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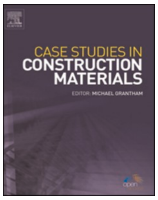

Case study

The applicability of the Wenner method for resistivity measurement of concrete in atmospheric conditions

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ABSTRACT

The Wenner probe method is an established, non-destructive method for the measurement of concrete resistivity. When testing is carried out for concrete in atmospheric conditions, electrode contact resistance is a major factor which can result in a measurement error, greatly influencing the accuracy and replicability of resistivity measurements. To achieve sufficient electrolytic contact between the Wenner Probe and concrete, surface wetting is commonly used. This is problematic as concrete resistivity is sensitive to changes in moisture content, resulting in variations in resistivity measurements. No resistivity testing Standards have been developed to achieve sufficient electrode contact without water saturation. This paper presents an innovative and practical method utilising existing Wenner Probe equipment, capable of eliminating and/or minimising the influence of these factors in atmospheric conditions. The new method minimises the impact of concrete surface variability by establishing an alternative, reliable electrolytic contact between the Wenner equipment probes and concrete.

1. Introduction

The measurement of electrical resistivity of concrete has primarily been used to evaluate concrete characteristics such as concrete durability, permeability, estimate acid permeation and chloride ion diffusivity [1–4]. The measurement of concrete resistivity can be used as an indicator of the corrosion resistance of embedded rebar in reinforced concrete structures [3,4]. In conjunction with the durability assessment of existing concrete structures, in recent years there has been increased awareness of the concrete resistivity impact on rebar corrosion and in concrete resistivity testing [5]. Concrete resistivity data is used for the assessment of corrosion risk of the embedded rebar and for assessing the compatibility of repair mortars used in conjunction with electrochemical protection systems. Normally, low concrete resistivity mortars are specified for concrete repair used in conjunction with electrochemical protection systems such as impressed current cathodic protection, galvanic corrosion systems, chloride extraction and realkalisation [5].

In concrete, the electrical current is carried by the dissolved charged ions flowing through the pore solution [6]. Resistivity of concrete is dependent on the concrete's microstructure such as capillary pore size distribution and interconnection. A finer pore network with less connectivity leads to lower permeability, equating to higher resistivity [7]. The size and pore structure are determined by factors such as cement type, water-cement ratio (w/c), pozzolanic admixtures and the degree of hydration of the concrete [8,9]. The effects of these physical characteristics are further influenced by the environmental conditions (primarily relative humidity) in which the concrete is located. Other influences such as chemical contaminants (chloride ingress in marine environments) can further

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affect concrete resistivity values. All these variables contribute to a concrete's resistivity, and for existing structures all these variables must be considered.

Concrete resistivity measurement can be performed using several destructive and non-destructive methods [10,11]. Although there are numerous methods of concrete resistivities which have been trialed in experimental works, four-point Wenner probe testing has generally been the preference for laboratory and on-site resistivity testing due to its non-destructive nature, quick measurement, and compact design [7].

Fig. 1 displays a four-point Wenner probe schematic. The four-point Wenner probe consists of four equally spaced linear electrodes with a distance (a) between each probe.

The measurement of electrical resistivity *(p)* is a ratio between impressed voltage *(V)* and measured current *(I)* multiplied by a cell constant. The following equation is used as a basis to calculate resistivity:

$$p = k \bullet \mathrm{R} = \mathrm{k} \bullet \left(\frac{\mathrm{V}}{\mathrm{I}}\right)$$

Where *(p)* is the electrical resistivity, *(k)* is the geometrical factor and *(R)* is the concrete resistance. Geometric correction factor *(k)* is calculated using the following formula [13]:

$$k \cong \frac{2\pi}{1.09 - \frac{0.527}{\frac{d}{a}} + \frac{7.34}{\left(\frac{d}{a}\right)^2}}$$

Where (d) is the diameter of the cylinder (mm), (a) is the probe spacing (mm).

Adoption of guidelines and standards for the measurement of concrete resistivity has been rather slow [7], with test methods only from the American Association of State Highway and Transportation Officials (AASHTO) [14] for four-point Wenner probe testing, and ASTM C1876 – 19 [15] for bulk electrical resistivity testing of concrete. AASHTO designation: T358−19 [14] is the most recent standard for concrete resistivity testing by four-point Wenner probe, detailing the method of concrete resistivity measurement for water-saturated concrete. The purpose of water immersion is to eliminate the relative humidity variable. Water-saturated concrete is typically used for the study of concrete permeability and chloride ion diffusivity research, with resistivity standards intended for this purpose [14,15].

However, concrete resistivity is highly dependent on environmental factors such as temperature and moisture content [16,17]. Research has found that when moisture decreases from 88 % to 77 %, the resistivity increased by an average of two times. When moisture decreases from 88 % to 66 %, resistivity increased by an average of 6 times [18]. Another research paper reported that in an air-dry state, concrete had approximately 50 % higher resistivity than that in saturated conditions [19].

A comparison was conducted [14] between field Wenner probe resistivity testing (testing on partially immersed sub-structure in

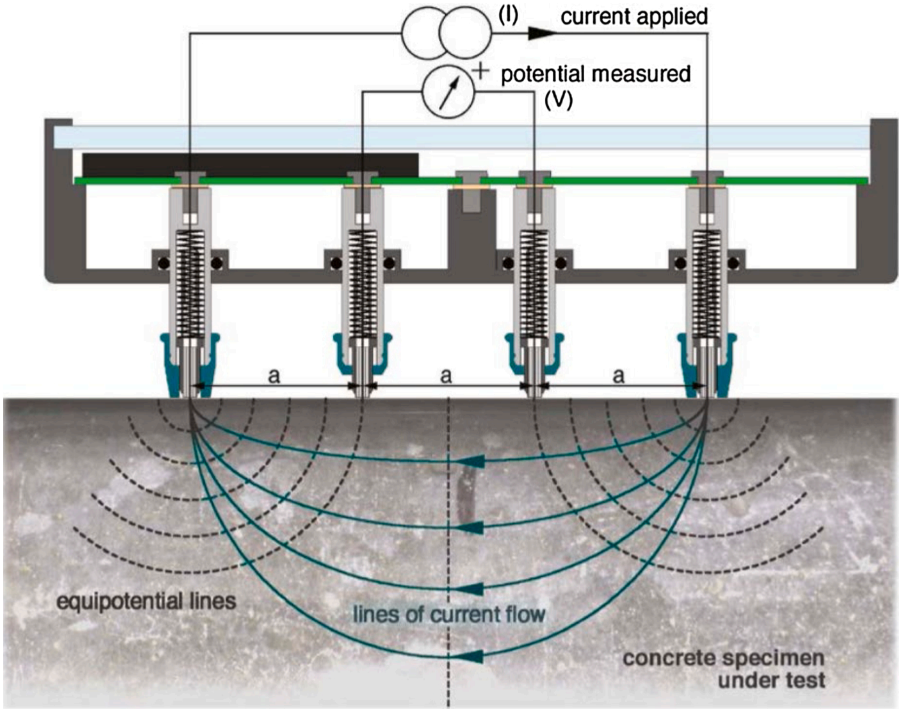

Fig. 1. Schematic of Four-point Wenner probe current flow. Images sourced from [12].

several elevations above marine growth) and laboratory tested extracted core samples from the same locations. A relationship between the field and the laboratory testing was found for a few concrete samples with low resistivity values, but no overall relationship between field testing and laboratory saturated core testing could be established [20].

Extracting core samples from a concrete structure (as per the current Standard [14]) in atmospheric conditions and exposing them to saturated laboratory conditions to determine the resistivity will result in non-comparative resistivity measurements for concrete in atmospheric conditions. Resistivity measurements of existing concrete structures must be carried out in a comparable environment to that of the structure, especially when resistivity testing is used for determining the selection of repair mortars, and for assessing the compatibility of concrete with electrochemical protection systems. However, when measuring the concrete resistivity of existing structures in the field using the four-point Wenner probe method, measurements in atmospheric locations have been found to be heavily scattered, even in single measurement locations. Concrete resistivity testing requires sufficient contact between the measurement device and concrete specimens' surface. Accurate resistivity measurements are highly dependent on the quality of this contact [21]. Various solutions involving the modification of the concrete surface to establish the electrolytic contact between the electrodes and the concrete surface have been suggested, such as the use of saturated sponges, soaked wooden plugs [22], conductive gel [23], or localised wetting [12]. The impact of these surface modifications on concrete resistivity measurements have not been studied. Research into how this contact can be achieved without the alteration of moisture caused by the addition of water or gels is limited [24]. Regardless of the recent development of new, advanced equipment for concrete resistivity measurement, there is no considerable improvement in relation to achieving a better contact between the contact probes of the resistivity equipment and the concrete surface.

Currently, there is no international standard for concrete resistivity measurements for non-saturated concrete specimens [13]. A test method statement by Main Roads Western Australia [21] briefly outlines a method of concrete resistivity testing using embedded steel probe probes, but no research work has been performed to validate this method. The use of embedded steel probes could be considered as a viable option to provide the necessary contact between a four-point Wenner probe and the concrete surface without surface moisture modifications [25,26].

The aim of the present work was to confirm the impact of water immersion on dry concrete, to confirm the validity of using embedded probes as an alternative method of achieving reliable electrolytic contact for resistivity measurement of non-saturated concrete and to identify a percentage variation between surface and embedded probe depth measurements of numerous exposure conditions and concrete mixtures. The level of variation between surface and probe measurements at selected depths was assessed. Though the comprehensive testing and verification of this method, a reproducible method to accurately measure the resistivity of concrete structures in atmospheric/non-saturated conditions has now been proposed.

2. Materials and methods

For this work, the comparison of resistivity measurements was performed between surface measurements and embedded steel probes at depths of 10–35 mm at 5 mm intervals.

Eight cylindrical concrete samples labelled 1–8 were used. Samples 1, 2 and 5 comprised of polymer modified repair mortars. The compositions of the remaining concrete mixtures are presented in Table 1. The samples were exposed to different environments: saturated/dry, tested at different time periods from curing, and comprise of different concrete mixtures to compare a broad range of environmental exposure conditions and resistivity values. The samples exposure conditions are detailed in the following sections:

3.1 Resistivity surface and probe measurements of water-saturated concrete
3.2 Resistivity surface and probe measurements of concrete in laboratory dry conditions
3.3 Resistivity surface and probe measurements of newly cast concrete in laboratory dry conditions
3.4 Resistivity surface and probe measurements of concrete before and after water immersion

Samples 1, 2 and 3 were prepared in accordance with manufacturer technical specifications. Each test sample was mixed using a paddle mixing rotary tool for a duration of 10 min. The samples were cast into ø100 x 250 mm cylinders, with samples being cured for 24 h in their PVC casts. In order to eliminate variables which may impact on the accuracy of the resistivity results, no aggregate or

Table 1
Sample compositions (gravimetric %) and exposure conditions.

Samples	Exposure Condition	GP Cement	Silica Sand	Ground Slag	Fly Ash	NaCl	Water
1	Saturated condition, long Term	Polymer modified Concrete Repair Mortar (L)					
2		Polymer modified Concrete Repair Mortar (S)					
3	Laboratory dry condition, long term	41.0 %	41.0 %				18.0 %
4		25.0 %	16.0 %	41.0 %			18.0. %
5		Polymer modified Concrete Repair Mortar (L)					
6	Laboratory dry condition, short term	25.0 %	16.0 %	41.0 %			18.0 %
7	Combined dry/saturated condition, short term	14.0 %	41.0 %		27.0 %		18.0 %
8		13.8%	40.8 %		26.8 %	0.6 %	18.0 %

rebars were used for the concrete samples.

For the temporary embedment of internal probes prior to testing each sample, four 3 mm holes spaced 50 mm apart were drilled into each concrete sample. Four 316 stainless steel marine CSK Phillips self-taping screw A4 6-gauge x 50 mm were screwed initially to the test depth of 15 mm. After the resistivity measurement at 15 mm, the screws were progressively drilled at 5 mm increments for further measurements, to the final depth of 35 mm. A four-point Wenner probe array with 50 mm spacing was used for the testing. The experimental setup for the measurement of concrete resistivity with the use of embedded probes is displayed in Figs. 2 and 3. Embedded probe depths of 15–30 mm were used in Sections 3.1 and 3.2 and 10–30 mm in Sections 3.3 and 3.4. The Wenner probe tips were placed in direct metal to metal contact with the 316 stainless-steel screws. Measurements were conducted using a commercial device for concrete resistivity measurement (Proceq four-point Wenner probe - 50 mm probe spacing which operates at a digitally generated 40 Hz AC current).

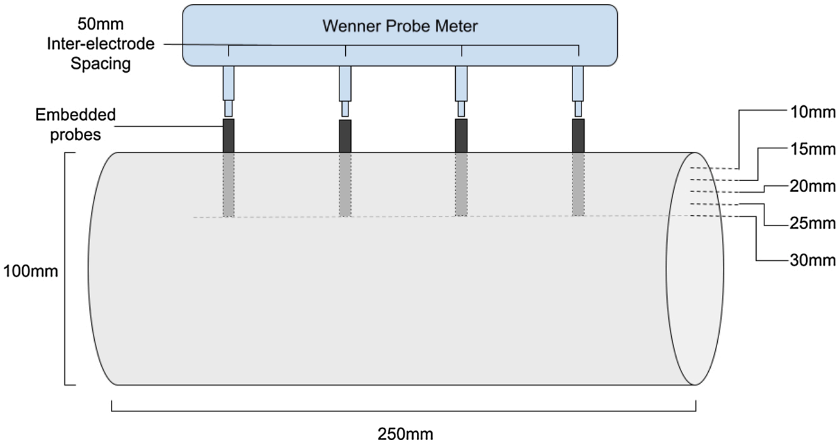

Fig. 2. Schematic of resistivity probe measurement. Figure showing 30 mm probe depth.

Fig. 3. Image of sample with embedded probes. Embedded probes installed in accordance with AASHTO Designation T359-19 surface measurement locations at 0 °, 90 °, 180 ° and 270 °.

3. Results and discussion

3.1. Resistivity surface and probe measurements of water-saturated concrete

Samples 1 and 2 were used to confirm the correlation between surface resistivity in saturated conditions (as per AASHTO T358−19 Standards) and the resistivity measured at depth using embedded stainless-steel probes.

The electrical resistivities of Samples 1 and 2 were measured in accordance to AASHTO T358−19 [14]. The samples were immersed in water for a duration of 6 months prior to testing. To perform the testing, the samples were removed from the water and the surface was cleaned with a wet sponge. Eight surface point measurements were carried out and averaged as per AASHTO T358−19 [14]. Drilling was then carried out by a 3 mm masonry drill bit. Four screws were screwed into the holes, and the first readings were measured at 15 mm screw depth. The screws were then progressively drilled and tested at depths of up to 30 mm. The results from Samples 1 and 2 are presented in Table 2.

The results show a consistent decrease in resistivity with increased probe depth. Samples 1 and 2 displayed a resistivity measurement decrease of 4.79 % (from 68.8 kΩcm to 65.5 kΩcm) and 6.84 % (from 55.5 kΩcm to 51.7 kΩcm) between the surface measurement (tested in accordance with AASHTO T358−19) and 15 mm probe depth. The data shows that the largest change in resistivity for both Samples 1 and 2 were between the surface and 15 mm probe depth measurement. For both samples, an average decrease of approximately 1% was identified between probe depth measurements.

To validate the proposed embedded probe method a comparison of results must be made with a current universally adopted Standard, in this case AASHTO T358−19 [14]. The data of Samples 1 and 2 plotted in Fig. 4 verifies a relationship between the existing AASHTO T358−19 [14] Standard (surface measurement) and the new proposed method (probe measurements). Fig. 4 displays consistent, decreasing measurements all within a range of less than 10 % between surface measurements and probe measurements. If similar results are identified when testing concrete in atmospheric conditions, verification of this trend may lead to the development of an adjustment factor between the AASHTO Standard and the proposed probe method.

Table 2
Comparison between AASHTO T358-19 surface resistivity measurements and probe resistivity measurements of saturated samples.

	Sample 1		Sample 2	
Depth	kΩcm	% Change	kΩcm	% Change
Surface	68.8	–	55.5	–
15 mm	65.5	4.79 %	51.7	6.84 %
20mm	64.8	5.81%	51.4	7.38%
25 mm	63.9	7.12%	50.8	8.46%
30 mm	62.9	8.57%	50.3	9.36%

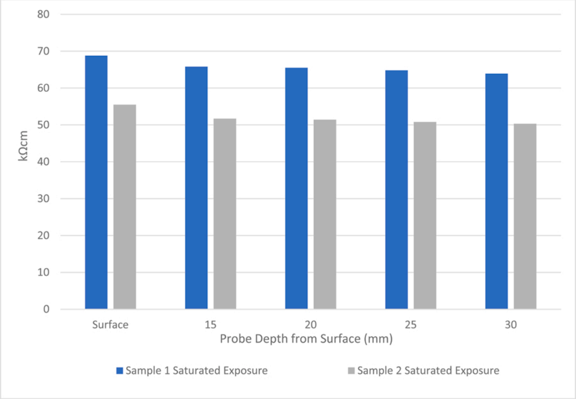

Fig. 4. Trend line of surface and probe depth resistivity measurements of saturated concrete Samples 1 and 2.

3.2. Resistivity surface and probe measurements of concrete in laboratory dry conditions

Samples 3, 4 and 5 were used to study the resistivity values between dry surface measurements and embedded probes at depths between 15 mm and 30 mm. The mixture compositions for these samples were designed to obtain samples with varied resistivities, with Sample 3 being low resistivity, and Samples 4 and 5 being high resistivity. These samples were cast and stored in dry laboratory conditions at a temperature of 23 ± 1 °C and humidity of 55 ± 10 % and tested six months after casting.

A comparison of resistivity data between surface measurements for samples in dry laboratory conditions and measurements using embedded probes at depths between 15 mm and 30 mm was carried out. The surface measurement was performed using the recommended procedure for the testing equipment [12] which included localised wetting of the concrete surface by water discharged from the equipment probe at the probe/concrete contact. The test results are presented in Table 3.

Surface resistivity measurement for the three samples could not be performed, indicating a surface resistivity value greater than the Wenner probe equipment limit of 2000 kΩcm. This data suggests that the surface of concrete samples exposed to dry laboratory conditions are unsuitable for concrete resistivity measurements beyond the recommended procedure [12] of the testing equipment (using localised concrete surface wetting at the probe contact location). It was also found that the external surface of a concrete sample kept in dry laboratory conditions for a six-month duration was not representative of the sample’s internal resistivity.

Resistivity measurement using embedded probes were performed at 15–30 mm depths and the data is presented in Table 3. The 8 resistivity measurements at each probe depth were stable, consistent, and repeatable. The resistivity data indicates a percentage change of 1.40 %, 2.54 % and 1.13 % respectively for Samples 3, 4 and 5 for each 5 mm increment with an average resistivity change of 1.69 %. The percentage change was not impacted by the resistivity magnitude (resistivity of Samples 4 and 5 was higher in comparison to Sample 3). The resistivity trend of the samples is displayed in Fig. 5.

Fig. 5 plots the probe resistivity data from Samples 3, 4 and 5. The embedded probe measurements show consistent and trends with Samples 1 and 2. This suggests that the use of internal probe measurements can be considered as a suitable and reliable alternative to surface saturation, with consistent probe measurement trends observed in both water-saturated and dry laboratory exposed concrete.

Table 3
Resistivity embedded probe measurement of dry concrete samples after 6 months from casting (concrete surface too dry for surface measurements).

Depth	Sample 3 kΩcm	Sample 4 kΩcm	Sample 5 kΩcm
Surface	>Limit	>Limit	>Limit
15 mm	42.8	340	311
20mm	43.1	334	313
25 mm	42.3	327	309
30 mm	41.6	314	304

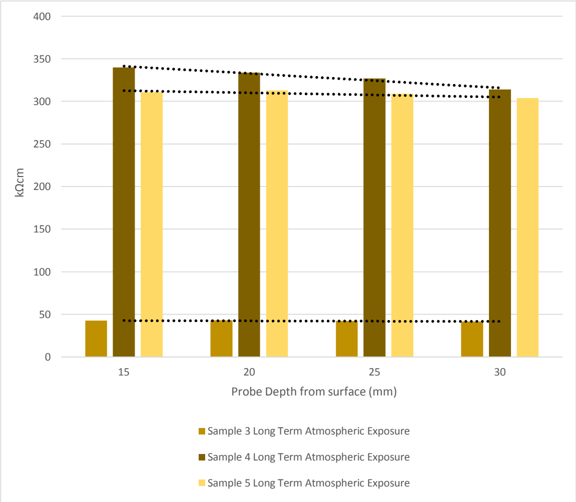

Fig. 5. Trend line of surface and probe depth resistivity measurements of dry concrete Sample 3 (low resistivity), Samples 4 and 5 (high resistivity).

3.3. Resistivity surface and probe measurements of newly cast concrete in laboratory dry conditions

Sample 6 was used to compare surface resistivity testing and embedded probe resistivity testing while the moisture content of the concrete was still high after a relatively short duration from casting (14 and 30 days).

Sample 6′s mixture was designed to obtain rapid resistivity increase over a short period of time (with the addition of fly ash in the composition). The sample was stored and tested in dry laboratory conditions at a temperature of 23 ± 1 °C and a humidity of 55 ± 10 %. The resistivity test was performed at 14 days and 30 days from the date of casting. The data gathered is presented in Table 4.

Surface resistivity measurements of Sample 6 were performed without the use of any surface saturation. This was due to the available surface moisture from the sample casting after both 14 and 30 days. As the surface resistivity of Samples 3, 4 and 5 could not be measured after six months of exposure to dry conditions, the data suggests that the drying out of the concrete surface may be the contributing factor. This is further supported by the increase in resistivity readings for Sample 6 between the surface and the 10 mm probe depth reading of 0.15 % (from 66.3 kΩcm and 66.2 kΩcm) at 14 days, and 5.08 % (from 342.4 kΩcm and 325 kΩcm) at 30 days.

Fig. 6 plots the surface and probe depth resistivity measurements of Sample 6. Embedded probe measurements showed similar trends to saturated and dry concrete samples as tested in Samples 1–5, with the results consistent and replicable.

Based on this experiment, resistivity testing could be carried out without the addition of surface wetting or saturation up to 30 days from casting. Within this period, the level of surface moisture can be assumed to be sufficient to establish electrolytic contact. In practice, varied exposure conditions will impact on the level of surface moisture, affecting this 30-day timeframe.

Table 4
Resistivity measurement of dry sample at 14 and 30 days after casting.

	Sample 6 (14 Days)		Sample 6 (30 Days)	
Depth	kΩcm	% Change	kΩcm	% Change
Surface	66.3	–	342.4	–
10 mm	66.2	0.15	325	5.08
15 mm	64	3.46	314	8.29
20mm	62.4	5.88	300	12.38
25 mm	57.5	13.27	290	15.30
30 mm	56.7	14.47	288	15.88

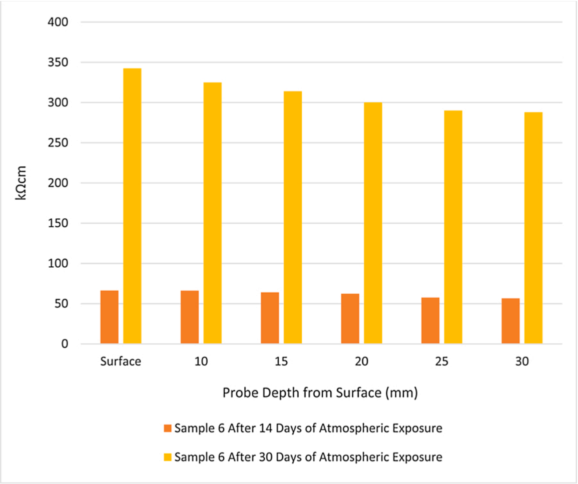

Fig. 6. Trend line of surface and probe depth resistivity measurements comparing effect of dry laboratory exposure duration (14 and 30 days) on resistivity measurements.

3.4. Resistivity surface and probe measurements of concrete before and after water immersion

Samples 7 and 8 were used to evaluate the impact of water immersion on the resistivity value between surface measurements and measurements using embedded probes in the concrete. Two sample mixtures (samples 7 and 8) were designed to provide different resistivities. Samples 7 and 8 were cast and stored in dry laboratory conditions for six months at a temperature of 23 ± 1 °C and a humidity of 55 ± 10 %.

Surface and probe resistivity measurements were carried out in dry laboratory conditions. Immediately following the dry surface and probe depth measurements, 7 and 8 were immersed in water with surface resistivity measurements carried out at 1, 2, 3, 24, 48 and 72 h from water immersion. The data gathered from Samples 7 and 8 is presented in Table 5.

The results from Samples 7 and 8 can be divided into two groups: Group one before immersion and Group two after immersion. Group one results indicate that the resistivity test measurements at surface dry conditions and using probe depth between 10 mm and 30 mm is consistent with the testing of the previous experiments. The percentage change is lower for the sample with low resistivity (3.55 % at 15 mm depth for Sample 7) and relatively higher for the sample with relatively higher resistivity (7.92 % at 15 mm depth).

For the resistivity readings following immersion (Group two), the data shows a large drop in resistivity between dry and saturated conditions with a decrease in resistivity of over 80 % for both Samples 7 and 8 after 72 h of immersion.

Sample 7 indicated a surface resistivity of 50.6 kΩcm, the immersion impact ranged between 8.3 % (from 50.6 kΩcm and 46.4 kΩcm) after 1 -h of immersion to 81.81 % (from 121.1 kΩcm and 21.8 kΩcm) after 72 h of immersion.

For Sample 8 which indicated a surface resistivity of 121.1 kΩcm, the immersion impact ranged between 81.99 % after 1 -h of immersion to 96.44 % after 72 h of immersion.

Samples 7 and 8 indicated that immersion of the concrete substantially alters the measured concrete resistivity. The current procedure for testing atmospheric concrete based on the AASHTO T358−19 [14] by extracting cores and testing concrete resistivity of these cores under saturated conditions will result in highly inaccurate and non-representative resistivity data for concrete in

Table 5
Resistivity measurements of dry concrete samples before and after water immersion.

		Sample 7		Sample 8	
		kΩcm	% Change	kΩcm	% Change
Surface Readings	Dry	50.6	–	121.1	–
	Saturated 1h	46.4	8.30%	21.8	81.99 %
	Saturated 2h	37.5	25.88 %	8.0	93.39%
	Saturated 3h	25.7	49.20%	5.6	95.37%
	Saturated 24h	11.3	77.66 %	3.8	96.86%
	Saturated 48h	9.8	80.63%	4.0	96.69%
	Saturated 72h	9.2	81.81 %	4.3	96.44 %
Probe Depth (In Dry Conditions)	10 mm	47.5	6.12%	111.1	8.25%
	15 mm	48.8	3.55 %	111.5	7.92 %
	20mm	49.5	2.17%	111.6	7.84%
	25 mm	49	3.16 %	110	9.16 %
	30 mm	47.7	5.73%	108.5	10.40%

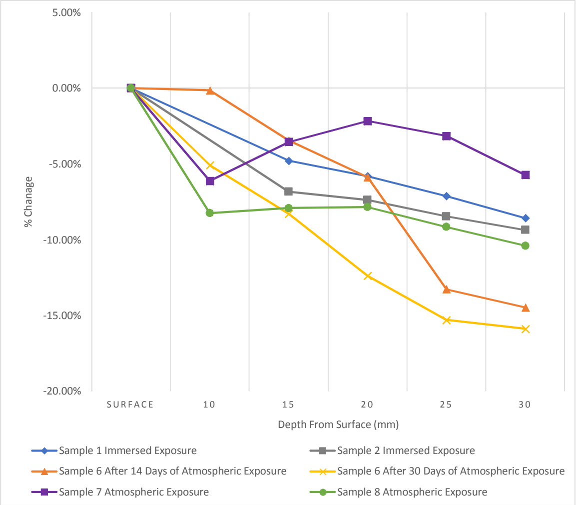

Fig. 7. Percentage change from surface resistivity measurement and measurements at probe depths between 10 and 30 mm.

atmospheric conditions.

Samples 7 and 8 confirm the need for a methodology which can provide the required electrolytic contact between the Wenner Probe and concrete without water saturation or surface wetting.

3.5. Depth of probe measurement percentage change

Fig. 7 displays the resistivity measurement data from Samples 1, 2, 6, 7 and 8 (samples where surface resistivity measurements could be performed). The chart displays the surface percentage decrease for these samples at the recorded probe intervals of 10, 15, 20, 25, 30 and 35 mm probe depths. The figure shows that all measurements at 10–15 mm probe depths are within 9% of surface measurements, with a 16 % range between 10–30 mm probe depths. The resulting trend is similar in all the samples tested, regardless of the admixtures or sample exposure conditions. The data shows that the range of variation between surface and embedded probes is consistent with samples tested in saturated and dry conditions.

Fig. 7 identifies that the smallest variation of measurements between the samples was recorded at 15 mm probe depths, suggesting that a 15 mm probe depth is most consistent when comparing probe depth resistivity measurements to sample surface resistivity readings in all tested conditions and all tested concrete compositions. The data presented in Fig. 7 can be used to develop an adjustment factor between surface measurements and measurements at probe depth.

3.6. Applications

The AASHTO T358−19 [14] Standard was developed to indicate the concrete's ability to resist chloride ion penetration and has become a universally adopted method for Wenner probe concrete resistivity testing. This is due to the increasing adoption of the Four Point Wenner probe equipment as it is quick and simplistic, particularly with the development of new generation handheld Wenner Probe equipment [12].

In the field, a lack of an established method for testing concrete in atmospheric conditions has led to the adoption of the AASHTO T358−19 [14] Standard by concrete material manufacturers, as resistivity testing must be in accordance with a Standard. Due to this, concrete manufacturers commonly test in accordance with AASHTO T358−19 [14], conducting concrete resistivity testing in saturated conditions. As presented in Table 5 of this paper, water saturation will yield unrepresentative results, making current accepted practices with testing to the Standard problematic particularly for products being designed to be used in atmospheric conditions. In practice, these misleading results impact the selection process regarding the suitability of repair mortars, and the design of electrochemical cathodic protection systems.

This paper presents a simple methodology, utilising established Wenner probe equipment to measure resistivity in atmospheric conditions. The method presented in this paper identifies a relationship with the current AASHTO T358−19 [14] Standard. Further research and testing of this method may lead to the creation of a new concrete resistivity Standard, or the adoption of this methodology into the AASHTO T358−19 [14] Standard for the testing of concrete resistivity in atmospheric conditions. This would mean reduced errors caused by water saturation/surface wetting, and hence provide more representative results both in laboratory conditions and in the field.

4. Conclusion

This research identifies that water immersion of dry concrete greatly alters the resistivity measurements significantly, with concrete samples displaying a resistivity measurement decrease of over 80 % between dry conditions and after 72 -hs of water immersion. Testing concrete resistivity for atmospheric concrete based on AASHTO T358−19 [14] standard by extracting cores and testing the resistivity of these cores under saturated conditions will result in highly inaccurate and non-representative resistivity data for concrete in atmospheric conditions.

This establishes the need for a reliable method of achieving sufficient electrolytic contact without the alteration of the concrete surface's moisture content. This research identifies that by using temporary embedded steel probes, it is possible to eliminate the need for any surface moisture alteration or concrete sample immersion, which would otherwise introduce additional variations. In addition, the method proposed in this paper has shown to provide quick accurate and repeatable resistivity data, a method which can be carried out in not only laboratories but also on-site and using the widely adopted and available concrete Wenner probe equipment, without the need for any additional specialised equipment.

Based on the results in this work, a 15 mm probe depth was identified to provide the most consistent resistivity measurements of concrete in varied exposure conditions and compositions, with a resistivity measurement decrease of up to 8%, between surface and probe measurements.

The output from this research work can contribute to the development of guidelines for the measurement of concrete resistivity via the Wenner probe in atmospheric conditions.

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Declaration of Competing Interest

The authors report no declarations of interest.

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