive strength .

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