

Electrical resistivity measurement of unsaturated concrete samples

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Electrical conduction in concrete primarily occurs via the liquid in pores. Since concrete resistivity is sensitive to moisture content, resistivity can be used to infer other moisture-dependent concrete properties. However, quantitative assessment of the relationship between concrete resistivity and the pore liquid content can be a difficult task due to contact issues between electrodes and the surface of unsaturated concrete. Resistivity is usually measured using wet sponges to assess contact with a concrete surface. This is a very effective procedure for saturated concrete but implies minor alterations in the condition of unsaturated concrete. This paper deals with a contact method to measure the resistivity of unsaturated concrete samples. Resistivity measurements dispensing with wet contacts are performed on thin samples of conventional concrete. A dry contact is achieved by means of painted electrodes on the concrete surface. Dry and wet contact methods are compared when applied to saturated concrete, and resistivity values of unsaturated concrete are related to concrete moisture content and the relative humidity of the surrounding environment. As a result, resistivity is related to the volumetric fraction of conducting water in pores and its hygroscopic equilibrium with the surrounding environment.

Notation

A_s	tortuosity coefficient
F	formation factor
m	shape coefficient
ρ	concrete resistivity
ρ_s	resistivity of pore liquid
ϕ	volumetric fraction of pore liquid

Introduction

The durability of a reinforced concrete structure is related to the electrical resistivity of the cover concrete. A linear relationship between concrete resistivity and the rate of ingress of aggressive agents into concrete has been established (Whiting and Nagi, 2003). Moreover, when steel is under active corrosion, zones of low resistivity are found to be more vulnerable to corrosion. Resistivity refers to the ion transport rate between the anode and cathode in a corrosion cell circuit and it is therefore one of the controlling factors of corrosion rate. The relationship between concrete resistivity and the reinforcement corrosion rate after depassivation is thus based on the electrochemical nature of the corrosion process. From a practical point of view, if reinforcing steel is actively corroding, concrete resistivity measurements may indicate the locations in the structure where corrosion is more critical. From an evaluation of offshore concrete structures, Browne (1982) reported that concrete resistivity must fall below 5–10 k Ω cm for reinforcement corrosion to occur. According to Hope *et al.* (1985), reinforcement embedded in concrete with a

resistivity higher than 10 k Ω cm is not likely to develop corrosion at a significant rate. The same threshold value was recommended by Langford and Broomfield (1987) to prevent a moderate corrosion rate. It should be noted, however, that this threshold value should be considered to be dependent on cement type, given that supplementary cementitious materials have a significant influence on concrete resistivity (Whiting and Nagi, 2003). In any case, a practical correlation between concrete resistivity and reinforcement corrosion may be established.

Concrete resistivity is in the range between 0.1 and 100 000 k Ω cm (Whiting and Nagi, 2003), which allows concrete to be classified as a semiconductor. The two main parameters that define concrete resistivity are its pore volume and saturation degree. The electric current through concrete is entirely driven by the ions dissolved in the pore liquid (Hanson *et al.*, 1985), whereas aggregates can be regarded as electrically inert. The drier the concrete, the less electric current flows. Therefore, determination of concrete resistivity allows one to infer its moisture content. Provided that the resistivity of the pore liquid can be considered invariable, the content of pore liquid may be assessed through resistivity values. Hence, concrete resistivity is a useful indicator beyond durability concerns. In fact, concrete resistivity may be used as indicator for any moisture dependent property of the concrete.

Archie's law (Equation 1) (Whittington *et al.*, 1981) relates

concrete resistivity to the resistivity of the pore liquid. It establishes proportionality between the resistivity of concrete and a power of the evaporable moisture content. From this relationship, a so called formation factor (F) can be obtained, which refers to the ratio between concrete resistivity and the resistivity of its conductive phase (Whittington *et al.*, 1981) (Equation 2). Good agreement between results using Equation 1 and experimental data from cementitious materials has been reported (Villagrán Zaccardi *et al.*, 2009; Whittington *et al.*, 1981).

$$1. \quad \rho = \rho_s A_s \phi^m$$

$$2. \quad F = \frac{\rho}{\rho_s} = A_s \phi^m$$

Here, ρ is the resistivity of concrete, ρ_s is the resistivity of pore liquid, A_s is a coefficient, ϕ is the volumetric fraction of the pore liquid (total porosity if concrete is saturated) and m is a shape coefficient that depends on the properties of concrete. The formation factor, with values between 900 and 5000, is affected by several parameters, among which the water to cement (w/c) ratio is worth mentioning (Wilson *et al.*, 1985).

It must be pointed out that the preceding equations ignore no permanent variables that affect pore structure and the conductivity of pore liquid. Among these variables, the most relevant are the progression of hydration, carbonation, chloride ingress and microcracking. These influences may exceed the initial effect of pore geometry on the value of the formation factor (Hunkeler, 1996). They can affect the moisture content of concrete by reducing the free water content in pores or by modifying the hygroscopic characteristics of concrete.

In actual service, an increase in concrete porosity does not necessarily mean an increase in conductivity. Conductivity increases with the volumetric fraction of pores only if the concrete is fully saturated, a condition that may be assumed for concrete under water. In the case of unsaturated concrete, it is the moisture content of the concrete rather than its total porosity which is of interest in terms of conductivity. This moisture content depends on the hygroscopic characteristics of the concrete and the relative humidity (RH) of the surrounding environment.

The volume of free water in unsaturated concrete is in relation with sorption and condensation in pores, and the connectivity and size distribution of pores are of main interest in this regard. Water is introduced into a concrete matrix through connected pores, but, provided that there are no potentials for absorption or permeation, only pores up to a certain size (depending on the RH) are filled with liquid. The moisture sorption isotherms of concrete are type IV on the extended Brunauer scale (Brunauer *et al.*, 1940). This is of the sigmoid type, with a hysteresis loop typical of physical

adsorption. The occurrence of this hysteresis loop is due to the filling of the mesopores being governed by the capillary condensation phenomenon and percolating properties of concrete. Two broad categories of pores can be distinguished in concrete: capillary pores and gel pores. Below approximately 50% RH, capillary condensation cannot occur, and electric conduction will be due to the filling of gel pores and up to two molecular layers of moisture that will be adsorbed on the free surfaces of the capillary pores (Wilkoosz and Young, 1995). The conductivity of concrete is extremely low when the internal RH is below 42% due to the lack of free water (Hunkeler, 1996). Above 50% RH, capillary pores are progressively filled by condensation, and conductivity increases exponentially with moisture content (Saleem *et al.*, 1996; Wilkoosz and Young, 1995). Consequently, pore size distribution is more relevant than its total volume in relation to the electrical conductivity of unsaturated concrete.

Regarding the sorption isotherm, it is extremely difficult to experimentally determine the suction curve at absorption (Johanson, 2005) (i.e. the part of the sorption isotherm corresponding to RH > 98%) as moisture is supposed to be absorbed by a dry specimen at a certain negative pressure without having been previously exposed to free water (Nilsson, 2006). In this sense, it would be very helpful to assess the pore liquid content of concrete samples without disturbing them for weighing and a reliable relationship between electrical conductivity and moisture content would contribute to this.

The contact between electrodes and concrete surfaces is a problem when measuring the resistivity of unsaturated concrete (Larsen *et al.*, 2006; Newlands *et al.*, 2008). The most usual contact method is by means of wet sponges. This method requires that the surface of unsaturated concrete is moistened and a consequent systematic decrease in the resistance of the sample is inevitable. The absorption of moisture in the part of the specimen closest to the sponge may cause a decrease of nearly 6% between the first and third consecutive measurement (Olsson *et al.*, 2013). This bias may be more or less troublesome depending on the desired precision. Moreover, repeatability and reproducibility of the test procedure with wet sponges is uncertain, even though it is a robust method. Significant influences of contacting pressure, sponge squeezing by the operator and contact solution conductivity have been reported in resistivity measurements with the aid of interposed wet sponges between the electrodes and concrete surface (Newlands *et al.*, 2008). Accordingly, saturated calcium hydroxide and sodium chloride solutions have been proposed as the contact solution instead of water (Newlands *et al.*, 2008), with the latter being more convenient due to its higher conductivity. However, this is highly undesirable if resistivity needs to be repeatedly measured or for reinforced concrete structures in service.

A more adaptable contact mode may be to embed electrodes into fresh concrete. Resistivity measurements could thus be performed on hardened concrete at various moisture states without disrupting the contact or moisture content. Such a technique also allows for

more rapid measurements, which is a valuable advantage if frequent and/or numerous measurements are required. However, this contact method may require somewhat more complex moulds or formworks and it is hardly suitable for pre-existing structures. Furthermore, the sensors must be small enough to avoid complicating the concrete pouring operation, which is in contradiction with a realistic assessment of concrete resistivity if the distance between electrodes is insufficient to allow particles of coarse aggregate between them.

Another possibility for electrical contact is the use of painted electrodes on a concrete surface. Larsen *et al.* (2006) used this method to assess the influence of moisture content and temperature on concrete resistivity. They related the saturation degree of concrete to its resistivity. However, a corresponding relationship between the saturation degree and RH is also necessary to link resistivity to the pore structure of a particular concrete mix. In addition, studies at steady conditions (i.e. with homogeneous moisture content in the sample) are preferable to assess the homogeneous conductivity of concrete.

In work reported here, the electrical resistivity of concrete was measured through dry contact with painted electrodes on the concrete surface. The RH through the depth of normal concrete at natural exposure can vary widely. Therefore, to minimise the effect of the moisture gradient, thin concrete samples were evaluated after reaching a constant moisture content at fixed RH values. As a result, concrete resistivity, RH and pore liquid content were related for conventional concrete with w/c ratios between 0.35 and 0.50.

Experimental details

Materials

Natural aggregates were used for concrete manufacture. Coarse and fine natural siliceous sands (CSS and FSS) served as the fine aggregate. The coarse aggregate was granitic crushed stone of nominal size 6–20 mm (GCS6-20). The properties of the aggregates are listed in Table 1. Ordinary Portland cement (OPC) was used as the binder, and its chemical and physical properties are given in Table 2. A superplasticiser based on sulfonated naphthalene formaldehyde condensates was also used. Its solid residue after oven drying was 36.8% by weight and its density was 1.18 g/cm³.

Mix proportions

The proportions of the concrete mixes (N35, N40, N45 and N50, with the number in the notation indicating w/c ratio) and some

	FSS	CSS	GCS6-20
SSD density: g/cm ³	2.60	2.60	2.65
Material finer than 75 µm: %	1.52	0.71	0.55
Absorption: %	0.8	0.2	0.4
Fineness modulus	1.61	2.62	6.83

Table 1. Properties of aggregates

Blaine specific surface: m ² /kg	380
Material finer than 75 µm: %	1.30
Density: g/cm ³	3.11
Compressive strength 2 d: MPa	25.6
Compressive strength 28 d: MPa	45.2
Loss on ignition: %	2.14
Insoluble residue: %	2.50
Sulfur trioxide (SO ₃): %	2.41
Magnesium oxide (MgO): %	2.76
Silicon dioxide (SiO ₂): %	19.93
Iron oxide (Fe ₂ O ₃): %	4.00
Aluminium oxide (Al ₂ O ₃): %	4.30
Calcium oxide (CaO): %	60.38
Sodium oxide (Na ₂ O): %	0.14
Potassium oxide (K ₂ O): %	0.85
Chlorine (Cl ⁻): %	0.012

Table 2. Physical and chemical properties of OPC

concrete properties are listed in Table 3. The mix proportions were designed to maintain a similar relative volume of paste in all mixes. With different unit water content and w/c ratio for each concrete mix, slump was maintained at the same level by adjusting the dosage of superplasticiser.

Methodology

Standard cylindrical specimens (100 mm diameter, 200 mm height) and prisms (75 × 75 × 300 mm) were prepared for each batch. After casting, the samples were cured for 28 d in a curing chamber at a temperature of 23 ± 2°C and RH > 95%.

Cylindrical specimens of Ø100 × 50 mm were cut from the standard Ø100 × 200 mm specimens between 3 cm and 8 cm from their bases. This sampling was done in order to minimise the potential influence of bleeding in the specimens. Standard determinations of concrete resistivity in the saturated surface dry (SSD) condition were performed on these samples. Six samples for each concrete mix were assessed. The standard method involved applying a potential of 13 ± 1 V AC 50 Hz using stainless steel perforated discs on both sides. Electrical contact between the disc electrodes and concrete surface was assured by interposing natural fibre cloths moistened with water. The ensemble was pressed by a Sergeant screw to minimise the influence of pressing between electrodes and concrete surface.

The remaining cylindrical pieces of Ø100 × 120 mm were used for determinations of water absorption by immersion to assess the total accessible porosity. The accessible porosity refers to the part of the pore structure that is directly accessible from the surface of the specimen.

Slices of approximately 5 mm thickness were obtained by cutting the 75 × 75 × 300 mm prisms. The cross section of concrete prisms was satisfactorily represented by these samples, as the two

	N35	N40	N45	N50
w/c ratio	0.35	0.40	0.45	0.50
Water: kg/m ³	133	140	144	150
OPC: kg/m ³	380	350	320	300
FSS: kg/m ³	189	190	193	193
CSS: kg/m ³	749	754	766	767
GCS6-20: kg/m ³	980	980	980	980
Water reducer: l	6.2	5.9	6.0	3.6
Air content: %	3.0	3.1	3.0	3.1
Unitary weight: kg/m ³	2404	2417	2392	2404
Slump: cm	8.0	10.0	6.0	6.0
Water absorption in 24 h: %	3.37	3.64	3.78	3.78
Average porosity: %	8.0 (0.2)	8.7 (0.4)	8.9 (0.2)	8.9 (0.4)
Average resistivity in saturated state: kΩ cm	17.3 (0.8)	13.8 (1.1)	10.7 (1.2)	12.8 (0.7)
Compressive strength at 28 d: MPa	60.2	53.8	48.3	44.3

Table 3. Mix proportions and concrete properties; values in brackets under average porosity and resistivity are the standard deviations

largest dimensions were greater than three times the maximum aggregate size. The shortest dimension was necessary to achieve fast hygroscopic equilibrium with the surrounding environment. Ten samples for each concrete mix were used to assess sorption and resistivity in the unsaturated state. These samples were placed in a humidity controlled chamber at a constant temperature of 25°C. The chamber was set at increasing steps of RH (40, 55, 70, 80, 90, 95 and 97%) for a period of time that assured hygroscopic equilibrium. The moisture content of samples was determined by weighing them, and hygroscopic equilibrium was considered when 24 h variations in mass were less than 0.01 g. Resistivity measurements were then performed for each RH step. Finally, resistivity and moisture content of samples in the SSD state after 24 h of immersion were determined.

To measure the resistivity of unsaturated samples, a 3 mm wide band was painted with silver conductive paint on opposite surfaces of 75 × 75 mm of each thin sample. Silver/silver chloride monitoring electrodes were stuck at one end of these bands, to create a permanent electrical contact (Figure 1). Conductivity was determined by applying a potential of



Figure 1. Samples for water sorption and resistivity determination of unsaturated concrete

13 ± 1 V AC 50 Hz and measuring the corresponding current flow.

Results and discussion

The porosity (determined by evaporable water content) and resistivity of the saturated specimens are shown in Table 3: as w/c ratio increases, porosity increases while resistivity decreases. The electrical resistivity of saturated concrete depends on its pore liquid content and is therefore directly related to the total volume of accessible porosity when concrete is saturated.

Figure 2 shows the relationship between resistivity and total accessible porosity. The volume of capillary pores is reliant on w/c ratio and therefore the relationship in Figure 2 is also illustrative of the relationship between resistivity and w/c ratio.

To analyse the reliability of the results, mean values of the total

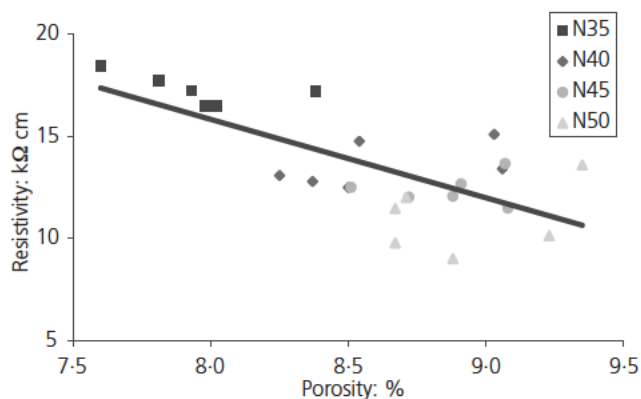


Figure 2. Resistivity–porosity relationship

accessible porosity determined by water content after saturation of 100×200 mm cylindrical specimens and 5 mm thick slices are compared in Figure 3. The analogous comparison for resistivity is shown in Figure 4, which compares the resistivity values of 100×50 mm cylindrical specimens and 5 mm slices. Equality lines are drawn in both figures to assist with the comparison and respective standard deviations are also included in both figures. Data scattering in Figures 3 and 4 is higher for slices than for specimens. The cylindrical specimens are larger in volume than the slices and more uniform results are therefore obtained for the former samples. Considering that the height of the cylindrical specimens is about ten times the thickness of slices, one specimen corresponds to the volume of approximately ten slices. The result from a single measurement in a specimen may therefore be considered equivalent to the weighted average value of the measurements of ten corresponding slices. It should be noted that, although a single value is obtained for each specimen, the variation of electrical conductivity through the sample is not appraised. As a consequence, differences in the dispersion of results may be attributed to the size of samples used for each method, as the relationship between average values of specimens and slices is consistent.

Figure 5 shows evaporable water content as a function of RH. Thin samples (concrete slices of 5 mm thickness) were used for the determination of moisture sorption isotherms. The number of samples (ten) for each concrete mix was chosen to compensate for any possible non representative result due to the small thickness in comparison with the maximum aggregate size. Figure 5 presents the mean values of ten measurements for each concrete mix.

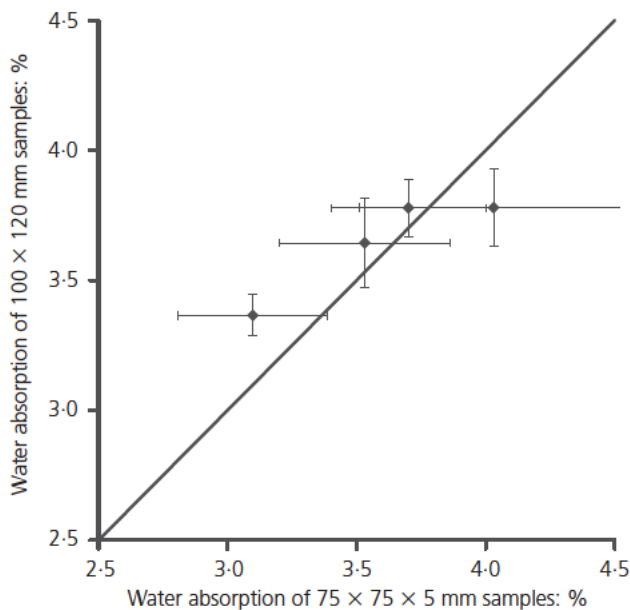


Figure 3. Relationship between maximum evaporable water content in $\varnothing 100 \times 200$ mm cylinders and 5 mm thick slices

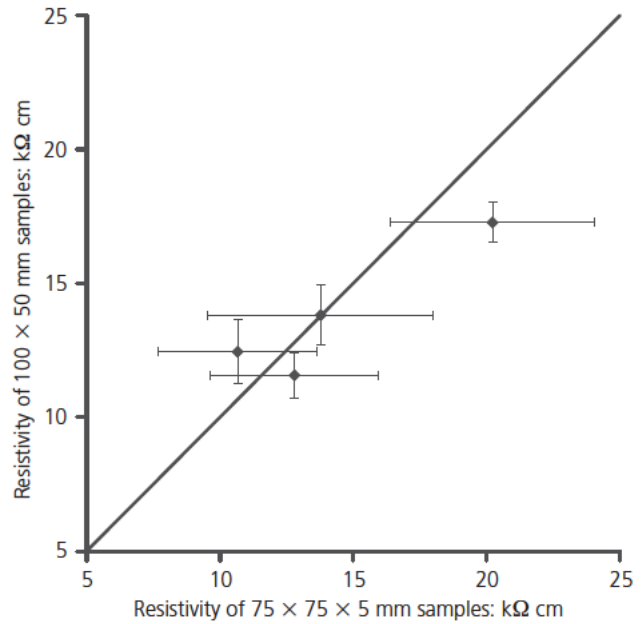


Figure 4. Resistivity of 100×50 mm cylindrical samples against resistivity of $75 \times 75 \times 5$ mm samples

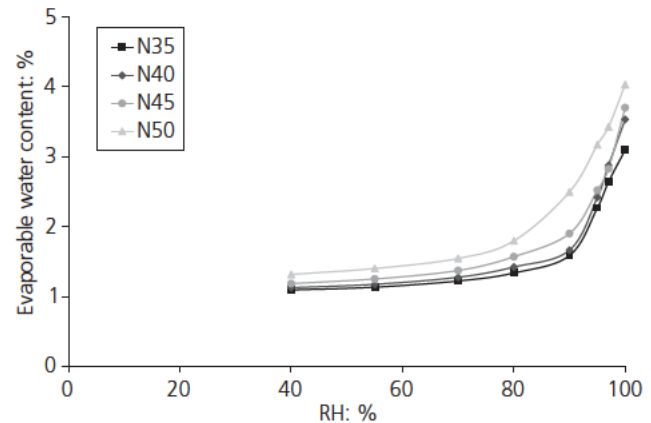


Figure 5. Water sorption isotherms of concrete

A lower moisture sorption with decreasing w/c ratio is observed. The data presented are for the sorption branch. No hysteresis effects were evaluated as desorption was not assessed. This implies that the type of isotherm cannot be verified. Nevertheless, upward curves (sorption branches) are assumed to be type IV curves on the Brunauer scale (Brunauer *et al.*, 1940) without plateaus near saturation.

Pore liquid content for concrete at hygroscopic equilibrium at $RH > 40\%$ and up to the saturation state can be derived from the curves in Figure 5. Differences between concrete mixes in the evaporable moisture content for $RH < 80\%$ show differentiations

in terms of their pore structures. Higher moisture contents in N50 are noted in comparison with the other concrete mixes. This allows one to infer a larger specific surface of the pore structure and hydration products with larger volume in N50, provided that the adsorbed layer was of similar thickness in all concrete mixes (Baroghel Bouny, 2007). However, the level of significance of these differences is low for the respective w/c ratios. The low mixing water contents used for the preparation of these concrete mixes are the main justification for this result.

Figure 5 shows small relative increases in moisture content with RH in all concrete mixes over RH = 90%, which are especially unexpected in the interval between RH = 97% and saturation. At first, it may be considered that moisture sorption would lead to a significant increase in moisture content in samples that were not previously in contact with free water but only with a humid atmosphere. However, these limited increases are consistent with concrete mixes with low capillary porosities.

Figure 6 shows the relationships between resistivity and RH. The data are plotted in a semi logarithmic scale for better appreciation. The greater relative differentiation between concrete mixes occurs at RH > 80%. Electrical current is small below this value and it should be considered that the relative error of the reading increases. At RH = 40%, the resistivity values of the four concrete mixes are very similar. Conductivity is drastically reduced at RH near 40% because moisture remaining in the pores below the critical RH = 42% can be considered as a non conducting phase (Hunkeler, 1996) (i.e. concrete conductivity tends to zero). At this condition, it is unrealistic to assume that resistivity may reflect moisture content or the specific surface of the pore structure. Moreover, the differentiation between concrete mixes according to change in weight (Figure 5) is not reflected by the changes in resistivity (Figure 6) with the same sensitivity below RH = 80%.

It is therefore of interest to compare resistivity with the evaporable water content of samples. Figures 6 and 7 respectively show

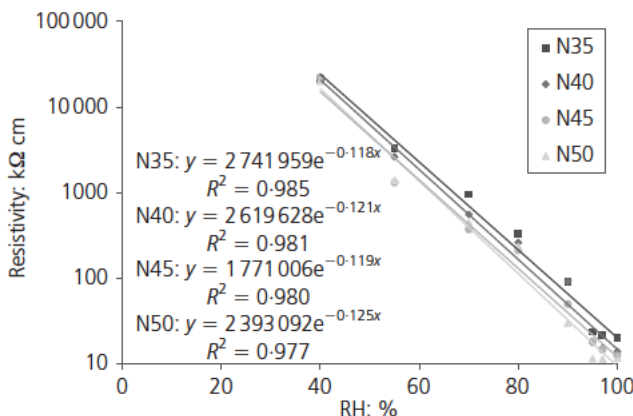


Figure 6. Resistivity–RH relationships

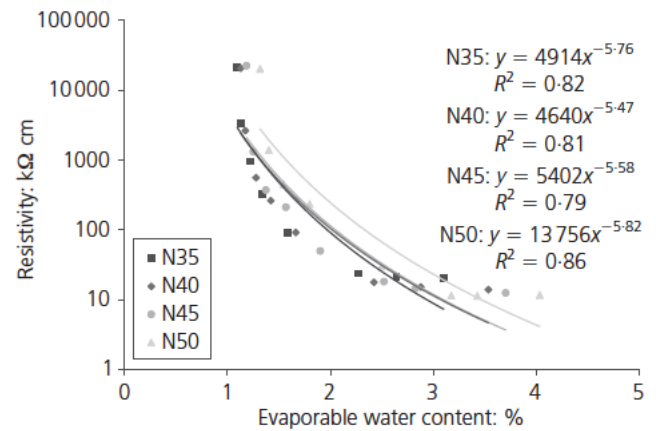


Figure 7. Relationship between resistivity and evaporable water content

the resistivity RH and resistivity evaporable water content correlations, and regression curves to Archie's law (Equation 1), for each concrete mix are presented. Only partial agreement of the data with Archie's law is obtained in both figures. The main reason for this may be that conductivity increases with the volume of conductive liquid phase as RH increases, but at low RH (< 55%), an important fraction of water is adsorbed and non conducting. The differences between the concrete mixes in this range could be related to different contents of non conducting evaporable water. However, as shown in Figure 7, there is little difference among the concrete mixes: N35, N40 and N45 have very similar relationships and only N50 shows a discrepancy with the others. Therefore, the pore solution in the four studied concrete mixes may be considered equivalent as regards conductivity, and resistivity can be related to the volume of pore liquid by a single regression to Archie's law derived from data from the four concrete mixes (Figure 8). The correlation of values to Archie's law is improved if the values for low moisture contents (RH < 55%) are not considered. This is feasible considering that Archie's law may be used to relate concrete resistivity with only the volume of conducting water rather than the total volume of

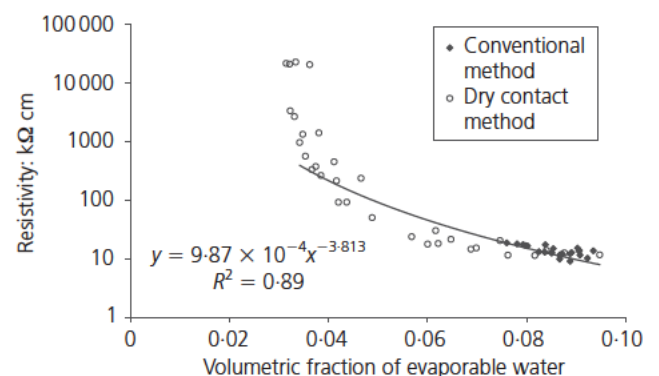


Figure 8. Resistivity versus the volumetric fraction of evaporable water

evaporable water. Therefore, values greater than 1000 k Ω cm were discarded for the regression analysis presented in Figure 8. Here, reliability is also improved by a reduction of the influence of the inherent appraisal error for the very low conductivity values, but there is still some minor influence of the non conducting water content, which causes a deviation in the data from the theoretical value modelled by Archie's law, especially between 100 and 1000 k Ω cm. In this sense, fitting could be improved if resistivity values were compared with only conducting water content. A method for differentiated measurements of conducting and non conducting water contents is necessary to completely validate Archie's law.

A practical application of the resistivity of non saturated samples thus appears. Resistivity measurements could be used to assist limited drying of samples, no further than the limit for which no free water is present in the pores. Over drying of samples would then be prevented, which is very useful when this pre conditioning procedure is required for microstructural analyses. For instance, the drying process should continue until resistivity increases over a determined threshold, which may be in the range 100 1000 k Ω cm.

Finally, Figure 8 also compares dry and wet contact methods to assess resistivity. The values obtained by both methods when applied to saturated concrete are contrasted and a remarkable coincidence is noted. It is therefore suggested that painted electrodes can be considered as efficient as interposed wet sponges for making electrical contact to a concrete surface.

Conclusions

Painted electrodes on concrete surface were used for unsaturated concrete resistivity measurements. These results were compared with those obtained by the conventional method of using external electrodes with interposed wet sponges. The main advantage of painted electrodes is that the dry contact between the electrode and the concrete surface avoids any alteration in the moisture condition of the unsaturated concrete surface.

When applied to saturated concrete with w/c ratios between 0.35 and 0.50, consistent results were obtained with both dry and wet contact methods for the assessment of concrete resistivity. Painted electrodes are thus as efficient as interposed wet sponges in terms of making electrical contact to a concrete surface.

Moreover, resistivity values were related to the conducting water content of concrete in both saturated and unsaturated states. Concrete resistivity did not agree well with Archie's law for resistivity values higher than 1000 k Ω cm and when the concrete was in hygroscopic equilibrium with the atmosphere at RH < 50%. A better correlation was found for lower resistivity values. No influence of w/c ratio was detected in this relationship, which is an indication that pore liquid conductivity is not significantly affected by the w/c ratio of concrete.

The results obtained reveal that resistivity is a useful descriptor of concrete microstructure, which could be enhanced with a simultaneous evaluation of pore liquid conductivity. This would provide complementary descriptions of concrete as a multi phase material and relationships between phases in concrete may be established on this basis.

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