ESTIMATING LONG-TERM DURABILITY PARAMETERS BASED ON ELECTRICAL RESISTIVITY MEASUREMENTS

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Abstract

Concrete's electrical resistivity is one of the main parameters controlling the initiation and propagation of reinforcement corrosion. It is common knowledge that concrete electrical resistivity is mainly dependent on the porosity, temperature and the moisture content. This research work studies the possible relationship between concrete electrical resistivity and compressive strength of concrete. It is intended to evaluate the possibility of predicting the strength gain of concrete at a given time using the resistivity measurements. Furthermore, in order to take account of temperature effect, the variation of resistivity due to temperature is studies.

Results obtained indicate that there is a strong relationship between compressive strength at a given age and the electrical resistivity. A relationship for prediction of the compressive strength using electrical resistivity of concrete is suggested that allows the estimation of the compressive strength based on the electrical resistivity value. Furthermore, it was observed that temperature has a significant influence on the electrical resistivity of concrete. Based on test results, a relationship similar to the Arrhenius equation is also suggested that can be used for prediction of electrical resistivity with temperature.

It is suggested that a method, similar to the maturity method for predicting the strength gain with time and temperature, can be used successfully to account for prediction of electrical resistivity with time and temperature. Based on this method, the electrical resistivity and compressive strength of concrete at 28 days is predicted using values of electrical resistivity of up to 4 days. Errors in estimates were less than 15 %. If values of up to 7 days are used, the error associated with the estimates is less than 5 %.

1. INTRODUCTION

The electrical resistivity of concrete is one of the main parameters controlling the initiation and propagation of reinforcement corrosion. The prediction of electrical resistivity values is of interest for both the durability design of concrete structures and the necessary update of the service life design performed. Electrical resistivity is a non-destructive test that can be easily performed on the surface of the structure or in the laboratory on the concrete specimens.

Concrete compressive strength development is crucial for concrete quality control program and on time removal of formworks on the construction site. This is commonly performed on specimens cast during construction. Little or no information on the compressive strength of the actual finished structure is normally determined.

Establishing a relationship between compressive strength and electrical resistivity is important because it would allow large areas of a structure to be tested, indirectly, with regards to estimating the actual compressive strength. Modelling the development of the electrical resistivity with time and temperature may be used for both long term values for durability design update and predicting the gain in compressive strength.

2. EXMPERIMENTAL PROGRAM

The experimental program dealt with two complementary issues. One related to the effect of temperature on the resistivity of mortar specimens and the second related to establishing the relationship between compressive strength and electrical resistivity development with time.

Results will be used for analysing the possible relationships and proposing models for predicting the compressive strength development based on electrical resistivity measurements and predicting the development of electrical resistivity with time and temperature.

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2.1 Materials and mixes

Portland cement used in this research work was cement type CEM I 42.5 R. Tables 1-3 show the chemical, physical and mechanical properties of the cement. Two aggregates were used: river sand with a module finesse of 2.9 and a maximum particle size of 2.4 mm; and a crushed granitic coarse aggregate with a finesse module of 6.6 and a maximum particle size of 12 mm.

Table 1 – Chemical composition

Composition	%
SiO_2	20.34
Al_2O_3	4.05
Fe_2O_3	2.96
CaO	63.01
MgO	2.58
SO_3	2.90
Cl-	0.02
Free CaO	1.31
Unknown	1.77
Loss on Ignition	2.40
Insoluble Residue	0.90

Table 2 - Physical properties

Properties	Value
Density (g/cm^3)	3.17
Dry residue < 45μm (Wt.%)	4.7
Surface area, Blaine (cm^2/g)	3908
Expansion Le Chatelier (mm)	1.0

Table 3 - Mechanical characteristics

Test	MPa
Flexural strength (28days)	9.4
Compressive strength (2 days)	30.1
Compressive strength (28 days)	52.5

The production of the mortar mix was based on the EN 196-1 [1]. After mixing, prismatic moulds of 40x40x160 mm^3 were filled with mortar, compacted and stored in a vapour chamber (20ºC/95 % r.h.) for a day, after which they were demoulded and stored in water at 21 ºC until testing.

The production of concrete mix was based on the NP EN 206-1 [2]. After mixing, cubic moulds of 50x50x50 mm^3 were filled with concrete, compacted and stored in a vapour chamber (20ºC/95 % r.h.) for a day, after which they were demoulded and stored in water at 21 ºC until testing. For the concrete mix, a naphthalene-based superplasticizer with a solid content of 42% was used.

The compositions for both the mortar and the concrete mixes are presented in Table 4.

Table 4 – Mortar and concrete mixes.

Constituents	Mortar (kg/m3)	Concrete (kg/m3)
Cement	585.9	350.0
Sand	1757.8	922.1
Course Agg.	---	854.9
Water	292.9	191.5
w/c	0.50	0.55
Superplasticizer	---	3.5

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2.2 Test procedures

The electrical resistivity (ρ_{DC}) of the mortar and concrete specimens was performed by measuring the current intensity when a 12 V dc electrical potential was applied. All measurements are an average of three specimens.

To study the effect of temperature, the specimens were submerged in a water bath. After the water temperature stabilization, the specimens where placed for 30 minutes in the bath, after which the electrical resistivity measurements were performed. For the negative temperatures, an anti-freeze solution was mixed with water.

The compressive strength test was performed according to the LNEC E-226 [3].

3. TEMPERATURE EFFECT ON RESISTIVITY

Electrical resistivity measurements were performed for a temperature range from -11 ºC to 54 ºC, on specimens 90 days old. Table 5 shows the variation of electrical resistivity with temperature. The mean current intensity, I_M, and standard deviation values are also shown.

These values reflect the importance of temperature on electrical resistivity measurements (Figure 1). Assuming that the conductivity (inverse of resistivity) is a function of the mobility of the ions in the mortar liquid phase, it can be expected that the conductivity varies with temperature in the same way that the diffusion of ions varies in a liquid phase. This variation is governed by the Arrhenius equation. Therefore, for the variation of electrical conductivity with temperature can be expressed by the following equation

$$C = C_0 . exp(-E/RT) \quad (1)$$

where C is the conductivity at any temperature, $(\Omega m)^{-1}$; C_0 is the conductivity when the temperature tends towards infinity, $(\Omega m)^{-1}$; E is the activation energy, J/mol; R is the gas constant, 8.314 J/mol.K; and T is the absolute temperature, K.

Table 5 – Electrical resistivity variation with temperature

T (ºC)	I_M (mA)	Std. Dev.	ρ_{DC} (Ωm)
-11.0	0.603	0.021	198.9
-7.0	0.786	0.019	152.6
3.3	1,537	0.029	78.1
6.3	1.696	0.015	70.8
0.0	1.821	0.047	65.9
14.0	1.996	0.065	60.1
17.8	2.375	0.075	50.5
20.1	2.764	0.021	43.4
22.2	2.730	0.019	44.0
25.0	3.092	0.009	38.8
30.5	3.463	0.091	34.7
34.0	3.756	0.098	32.0
41.0	4.175	0.088	28.7
46.0	4.505	0.076	26.6
54.0	4.782	0.080	25.1

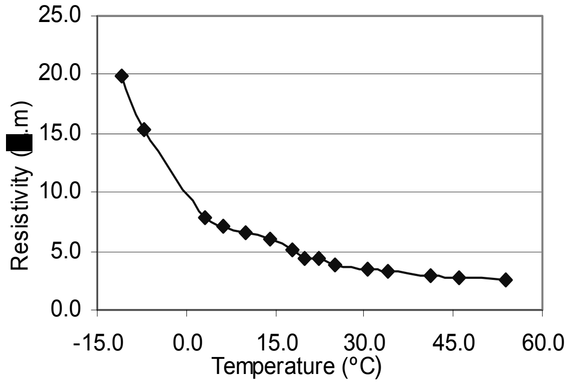

Figure 1 – Resistivity variation with temperature.

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In order to establish the relationship between electrical resistivity and temperature, and convert electrical resistivity measurements at any temperature to a reference temperature (21 ºC), the *E* and the C_0 must be determined. These values can be obtained for a given type of cement, concrete mix and curing conditions by linear transformation of equation 1. This is performed by applying the logarithm to both sides of the equation

$$Ln(C) = Ln(C_0) - E/RT \quad (2)$$

Parameters C_0 and E can be estimated using data from resistivity test at different temperatures. Figure 2 shows the best fit of data from Table 5. Numerical values of the estimate for this mix design are $E = 22.512$ kJ/mol and $C_0 = 0.00494$ $(\Omega m)^{-1}$.

To obtain the electrical conductivity for a reference temperature, usually 21 ºC, from any other temperature the following expression can be used:

$$\rho_{REF} = \rho.\varphi \quad (3)$$

where φ is given by

$$\varphi = exp(-E/R.T)/exp(-E/R.T_{REF}) \tag{4}$$

Figure 3 shows how φ varies with temperature in this case.

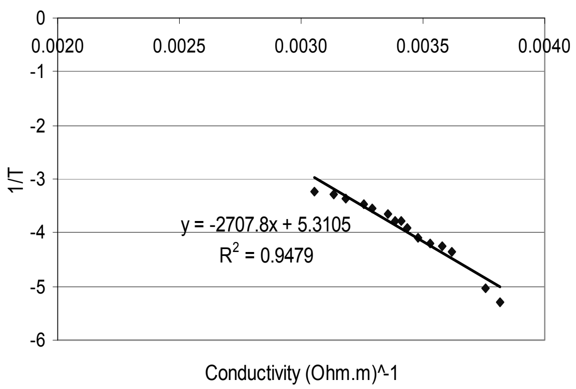

Figure 2 – Fitting equation 2 to the data.

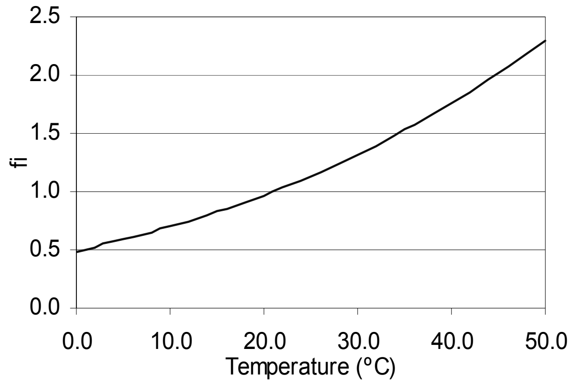

Figure 3 – Variation of φ with temperature.

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4. ESTIMATING COMPRESSIVE STRENGTH DEVELOPMENT WITH ELECTRICAL RESISTIVITY MEASUREMENTS

Table 6 shows results of compressive strength test and electrical resistivity measurements with curing time. Fig 4 shows the best fit of a linear equation to data from Table 5. A good correlation exists with a correlation coefficient of 0.92.

Figure 5 shows the compressive strength and electrical resistivity test results with curing time as a percentage of values at 28 days. Since compressive strength and electrical resistivity show similar development curves with time it can be assumed that the same equation can explain both set of data. An empirical equation (see equation 5) commonly used for predicting strength gain with time is suggested to explain also the electrical resistivity development with time.

Table 6 – Development of compressive strength and electrical resistivity with time

t (days)	f_C (MPa)	ρ_{DC} (Ωm)
1	12.71	16.49
2	21.93	23.81
3	23.40	28.30
4	24.74	30.44
7	26.37	37.96
14	29.56	42.98
28	35.31	47.06
56	39.42	51.29

$$t/f_C = m.t + c \qquad (5)$$

in which t is time (days); f_C the compressive strength (MPa); m the rate constant (t^{-1}) and c is the inverse of the compressive strength when t → ∞ (MPa^{-1}). Adopting this model for the electrical resistivity development with time

$$t/\rho_{DC} = m.t + c \qquad (6)$$

where ρ_{DC} is the electrical resistivity (Ωm), and c is the inverse of the final electrical resistivity when t → ∞.

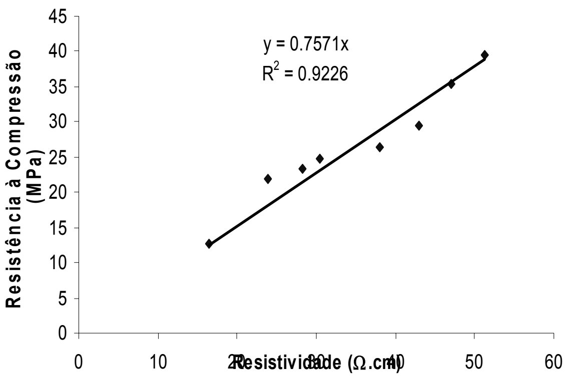

Figure 4 - Correlation between compressive strength and electrical resistivity.

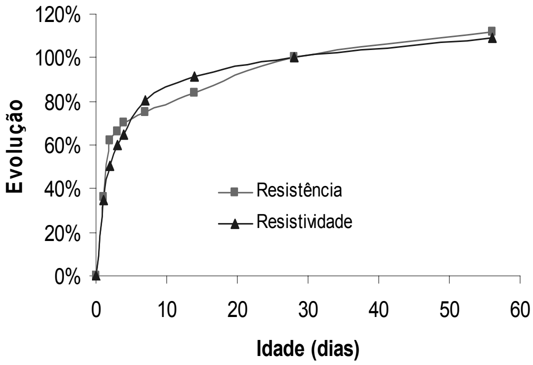

Figure 5 – Standardized development curves for compressive strength and electrical resistivity.

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Data given in table 6 are used in order to evaluate the model for estimating electrical resistivity development and strength gain. Fig 6 shows the best fit for data from day 1 to 4, while Fig 7 shows the best fit of data from day 1 to 7. The high values of coefficient correlation (R^2 = 0.999 and R^2=0.994) indicate that equation 6 can explain the data well. Electrical resistivity for any given time can be estimated using equation 6 with parameters thus obtained. The same procedure is valid for predicting the compressive strength at any age using data from the first 4 or 7 days curing time.

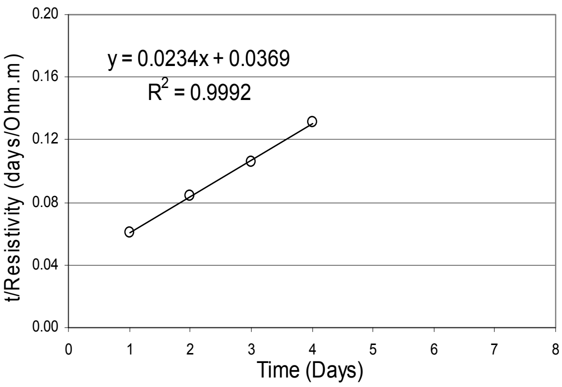

Figure 6 – Curve fitting model to 4 day data.

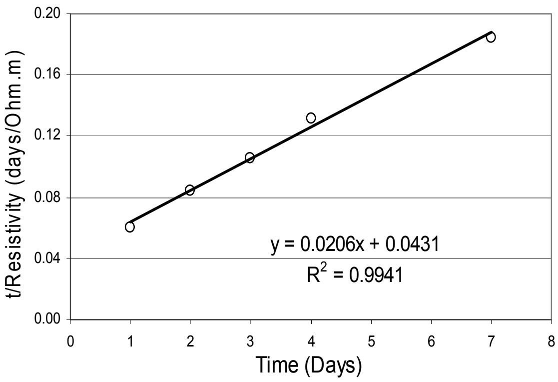

Figure 7 - Curve fitting model to 7 day data.

Figure 8 illustrates the test results and the prediction curves using the first 4 days, 7 days, and the full set of data (56 days). It can be observed that for fewer data the error is larger. For estimating the electrical resistivity at 28 days curing, the 4 days data generates an error of 14 % whereas the 7 days data indicates an error of only 4 %. These errors are similar for the compressive strength estimations when using the electrical resistivity measurements. However, whilst the compressive strengths estimations are conservative the electrical resistivity estimations are not, as can be observed from figure 9.

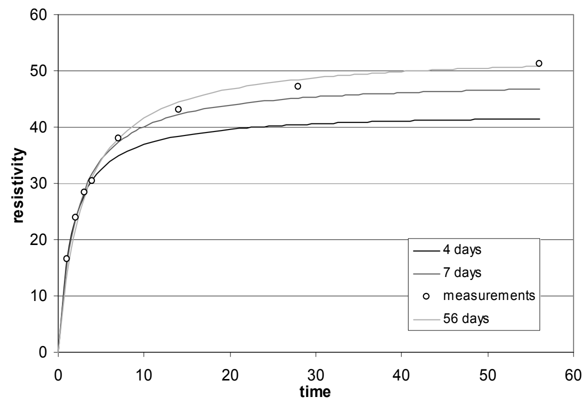

Figure 8 – Comparison of model to obtained data for resistivity.

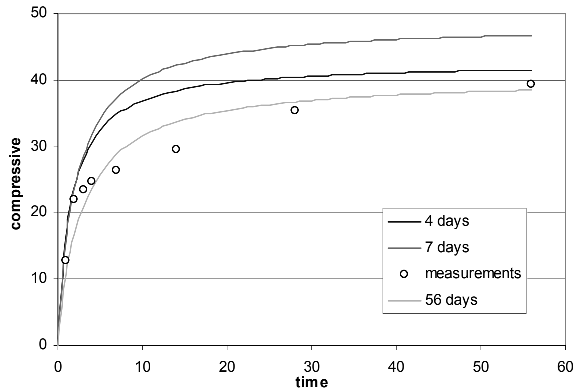

Figure 9 - Comparison of model to obtained data for compressive strength.

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5. CONCLUSION

The results of this research work indicate that the compressive strength and the electrical resistivity show similar development curves with time. It is suggested that a hyperbolic empirical equation can be used for predicting the development of electrical resistivity and compressive strength with time. Errors of up to 15% were obtained when estimating 28 days values using test results of the first 4 days, and errors in estimates of up to 5% were obtained when test results of the first 7 days are employed.

The maturity model presented was conservative when estimating compressive strength and non-conservative when estimating the electrical resistivity. Errors in estimates of up to 15% were obtained when estimating 28 day values with results of up to 4 days, and, errors in estimates of up to 5% were obtained when estimating 28 day values with results of up to 7 days.

Results obtained in this research work indicate that electrical resistivity changes exponentially with temperature. It is suggested that an equation similar to Arrhenius equation can explain well this relationship. It is shown that this equation can be used to estimate the electrical resistivity for any given temperature, such as a reference temperature (20ºC).

As a result of this preliminary research, a more comprehensive research program is now underway. Other maturity models are being studied on varying concrete with different cement types. The electrical resistivity measurements are being made with Werner electrode, more appropriate to in-situ measurements, on concrete specimens commonly used for concrete conformity.

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