Quality control based on electrical resistivity measurements

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Summary

The electrical resistivity of concrete 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 w/c ratio (pore connectivity), volume and type of cement, temperature and the moisture. This research work studies the effect of specimen shape and temperature of measurement on electrical resistivity measurements of concrete using the four-point Werner electrode. In addition, the estimation of future values based on early age measurements is also studied.

Research has indicated that there is a strong relationship between electrical resistivity and durability indicators at a given age. A relationship for the estimation of the electrical resistivity using early age measurements is suggested. 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 conversion of electrical resistivity measurements to a reference temperature.

Based on these equations, the electrical resistivity and compressive strength of concrete at 28 days is predicted using values of electrical resistivity of up to 7 days. Errors depend on the equation used but are approximately 5 % for estimates up to 28 days..

KEYWORDS
Electrical resistivity, durability, quality control

1. Introduction

The electrical resistivity of concrete is one of the main parameters controlling the initiation and propagation of reinforcement corrosion [1]. It is common knowledge that concrete electrical resistivity is mainly dependent on the w/c ratio (pore connectivity), volume and type of cement, temperature and the moisture [2].

Typically, quality control programs test only compressive strength based on specimens molded on site. There is often no quantification of actual in situ compressive strength. With regards to durability indicators, rarely are they measured on the cast specimen, let alone on the construction. It is necessary to introduce into the quality control program other tests than compressive strength as this test is inappropriate for quantifying the durability of concrete [3,4]. Although many tests can be performed in a non-destructive manner, few are as easy to use at the four-point Werner electrode for electrical resistivity measurements. Quickly, large areas of the structure can be assessed and evaluated with regard to quality of the concrete [5]. This is possible because electrical resistivity measurements correlate well with many other durability indicators such as diffusion coefficient [2,6], permeability coefficients, capillary absorption, and porosity [6].

The development of durability indicators is crucial for concrete quality control program starting from the removal of formworks on the construction site. This is commonly performed only for compressive strength and on specimens cast during construction. Little or no information of the durability indicators of the actual finished structure is normally determined [5].

Establishing a relationship between durability indicators and electrical resistivity is important because it would allow large areas of a structure to be tested, indirectly. Estimating the development of the electrical resistivity with time and temperature may be used for obtaining values for durability design update [7].

2. Experimental Programme

2.1 Materials and mixes

The cement used in this research work was a 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 concrete mix was based on the NP EN 206-1. After mixing, several specimens (10 cm and 15 cm cubes; ∅10 cm x 20 cm cylinders) were moulded, compacted and stored in a conditioning 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 – Concrete mix design.

Constituents	Concrete (kg/m3)
Cement	350.0
Sand	1053.0
Course Aggregate	718.3
Water	156.8
w/c	0.45
Superplasticizer	3.5

2.2 Test procedures

The electrical resistivity of the concrete specimens was performed using a four-point Werner electrode according to published recommendations [8] and internal laboratory test procedure [9]. Measurements where performed on 10 cm (C10) and 15 cm (C15) cubes as well as on 10 cm x 20 cm cylinders (Cy10). Prior to measurements, the specimen surface is cleared of excess water with a dry cloth and place on a dry wooden support. The specimens are measure in different ways: - the cylinders are measured every 180 º with two opposite measurement (total six values per specimen); - the cubes are measured on two lateral surfaces and the bottom surface with two reading, 90 º apart (total six values per specimen). The spacing between electrodes was 4.0 cm for C15 and Cy10. The spacing was 2.5 cm for C10. To study the effect of temperature, three C10 specimens where submerged in water at the temperature of 10 º C for an hour prior to testing. The compressive strength test was performed according to the EN 12390-3. All tests were performed at different ages up to 90 days.

3. Experimental Programme

The results of the electrical resistivity measurements and the compressive strength measurements are presented in Table 5.

Table 5 – Electrical resistivity and compressive strength of the concrete specimens with time.

T (*days*)	*C10* ρ (*Ωm*)	*C15* ρ (*Ωm*)	*Cy10* ρ (*Ωm*)	*C10 (10ºC)* ρ (*Ωm*)	f_C (*MPa*)
1	16.8	16.3	24.1	16.7	17.5
2	27.4	26.8	35.9	38.9	26.5
3	33.3	32.7	46.9	49.4	---
4	35.0	35.0	50.2	52.3	33.2
7	45.0	42.6	62.0	61.4	35.5
14	51.2	47.5	72.8	67.7	44.7
28	56.5	56.6	79.1	85.0	51.3
56	65.1	64.8	90.1	94.7	53.8
90	66.1	66.7	95.8	95.0	52.3

The dependence of electrical resistivity on the amount of evaporable capillary water and the gel density explains the rise in the electrical resistivity with a higher age and with an increasing degree of hydration [11]. During the first three weeks after production a rapid increase can be measured in the electrical resistivity. The content of free water drops steadily with an increasing hydration age until hydration has been completed. The bonded water is no longer available to carry the current, the electrical resistivity rises. In addition, the space between the cement particles fills up with cement gel and the capillary pore space that was initially present is reduced [12].

3.1 Effect of temperature on electrical resistivity measurements

Temperature changes have important effects on concrete resistivity [7,8,10]. A temperature decrease causes an increase of resistivity and vice versa. This is the result of temperature influences on ion mobility, ion-ion and ion-solid interactions. Due to the complex nature of the interactions, an empirical approach must be followed [8]. Assuming that the conductivity ($C = 1/\rho$) 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, (Ωm)-1; C0 is the conductivity when the temperature tends towards infinity, (Ωm)-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. The values of these parameters for this mix design are E = 22.512 kJ/mol and C0 = 0.00494 (Ωm)-1 [7]. To obtain the electrical resistivity for a reference temperature, usually 21 ºC, from another temperature:

$$\rho_{REF} = \rho . \varphi \quad (2)$$

where φ is given by

$$\varphi = exp(-E/R.T)/exp(-E/R.T_{REF}) \quad (3)$$

Equation 3 is applied to the measurements performed on the specimens at 10 ºC in order to convert them in to reference temperature values. Figure 1 illustrates the original measurements at 21 ºC and 10ºC and the conversion. The electrical resistivity performed at lower temperatures resulted in higher measurements as shown in figure 1. The conversion of the measurements from 10 ºC to 20 ºC with equation 3 has a good correlation with actual measurements measured.

3.2 Effect of specimen size on electrical resistivity measurements

Theoretically, concrete electrical resistivity is a geometry-independent material property that describes the electrical resistance, that is, the ratio between applied voltage and resulting current in a unit cell [8]. In concrete, the current flows through the pore liquid in the cement paste. Aggregate particles are considered to be inert. As a result, concrete is not a homogeneous conductor and the flow of measuring current will be inhomogeneous [13]. Due to the electrical nature of the electrical resistivity test and the distribution of the electrical potential field with-in the specimen, variations are expected to appear in electrical resistivity measurements depending on the geometry of the specimen. Figure 2 illustrates the electrical resistivity measurements in Table 5 for three different specimen sizes.

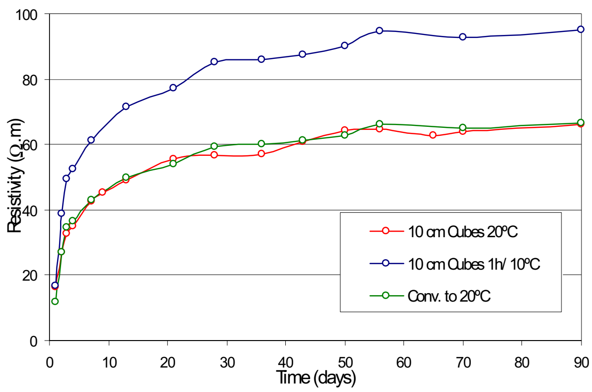

Figure 1 – Variation of ρ with temperature and conversion 10 ºC to 20 ºC.

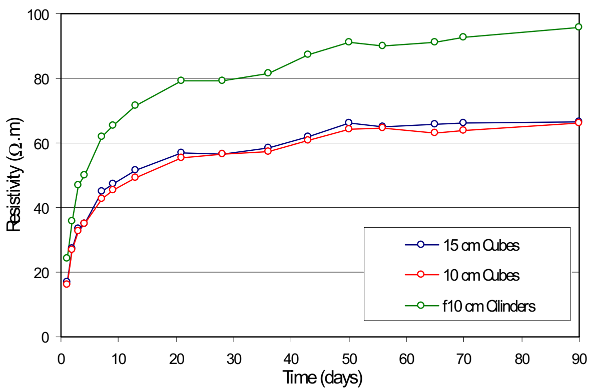

Figure 2 – Influence of specimen size on electrical resistivity measurements

From figure 2 it is observed that the specimen geometry plays an important role in the measurement of electrical resistivity. Electrical resistivity measurements for the cylindrical specimen are approximately 30 % greater than those measured on cubic specimens. Even between similarly shaped specimens (cubes), the C15 measurements are approximately 3 % larger than the C10.

The difference in measurement between differently shape specimens is related to the amount of concrete (pores) available for transporting the electrical currents. The volume ratio of concrete cylinder to that of the rectangular prism that contains it is 0.78. However, measurements show that ratio between cylinders and cubes is approximately 0.70. The resulting difference being that the cubes have a greater volume than the considered rectangular prism and therefore more pores to conduct the current with, hence the lower electrical resistivity

4. Estimating electrical resistivity measurements

The possibility of using early age electrical resistivity measurements for quality control of concrete structures (concrete durability indicators) is of great importance. For example, straight after formwork removal, the entire structure can quickly be assessed with regards to the parameter we so choose, as long as there has been established a good correlation with the electrical resistivity test for the given concrete. Therefore, the possibility of estimating future values based on early age measurements can play an important role in quality control and an effective update of the durability design of the structure can be performed.

Three equations are proposed and analysed for estimating early age development of electrical resistivity, until 28 days. From the data in Table 5, only data up to 7 days is used to perform the estimations. The practical implication is that on site, after a week of measurements, 28 days values can be estimated. Examples of other data sets other than 7 days can be found in [7]. Only data from C15 and Cy10 are used.

4.1 Hyperbolic equation

Due to the curvature of the electrical resistivity vs. time curve, a hyperbolic equation is proposed to simulate the development with time [7]. From equation 4 it can be seen that

$$y = \frac{x}{a \cdot x + b} \;\rightarrow\; \frac{x}{y} = a \cdot x + b \;\rightarrow\; \frac{t}{\rho} = a \cdot t + b \qquad (4)$$

in which t is time (days) and ρ is the electrical resistivity (Ωm). From the equation it can be seen that, $t \rightarrow \infty$, $\rho_{max} = 1/\alpha$. The proposed equation can be linearized which facilitates the calculation of the equation parameters. This equation can be used for different cement type as its variables are geometrical parameters [7].

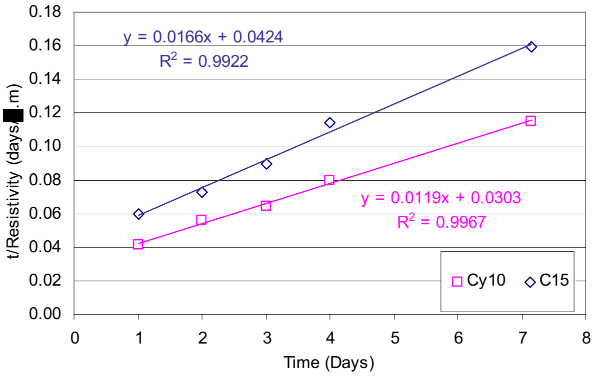

Figure 3 – Curve fitting of hyperbolic equation to 7 day data.

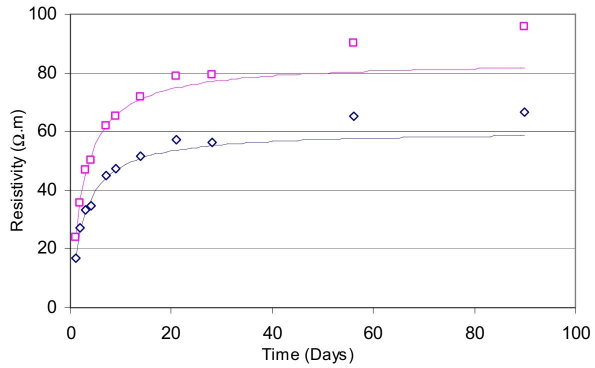

Figure 4 – Hyperbolic equation vs. measured electrical resistivity

Figure 3 illustrates the best fit of the 7 day data to the linearized hyperbolic equation. The coefficient correlation obtained ($R^2 \approx 0.99$) indicate that equation adjusts well. Table 6 shows the parameter determined and the error associated with the estimates. Prediction of 28 day values has an error of ≈ 4-5 %. This equation can not be used for estimating values further than 28 days as the ρ_{max} has already been reached with in this period. Figure 4 shows the equation estimate curve compared to the measured data. As can be seen, after 28 days the curve no longer accompanies the development of the measurements.

Table 7 – Equation variables for the estimation of 28 day electrical resistivities.

Specimen	*Estimation (Ωm)*	*Error (%)*	*a*	*b*	*ρ_{MAX} (Ωm)*
Cube	59.3	5.0	0.0166	0.0424	60.24
Cylinder	82.5	4.3	0.0119	0.0303	84.03

4.2 Nucleation and growth mechanism equation

The development of any durability indicator or compressive strength depends on the hydration of the cement and the gradual densification of the concrete matrix. An equation based on the principles of nucleation and growth mechanism of the formation of cementitious material [14] has been adjusted to strength development prediction [15]:

$$\rho = \rho_{\max} \cdot \left(1 - \exp\left(-K \cdot t^{n}\right)\right) \tag{5}$$

in which K is the rate for growth and is temperature dependant according to Arrhenius equation, and n is the dominant morphology of the formation process. This equation is asymptotic to a maximum value ρ_{max}.

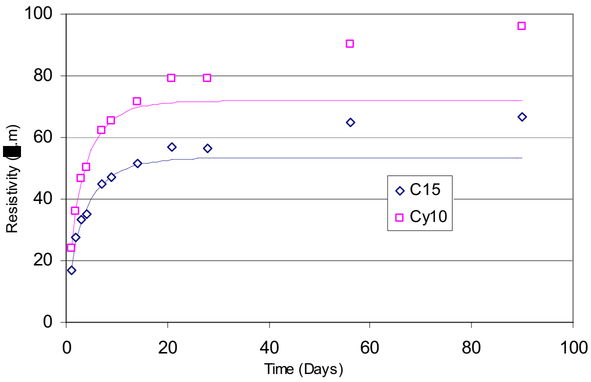

Figure 5 – Growth mechanism equation vs. measured electrical resistivity

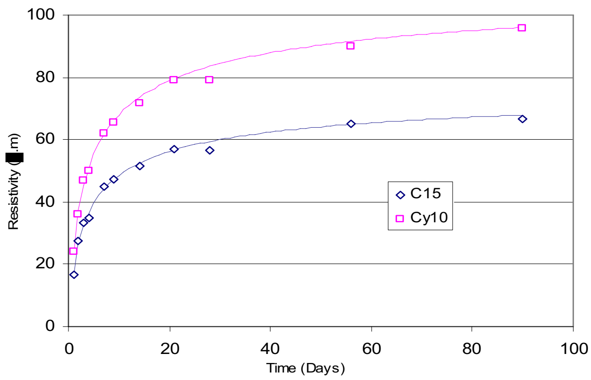

Figure 6 – Exponential equation vs. measured electrical resistivity

As can be seen from Figure 5, the best fit for the 7 day data adjust well to the measure value. The coefficient correlation obtained is $R^2 \approx 0.97$. In Table 7 the parameters determined and the errors associated with the estimates are presented. For this equation, prediction of 28 day values has an error of ≈ 5-6 %. This equation is useful for estimating values only up to 28 days as ρ_{max} has almost been reached within this period. This is also observed in figure 5.

Table 7 – Equation variables for the estimation of 28 day electrical resistivities.

Specimen	*Estimation (Ωm)*	*Error (%)*	*K*	*n*	ρ_{MAX} *(Ωm)*
Cube	53.2	5.9	0.397	0.771	53.52
Cylinder	74.9	5.3	0.407	0.812	75.10

4.3 Exponential equation

The use of exponential equation is common for modelling strength development relationships [16,17]. The following equation is proposed by [18]:

$$\rho = \rho_{\max} \cdot \exp\left(-\left(\frac{\tau}{t}\right)^{\alpha}\right) \tag{6}$$

in which t is the age, τ is the time constant and α is the shape parameter. This equation can model gradual electrical resistivity development during the cement hydration period and is also asymptotic to a limiting value. The time constant τ represents the age at which the strength has reached 0.37 ρ_{max}. Thus $1/\tau$ is the constant rate for the equation. The shape parameter α affects the slope of the curve during the hydration period and it affects the rate with which the electrical resistivity approaches the limiting value [19].

From Figure 6 it can be seen that 7 day data adjust well to the measure value right up to the 90 day measurements. High values of coefficient correlation obtained (R2 ≈ 0.97). In Table 8 shows the parameter determined and the error associated with the estimates. For this equation, prediction of 28 day values has an error of ≈ 5 %. As the asymptotic value is much larger than the predicted 28 day values, 90 day values are also measured with an obtained error of ≈ 2 %.

Table 8 – Equation variables for the estimation of 28 day electrical resistivities.

Specimen	*Age (days)*	*Estimation (Ωm)*	*Error (%)*	τ	α	ρ_{MAX} *(Ωm)*
Cube	28	59.4	5.1	2.493	0.481	81.18
	90	68.0	1.9			
Cylinder	28	83.5	5.6	2.661	0.470	116.26
	90	96.1	1.1			

5. Conclusions

The present experimental investigation was only based on a limited number of variables and the testing was performed on concrete made only with Portland cement. However, based on the test results obtained, the following conclusions appear to be warranted:

- Results obtained confirm that electrical resistivity changes exponentially with temperature. The equation based on the Arrhenius equation explains adequately the relationship. It is shown that this equation can be used to convert electrical resistivity for any given temperature to a reference temperature.

- Laboratory measurements of electrical resistivity on concrete specimens vary according to the shape of the specimen used. Cylindrical specimens have higher values when compared to cubic specimens.

- The proposed equations for electrical resistivity estimation are limited to 28 day values, with the exception of the exponential equation which can perform estimation up to 90 days and beyond. With in this limitation, and based only on 7 day data, the estimations are relatively accurate with errors in the range of 5 %. The exponential equation allows estimations at later ages without hindering increasing the error in the estimations. It is necessary to perform similar estimations with concrete of different cement type and also different water/binder ratios.

- Correlation with durability indicator should be established and prediction of these parameters using this procedure tested. If proven to be reliable, it may be a useful tool for the quality control procedure on site and condition assessment.

- Different cement types can be taken into account by the geometrical parameters of the proposed equations. However, the procedures require calibration to take into account local variables (concrete mix, climate, etc.). Estimations depend on number days in data set and the time of estimation.

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References

[1] Bertolini, L., *et al.* Corrosion of steel in concrete. Prevention, Diagnosis, Repair. Wiley-VCH, 2004, 392 pp.

[2] Andrade, C., The limit of service life of concrete structures. (*in Spanish*) Encontro Nacional Betão Estrutural 2004, FEUP, Porto, 2004, p.1-25.

[3] Elkey, W., Sellevold, E.J., Electrical resistivity of concrete. Norwegian Road Research Laboratory, Oslo, Publication n.80, 36 pp.

[4] Burchler, D., Elsener, B., Bohni, H., Electrical resistivity and dielectric properties of hardened cement paste and mortar. *In* Page, C.L. *et al* Proc. 4th Int. Symp. On Corrosion of Reinforcement in Concrete Construction. Society of Chemical Industry. 1996, p.283-293.

[5] Gjørv, O.E., Durability design and construction quality of concrete structures. CONSEC 04, 4th International Conference on Concrete under Severe Conditions: Environment and Loading, Seoul, Korea, June 27-July 1, 2004. pp.44-55.

[6] Ferreira, R.M., Evaluation of durability test. (*in Portuguese*) Master Thesis, Universidade do Minho, Guimarães, 2000, 246 pp.

[7] Silva, B.J., Jalali, S., Ferreira, R.M., Estimating electrical resistivity based on early age measurements. Pro. Int. RILEM Workshop Performance based evaluation and indicators for concrete durability, Madrid, 2006.

[8] Polder, R.B. Test methods for on site measurement of resistivity of concrete - A RILEM TC-154 technical recommendation. Construction and Building Materials. n.15, 2001 p.125-131.

[9] LMC test procedure

[10] Pruckner, F., Corrosion and protection of reinforcement in concrete measurements and interpretation. Doctoral Thesis, University of Vienna. 2001. 224 p.

[11] Brameshuber, W., Raupach, M., *et al.* Non-destructive determination of the water-content in the concrete cover using the multiring-electrode. Part I: Aspects of concrete technology. Pro. Int. Sym. NDT-CE, 2003

[12] McCarter, W.J., Forde, M.C., *et al.* Resistivity Characteristics of Concrete. Pro. Institution of Civil Engineering. n.71, 1981, March, p.107-117.

[13] Gowers KR, Millard SG. Measurement of concrete resistivity for assessment of corrosion severity of steel using Wenner technique. ACI Materials Journal, Sep-Oct. 1999, p.536-541.

[14] Jalali, S., Modelling the overall rate of reaction in lime-fly ash systems. 10th Int. Congress on the Chemistry of Cement, Goteborg, Sweden, 1997.

[15] Jalali, S., Abyaneh, M.Y., Prediction of final concrete strength in hot climates. Magazine of Concrete Research, n.47, 1995, p.291-297.

[16] Carino, N., Lew, H.S., The maturity method: From theory to application. Pro. Structures Congress and Exposition, Washington, USA, 2001, 19p.

[17] Yi, S., Moon, Y., Kim, J., Long-term strength prediction of concrete with curing temperature. Cement and Concrete Research. n.35, 2005, p. 1961-1969.

[18] Carino, N.J., The maturity method: From theory to application. Journal of Cement, Concrete and Aggregates (ASTM), Vol.6, n.2, 1984, pp.61-73.

[19] Carino, N.J., Knab, L.I., et al. Applicability of the maturity method to high-performance concrete. NISTIR-4819, USA, 1992, 64 pp.