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Electrical Resistivity as a Means of Quality Control of Concrete – Influence of Test Procedure

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ABSTRACT

The quality control of concrete, normally associated with the verification of the conformity of the mechanical and durability characteristics, usually requires lengthily procedures for the conditioning and preparation of the specimens, after which the specimen is typically destroyed while being tested.

In this paper, a part of the results of an ongoing research on the relationship between electrical resistivity measurements of concrete and other characteristics, such as the compressive strength.

The influence of several parameters on the relationship is taken into consideration, such as, different curing conditions of the concrete specimens, i.e., temperature, relative humidity, reading temperature, and the maturity of concrete. Another goal of the research is to establish a laboratorial procedure for the quality control of concrete enabling the NDT of several concrete characteristics based on electrical resistivity measurements.

Preliminary results demonstrate a good correlation between electrical resistivity and other characteristics of concrete. Different techniques on measurements on electrical resistivity are presented.

KEYWORDS

Electrical resistivity, Compressive strength, Quality control, Durability, NDT.

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1 INTRODUCTION

The quality control of concrete, normally associated with the verification of the conformity of the mechanical and durability characteristics, usually requires lengthily procedures for the conditioning and preparation of the specimens, after which the specimen is typically destroyed while being tested. As in the case of compressive strength, testing is typically performed on standardized specimens at the age of 28 days. To keep up with the fast pace of construction, early age specimens are tested to obtain some insight as to what the 28-day compressive strength of concrete might be. Often there is no precise knowledge of the quality of the concrete, i.e. strength and durability performance. The influence of the environment on curing and concrete maturity is usually not considered.

In an attempt to ensure better construction quality and durability, there has been an increasing focus in recent years on the development of a better basis for performance-based quality control for concrete quality during concrete construction [[Gjørv 2004]; [Silva *et al.* 2006]; [Andrade 2004]]. One of the NDT commonly suggested in performance-based quality control programs is that of electrical resistivity (ER) [Ferreira & Jalali 2010].

The ER of concrete can be measured by several means [Polder *et al.* 2000]. Typically, electrodes are placed on the surface and the resistance is measured. From the cell geometry, the resistivity can be calculated. The resistivity is often related to corrosion and protection of steel reinforcement and to durability performance of concrete [[Sengul & Gjørv 2008]; [Ferreira & Jalali 2010]].

In concrete, the current flows through the pore liquid in the cement paste. Aggregate can be considered essentially inert. As a result, concrete is not a homogeneous conductor and the flow of measuring current will be heterogeneous. Concrete ER is a geometry-independent material property that describes the electrical resistance, i.e., the ratio between applied voltage and resulting current in unit cell geometry.

2 ELECTRICAL RESISTIVITY

The ER of concrete is related to the microstructure of the cement matrix, its pore structure, porosity, and pore size distribution. These characteristics are controlled by the degree of hydration of cement paste in concrete. As a result, ER of concrete will increase with time. One of the factors that control these features is the hydratation degree of the cement paste of concrete, thus resulting in an increase of ER with time. Others influential factors are the relative humidity, the concrete temperature, and the ions concentration and their mobility in the pore solution [Polder 2001]. Cement chemistry, cement content, water-cement ratio, and use of admixtures and supplementary cementations materials are factors which influence the microstructure of concrete as well as the pore solution chemistry, and therefore influence its ER [Ferreira & Jalali 2010].

ER can gauge the quality and durability performance of concrete. The ER of concrete may vary over a wide range, from 10^1 Ωm to 10^5 Ωm, influenced by the moisture content of the concrete (direct relation to the environment), the temperature and concrete quality (composition, cement type, etc.) [[Silva *et al.* 2006]; [Andrade 2004]; [Polder *et al.* 2000]].

In practice, the ER measurement of concrete is used mainly as an indicator of reinforcement corrosion activity. It plays a significant role in controlling the reinforcement corrosion rate. The higher the resistivity, the lower is corrosion current passing between anodic and cathodic areas of the reinforcing steel [[Gowers & Millard 1999]; [Broomfield 1997].

However, ER is directly related to durability performance parameters based on the theoretical background of the phenomena. For example, with regards to the diffusion coefficient of concrete, the Nernst-Einstein equation can be used [[Pruckner 2001]; [Andrade *et al.* 2007]]. In addition, research has shown correlations between the electrical resistivity and the durability performance parameters of a given concrete [[Silva *et al.* 2006]; [Ferreira 2000]; [Sengul & Gjørv 2008]].

There are several test methods to measure the ER of concrete that can differ in the type of applied current (alternating current (AC) and direct current (DC)) and electrode configuration used. According to Polder [2001], the measurement of ER in the concrete must be carried out using AC. The use of a DC equipment is not advisable because of the effect of inducing the electrodes polarization, resulting in significant errors [Polder et al 2001]. In this research two test method where used: the two plate electrode method applying AC and DC and the four-point electrode (Wenner) applying AC. A brief description follows of the test procedures used are described in the following paragraphs.

2.1 Two-Plate Electrode Method

The test procedure was performed at the LABEST-FEUP, and is based in the procedure propose by Polder [2001]. During testing, a low frequency electrical current passes between the two electrodes (passing through the entire specimen) while the voltage drop is measured. For AC measurements it was used a wave generate of brand mark Tektronic (model CFG253), and the power source for DC measurements is an Univolt equipment (model DT305TD). For both types of measuring AC and DC, was used a multimeter with high accuracy KEITHLEY (model 2000).

Specimens were removed from the curing conditions only a few moments before the test start. Each specimen was wiped with a damp cloth to remove excess surface water. To ensure good electrical contact between the specimen and electrodes (stainless steel plate with 1.95 mm thick) a wet sponge were placed and a force was applied to maintain a constant and uniform stress distribution over the entire face of the specimen. First measurements is performed on AC and then on DC current. **Figure 1** show, the test set-up used to ER measurements using the two-plate electrode method (AC and DC) on standard cubic and cylindric specimens.

Figure 1. Test layout of the two-plate electrode method for ER measurements the ER on cubes (left) and cylinders (right).

A preliminary study was undertaken to evaluate what type of wave frequency should be used in AC measurements. In this case, results showed that the sinusoidal current wave with a frequency of 10 kHz, had the best performance with good reproducibility to characterized the concrete. The electrical resistivity measurements using the technique of two-plate electrode method is obtained from the average of two measurements.

2.2 Four-point Electrode Method

The four-point electrode method is currently the most widely used technique for field concrete resistivity measurements. During testing, a low frequency AC current is applied between the two outer electrodes while the voltage drop is measured in the two inner electrodes. In this research, the ER measurements were performed with a commercially available four-point resistivity meter (Canin, Proceq).
The resistivity meter, with fixed electrode spacing of 50 mm, uses an AC with a frequency of 72 Hz, an impedance of 10 MΩ, a measuring range from 0 to 99±1 kΩ.cm. The apparent ER determined by the equipment is obtained from Eq. **(1**) considered valid for a homogeneous semi-finite volume of the material.

$$\rho = 2\pi aU/I \quad (1)$$

where ρ is the electrical resistivity (Ω.m), a is electrode spacing (m), U is voltage drop (V), and I is the current (A).

ER measurements on cubic specimens (150 mm) are performed on opposing surfaces, and in perpendicular directions on each surface. The average resistivity is obtained from six measurements taken on each side. The measurement of ER in cylindrical specimens (ϕ150 mm x 300 mm) are made in groups of two (performed in opposing directions), 120º apart on the surface of the specimen. The ER value represents an average of 6 readings. In **Figure 2**, the measurement procedure can be observed for both cubic and cylindrical specimens.

Figure 2. Performing four-point electrode method ER measurments on cubic (left) and cylindrical (right) specimens.

There are several factors that influence the resistivity measurement when the four-probe technique is used. These factors include 1) geometrical constraints, 2) surface contact, 3) concrete inhomogeneity, 4) presence of steel reinforcing bars, and 5) surface layers having different resistivity than the bulk of the concrete. These factors have been thoroughly investigated [[Gowers and Millard 1999]; [Whiting and Nagi 2003]; [Polder *et al.* 2001]; [Sengul and Gjørv, 2008]].

3 EXPERIMENTAL WORKS

The main goal of this research is to establish a laboratorial procedure for the quality control of concrete enabling the NDT of several concrete characteristics based on the ER measurements. To fulfill this goal, a comprehension of the relationship between ER and the mechanical and durability performance concrete characteristics, and the influence of external factors, is required. In this paper, only the influence of the external factors, namely temperature, relative humidity, test procedure and specimen type, on the relationship between ER and compressive strength is presented.

Several self-compacting concrete (SCC) specimens (150 mm cubes and ϕ150 mm x 300 mm cylinders) where concreted and cured in different conditions: in water at 30 °C, 20 ºC and 5 ºC, and in a climate chamber with 20 °C and 50 % RH. Three different measurements where performed on the specimens: two-plate electrode measurement with AC and DC, and four-point electrode measurements. Measurements have been performed on the concrete specimens at regular intervals starting with 24 hours up to 90/180 days.

3.1 Materials, Mix Design and Curing

In this study, a SCC mix was prepared with Portland cement (CEM I 42.5R) and limestone filler with a specific gravity of 3.11 and 2.68, respectively. The mean particle size of cement and limestone filler was 14.61 and 6.53 μm, respectively. A polycarboxylate type superplasticizer (Sika Viscocrete 3006) was used with a specific gravity of 1.05 and 18% solid content. Crushed granitic aggregate (2.36-12.5

mm), a siliceous natural fine sand (sand 1) with a fineness modulus of 2.47 and natural coarse sand (sand 2) with a fineness modulus of 2.87 were used (see Table 1). The specific gravity of the coarse aggregate, sand 1 and sand 2 were 2.64**,** 2.62 and 2.63, and absorption values were 1.15%, 0.40% and 0.20%, respectively. The composition of self- compacting concrete mix is given in Table 1**.**
The mixes were prepared in the laboratory in an open pan mixer in 50 liters batches. The mixing sequence consisted of mixing the sands and coarse aggregate with ¼ of water content during 2.5 minutes, waiting 2.5 minutes for absorption, addition of powder materials, addition of the rest of the water with superplasticizer and finally mixing concrete during 8 minutes.
After mixing, the fresh state of the concrete mixes was characterized with the following tests: Slump flow test (pr EN 12350-8), the V-funnel test (pr EN 12350-9), the L-Box test (pr EN 12350-10), and the segregation test (pr EN 12350-11). The average results obtained in each of the mixtures are presented in Table 2.

Table 1. Constituent materials.

Concrete mixture	(kg/m^3)
Cement (CEM I 42,5R)	407
Limestone filler	186
Sand 1	422
Sand 2	327
Course aggregate	823
Water	159
Superplasticizer (liquid)	7.7
water/cement	0.41
water/binder	0.28

Table 2. Fresh concrete test results.

D flow (mm, s)	735 (class SF2)
T50 (sec.)	2.6 (class SF2)
Tfunnel (sec.)	10.4 (class VF2)
L-Box	0.8 (class PA1)
Segregation resistance (%)	5.3 (class SR1)

After fresh concrete tests a series of 150 mm cubes as well as 150 mm x 300 mm cylinders were molded. All test specimens were demoulded one day after casting and immediately placed in the respective curing conditions: immersed in water at 30 °C, 20 ºC and 5 ºC; and in a climate chamber with 20 °C and 50 % RH.

4 RESULTS AND DISCUSSION

4.1 Influence of Specimen Type, Curing and Test Procedure on ER Measurements

Figure 3 presents the evolution of ER measurements with time performed on cylindrical (1, 3, 8, 15, 22, 29 and 91 days) and cubes (1, 3, 8, 29, 91 days) specimens, with the 4-point electrode method, for the different curing conditions. As expected the resistivity will increase (with time) because as the hydration reactions are occurring the concrete microstructure becomes more dense. Until 28 days the resistivity evolution is similar for all types of envoirements. After 28 days of age, cylinders placed in the environment of 20º C and 50% humidity, unlike the cylinders placed in other environments, have a great evolution of the resistivity, which may be related to some loss of moisture from the speciments.

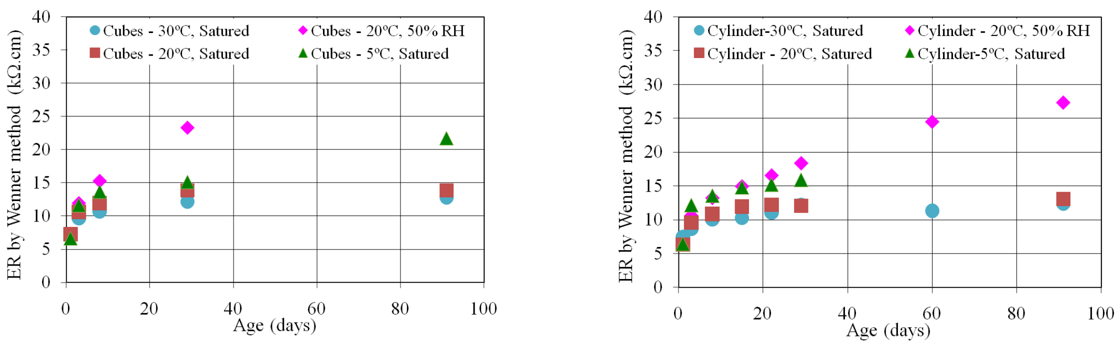

Figure 3. 4-point electrode ER measurements on cubic (left) and cylindrical specimens (rigth).

From **Figure 3** it is observed that the specimen geometry plays important role in the measurement of the ER. In this experimental program, and for the SCC used, it was observed that in the cubic specimens have higher ER compared with cylindrical specimens. A few exceptions exist such as the measurement of ER at 24 hours (not yet subject to different curing conditions). This is in agreement with research by Ferreira and Jalali [2010] and Sengul and Gjørv [2008]. These results can be justified by the boundary conditions of the specimens examined, for example, the spacing between the electrodes (e = 50 mm) and the geometrical particularities of the test method setup.

In the Figure 4, the relationship between ER obtained by four-point electrode method measurements and the technique by two-point electrode method (AC / DC), is presented.
Independently of the curing performed, there seems to be a consistent relationship between different ER measurement methods (lowest $R^2 > 0.9$). This is expected as the ER methods are influenced by the same factors (microstructure, etc.), the difference being arising from the different geometrical particularities of teach test method. Analyzing the results obtained using different techniques, by Wenner method and the measurement of two-plate electrode method (AC/DC), we conclude that the measurement of electrical resistivity using the technique of four-point (Wenner method) is highest around 45.7% (AC) and 36.1% (DC) measured in cubic specimens. The same trend is observed in cylindrical specimens, the measurement with the Wenner method is higher about 67% (AC) and 55% (DC).

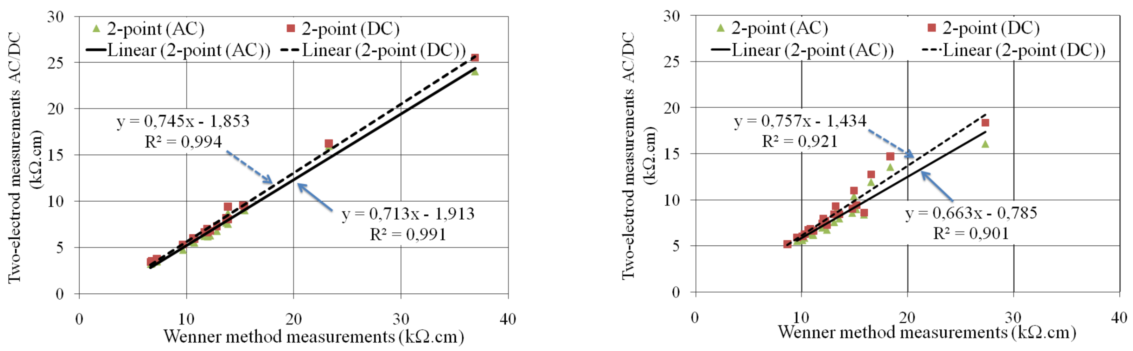

Figure 4. Relationship between ER obtained by Wenner method and two-plate electrode method (AC/DC), on cubic (left) and cylindrical (right).

The correlations on ER between the two point measurements and technique of the 4-point (Wenner method), obtained from cubic specimens of 150 mm edge were as follows: AC measurements (R^2= 0991), on DC (R^2 = 0994). In cylindrical specimens of 150 x 300 mm, the correlations obtained were as follows: measurements in AC ($R^2 = 0.901$) and DC ($R^2 = 0.921$).
With these results, it can be concluded that the correlations obtained by different assay techniques are satisfactory. It is observed that the ER measurements obtained by four-point electrode method are higher than those of the of two-plate electrode method (AC and DC).

In addition, in this work concludes that there a good relationship between ER measurements with AC and DC, for cubic (R^2=0.999) and cylindrical specimens was obtained (R^2=0.994), but measuring alternating current (AC) is lower than the measurement of electrical resistivity in DC. The ER (two-plate electrode method) measurement performed on cubic and cylindric specimens with alternating current (AC) is lower comparatively with DC measurements, about 7.17% on cubes and 6.71% on cylindric specimens.

4.2 Influence of curing on the correlation between ER and compressive strength

The average compressive strength was obtained from three 150 mm cubes tested in a Load Frame – MTS. The results of compressive strength test and ER measurements (4-point electrode), for different curing conditions, are presented in Table 3.

The correlation between compression strength and ER measurements are: 0.901 for speciments cured at 30ºC and saturated envoirement, 0.871 for speciments cured at 20ºC and saturated envoirement, 0.871 for speciments cured in climate chamber at 30ºC and 50% humidity and for speciments cured at 5ºC in a saturated envoirement the correlation coeficient was 0.932.

Table 3. Development of compressive strength and electrical resistivity (4-point electrode) with time.

	Curing conditions (cubes)							
	30ºC, Saturated		20ºC, 50 % RH		20ºC, Saturated		5ºC, Saturated	
t (days)	f_{cm}(MPa)	ρ_W(kΩ.cm)	f_{cm}(MPa)	ρ_W(kΩ.cm)	f_{cm}(MPa)	ρ_W(kΩ.cm)	f_{cm}(MPa)	ρ_W(kΩ.cm)
1	48.757	7.207	46.399	6.750	45.097	7.242	44.595	6.648
3	60.879	9.667	63.771	11.917	59.319	10.602	52.425	11.667
8	73.185	10.722	63.608	15.250	62.868	11.972	62.883	13.700
29	72.028	12.194	72.604	23.278	64.930	13.859	68.376	15.414
91	75.143	12.821	76.951	36.917	76.122	13.854	73.360	21.755
	(R^2 = 0.901)		(R^2 = 0.788)		(R^2 = 0. 871)		(R^2 = 0.932)	

The correlations between the compressive strength and electrical resistivity are very satisfactory, except for samples placed in a climatic chamber, 20 °C, 50% RH (R^2=0.788). As the humidity decreases, decreases the amount of water present in pores that carries the current, thus increasing the resistivity. Although the cement matrix still contains enough water for this relative humidity, the one that ends up trapped in the pores have a non-conducting behaviour.

The temperature plays an important role in the electrical resistivity, since the mobility of ions in the pores solution is largely affected by this parameter. In the Table 3 you can see that, for the same age, as the temperature increased (for a constant relative humidity) decreases the electrical resistivity.

5 CONCLUSIONS

Comparing the ER measurement performed with the Wenner method and the two-plate electrode method (AC/DC), it is observed that using the 4-point technique is obtained higher values than using 2 points technique. The technique of two-plate electrode method (AC/DC) show a good correlation. The evolution of electrical resistivity (NDT) presents an evolution identical to the mechanical strength, results demonstrate a good correlation.

The 4-point (Wenner method) is an simple and excellent technique for quality control the measurements of electrical resistivity on concrete.

The electrical resistivity may be an additional element of models for performance and durability of concrete structures, as defined in the project. This parameter can be measured during the construction and operation phase, thus contributing to sustainable development structures, minimizing repairs and maximizing the service life of concrete structures.

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