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The effect of curing, specimen thickness, and saturation on surface resistivity of concrete

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Abstract. Electrical resistivity measurements are used to assess the potential durability of concrete. The surface resistivity method is a popular method because of the ease of testing, non-destructive nature, and time efficiency. The moisture state of concrete has a significant influence on the resistivity results. Laboratory specimens cured using practical curing methods should be saturated before testing to eliminate this effect and avoid incorrect interpretation of the results. However, the available standard test methods for surface resistivity do not deal with this issue. Consequently, an experimental study has been conducted on the effect of drying on concrete resistivity values, as reported in this paper. The results show that a reduction in the specimen thickness can improve the ability of the surface resistivity method to be used for assessing curing effectiveness.

1. Introduction

Various tests have been developed globally for prequalification, quality control, and conformity assessment to ensure that relevant durability properties of concrete are measured using suitable means. Different types of electrical tests are available to verify the resistance of concrete against chloride-induced corrosion of reinforcing steel, which is pervasive in marine conditions and regions where the use of de-icing salts is common. In the case of chloride-induced corrosion, cover concrete plays the most crucial part in protecting the steel from chloride attack. Hence, the test used to evaluate the resistance of cover concrete against deleterious agents—in this case, chloride ions, moisture, and oxygen—are also required to be sensitive to the factors that may affect the quality of cover concrete and therefore the service life of the structure. This is essential in order to assist the designer to make proper design choices regarding materials, and processes. Some of these factors are binder type (chemical and physical microstructure), w/b ratio (degree of hydration and pore structure), compaction (porosity and voids), curing (degree of hydration, porosity, cracking, etc.), etc. [1].

Surface resistivity testing using the 4-probe Wenner arrangement is one of the easiest and quickest methods for this purpose. It has been used in different parts of the world for quality control and as a basis for service life prediction [2], [3]. The surface resistivity method (SR), while simple and efficient to perform, depends on factors such as moisture conditions, pore solution conductivity, the geometry of the specimen/member, probe spacing, and the presence of rebar, among other things [3], [4]. Among these factors, moisture content seems to be the overriding factor in situations where concrete cannot be kept under saturated conditions [5]. The AASHTO method for determining resistivity also prescribes that the specimens be kept under saturated conditions from the point of demoulding to the point of testing [6]. Curing methods used on site, whether membrane-based or water-based, always have a drying period associated with them before the standard 28-day testing is carried out for quality control or conformity assessment. The efficacy of the curing method adopted should ideally also be evaluated for its influence on the durability properties of concrete given the importance of curing on cover concrete properties.

In such cases where the cover concrete is under partial water saturation at best, the obvious issue with using the SR method is that it can give a false indication of better quality because the apparent resistivity increases as the degree of saturation of concrete decreases. Despite the implications of this factor on the use of SR as a durability indicator, most of the research on the influence of moisture state of concrete on SR deals only with the effect of loss of moisture from a saturated surface [7]. This study; therefore, focuses on the influence of an unsaturated state resulting from the practical curing methods such as plastic curing on SR for its use as a durability indicator.

This paper is an attempt to study these effects and explore ways to resolve this problem so that the SR method can be reliably used as a short-term test for a more realistic assessment of durability properties of concrete structures cured using field curing methods. The aspects investigated in this paper are as follows:

1. The effect of immersion time on concrete SR
2. The effect of specimen thickness on concrete SR
3. The effect of curing methods on the surface and bulk resistivity, and the porosity of concrete

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2. Experimental program

2.1 Concrete mix proportions and curing methods

A total of 6 mixes were selected with different binder types, and w/b ratios to cover a wide range of concrete mixtures. The mix proportions and other properties are shown in Table 1. 150-mm cube specimens were cast for each mix in the lab according to the standard procedures. One specimen from each mix was subjected to one of the two different curing regimes used in this study.

The two curing regimes used in this study are described as follows: 1. Wet curing (W): In this curing regime, the specimens were stored in a lime water bath (21ºC) after demoulding until the age of testing, and 2. Plastic curing (PL): In this curing regime, the specimens were wrapped with 2 layers of Cling Wrap® for 7 days and stored at 21ºC and 55% RH. At the end of 7 days, the plastic wrapping was removed, and the specimens were left in the same environment until the age of testing with the test surfaces exposed to air.

The wet curing regime represents the standard lab curing practice typically followed for surface resistivity testing—and lab testing in general, while the plastic curing regime attempts to simulate a common curing practice followed on site. Plastic curing regime involves a drying period between the removal of the plastic film and the age of testing. This results in the gradual progression of the drying front from the surface to the interior of concrete due to evaporative losses of moisture to the environment. Since the specimens used for this study were of age greater than 400 days, there was some carbonation observed. This is not ideal, but the average carbonation thickness was under 5 mm in the plastic cured specimens for most mixes [PC-0.4 (0 mm) BS(50)-0.5 (6 mm)], which is under 1/10th of the probe spacing (50 mm) and is expected not to have significant implications for the results of this study.

2.2 Specimen preparation and pre-conditioning

Two directly opposite moulded faces of the specimens were selected randomly for each of the plastic cured specimens and the remaining faces were coated with a 2-part epoxy coating. The epoxy coating was left to dry for a day and then the specimens were placed in the same lime water bath as the wet cured specimens—to eliminate possible temperature differences. The epoxy coating was applied to ensure that water absorption is allowed from only one direction to simplify analysis. No coating was applied on wet cured specimens as all sides were already exposed to water for a long time (>400 days) and no further significant water penetration could be expected from the sides perpendicular to the test faces—two opposite moulded faces were selected for this curing type, too.

For the first part of the investigation (Section 3.2), the specimens were kept immersed for 7 days in total, before they were cut to reduce the specimen thickness. Three specimen thicknesses were investigated: 150 mm, 75 mm, and 50 mm using the same cross-section area (150 mm x 150 mm). The minimum thickness was restricted to 50 mm to avoid disrupting the current density excessively. The outer face of the specimens was kept intact for each thickness and rather the thickness was reduced from the inner face. This was done to ensure that the portion of the specimen, which will be most affected by curing is never removed. After every cutting operation, the specimens were returned to the lime water bath for 48 hours before testing. Resistivity measurements were performed after 48 hours of immersion in lime water in an attempt to saturate the cut side of the specimen and reduce the unsaturated portion of concrete.

Two 70-mm diameter cylindrical cores were extracted from each section after the testing on 50-mm sections were completed. The inner 20-mm deep section was sliced off to obtain 30-mm thick slices for porosity and bulk resistivity testing.

Table 1. Mixture proportions (kg/m^3) and other details *[FA (fly ash), BS (ground granulated blast-furnace slag)]*

Binder type	w/b	CEM I 52.5N	FA	BS	Water	Stone*	Sand#	SP^ (%b)	Slump (mm)	Density	Age (days)
PC	0.4	425			170	1000	876	0.4	90	2424	483
PC	0.6	283			170	1000	997	0.4	80	2403	625
FA-15	0.6	236	42		167	1000	998	0.3	115	2396	511
FA-30	0.4	285	122		163	1000	877	0.2	100	2400	476
BS-25	0.6	211		70	169	1000	998	0.4	115	2400	615
BS-50	0.5	167		167	167	1000	948	0.4	120	2402	666

Western Cape Greywacke stone (Hornfels)| #Dune sand : crusher sand - 60 : 40 (by mass)| ^PCE based

2.3 Testing

2.3.1 Surface resistivity

Surface resistivity was measured using a commercially available 4-probe Wenner resistivity arrangement with a uniform probe spacing (‘a’) of 50 mm. The resistivity was calculated using the Wenner expression (Eq.1), where R (resistance) is calculated as (V/I) using Ohm’s law. The measurements were taken on both the diagonals of each 150-mm square cross-sections and the results were averaged on these four observations from two different faces [8]. The probes were wetted with lime water before taking measurements to establish proper electrical contact with the concrete surface.

$$\rho = 2\pi a R \qquad (1)$$

2.3.2 Bulk resistivity

Bulk resistivity (BR) was performed on the 2-electrode setup consisting of two steel metal plates encased in an acrylic housing and clamped tightly on either side of the specimen [8]. A thin (about 2-mm thick) layer of paper towels soaked with lime water (which is a conductive solution) was inserted between the electrodes and the concrete surface to ensure proper electrical contact. The setup was then connected to the same Wenner probe used for surface resistivity measurement and the results obtained were corrected for the difference in the cell constants between the surface and the bulk resistivity arrangements. The bulk resistivity measurements were taken on a vacuum saturated specimens of 30-mm thickness and 70-mm diameter. The specimens were prepared as described in the next section.

2.3.3 Porosity

Porosity was measured on 70-mm diameter, 30-mm thick slices using the vacuum saturation method after 7 days of oven drying at 50ºC [9]. The top 5 mm layer was removed from the concrete during the preparation of these specimens, which means that these specimens were extracted from the thickness portion 5-35 mm of the parent concrete, which effectively removes the skin layer affected by surface defects and carbonation.

3. Results and discussions

3.1 Surface resistivity and curing methods

The specimens (150-mm cube) were immersed in lime water for 48 hours at the age of testing (28 days and 365 days) to negate the effect of drying on the resistivity results and obtain a measure of difference in the qualities of the concretes subjected to different curing conditions. However, even after 48 hours of immersion—as Table 2 shows—the surface resistivity of all the mixes cured with plastic curing are higher at one or both ages of 28 and 365 days compared to those for wet curing (with the clear exception of FA(30)-0.4). The resistivities increase with an increase in the duration of wet curing for all the binder types and w/b ratios. The order of improvement is FA>BS>PC, where concretes with higher binder replacement levels seem to improve more. This primarily seems to be due to the increased degree of hydration and the resulting densification of the microstructure with prolonged curing.

The resistivities of plastic cured concrete also increase with age; however, the reason for those increases may be different. In this case, the reduction of the degree of saturation of concrete due to drying will also play a significant role in increasing the resistivity in addition to the possible, although uncertain, increase of the degree of hydration of the portion of concrete that remains shielded enough from drying. These results, at a first glance, gives the impression that the quality of curing does not have any beneficial influence on the resistivity of concrete and even the "less effective" curing method—plastic curing—would be better for durability. To investigate whether this confounding effect of moisture state of concrete on resistivity can be eliminated or at least reduced significantly for practical purposes, further investigations were carried out on the same specimens.

3.2 Effect of immersion time on absorption and resistivity

The plastic cured specimens, after the resistivity measurements at the age of 365 days, were returned to the drying environment for at least 100 days. At the age of testing as shown in Table 1, the mass of the test specimens was measured and considered to be the dry mass of concrete on which the degree of water absorption is based. These specimens were stored in lime water, and their masses and surface resistivities measured at regular intervals as shown in Figure 1 and Figure 2, respectively.

Table 2. Average surface resistivity in kohm.cm (± standard deviation) for 150-mm cube specimens under different curing conditions at the age of 28 and 365 days

Mix	Wet curing		Plastic curing	
	28 days	365 days	28 days	365 days
PC-0.4	11 ± 0.6	18 ± 1.4	11 ± 0.6	20 ± 1.5
PC-0.6	7 ± 0.4	11 ± 0.5	8 ± 0.5	15 ± 1.0
FA(15)-0.6	8 ± 0.4	37 ± 1.6	9 ± 0.6	29 ± 2.3
FA(30)-0.4	25 ± 1.3	167 ± 8.1	23 ± 1.6	142 ± 8.1
BS(25)-0.6	18 ± 0.6	46 ± 2.2	20 ± 1.7	60 ± 4.7
BS(50)-0.5	44 ± 2.1	134 ± 8.8	51 ± 3.6	167 ± 6.1

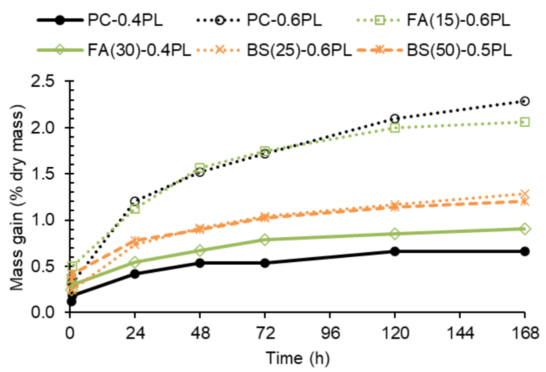

Figure 1. Mass of water absorbed, as a percentage of the dry mass of the corresponding 150-mm cube specimens (plastic cured), with immersion time (from 30 minutes to 7 days)

In Figure 1, the amount of absorption seems to depend on the w/b regardless of the binder type used, in general; however, it is not a rule. The 0.6 w/b concretes absorbed more than double the amount absorbed by the 0.4 w/b concretes. The high w/b concretes also tended to continue to gain mass for longer, i.e., while the mass gain for the 0.4 and 0.5 w/b concretes slowed down after 48-72 hours considerably, the 0.6 w/b concretes were still gaining mass after 6 days.

The surface resistivity results (Figure 2) show that the 1-hour values are at the minimum 90% higher than the 7-day values, which demonstrates that SR measurements on field structures would still suffer from inaccuracies even when some effort—1 hour of water sprinkling, for instance—is put into wetting the cover concrete. The surface resistivities decrease sharply within 24 hours of immersion. However, reduction continues albeit slowly even after 3 days.

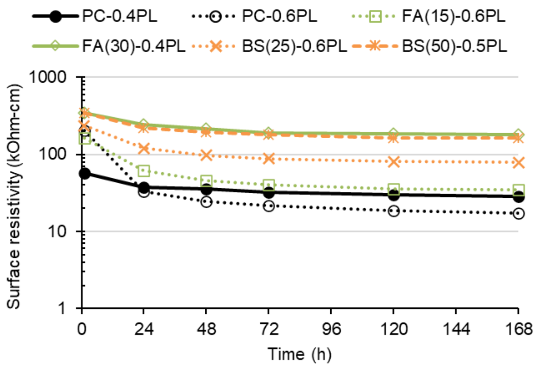

Figure 2. Surface resistivity (on a $\log_{10}$ scale) measured on 150-mm cube (plastic cured) with duration of immersion (from 1 hour to 7 days)

The SR values of plastic cured specimens remained higher than those of the corresponding wet cured specimens even after 7 days of immersion, which indicates that it would not be possible to saturate the region of influence of 4-probe method with a specimen thickness of 150 mm in a relatively short amount of time to be practically feasible as a short-term test. Therefore, the thickness of the specimen was reduced to observe if water absorption from both the ends—being less far apart—could resolve this issue.

3.3 Effect of specimen thickness on resistivity

Figure 3 and Figure 4 show the influence of specimen thickness on SR. The SR obtained after 7 days of immersion are used for the thickness of 150 mm in these results and 2 days of immersion for the other thicknesses. Same specimens were used for the entire analysis and therefore the test faces were always exposed to water—except during the cutting operation—and the 48 hours of further immersion after cutting was essentially for the cut faces to absorb water. The duration of 48 hours was selected as a compromise between the time spent on the saturation process and the degree of absorption obtained (see Figure 2). Additionally, the rate of absorption for *wet cured* specimens is expected to be lower than those depicted in Figure 2 (plastic cured concretes) because of lower penetrability of well cured concretes and lack of external drying of the pore structure. This is important because wet cured concretes are considered as control specimens to assess plastic cured specimens and therefore any effect other than the specimen thickness on the resistivity results must be avoided in order to use these results to isolate the effect of degree of saturation in the plastic cured specimens. It is, therefore, considered an appropriate assumption that the duration of 48 hours is expected to minimise any effect of lack of saturation in the wet cured specimens in a relatively short period of time.

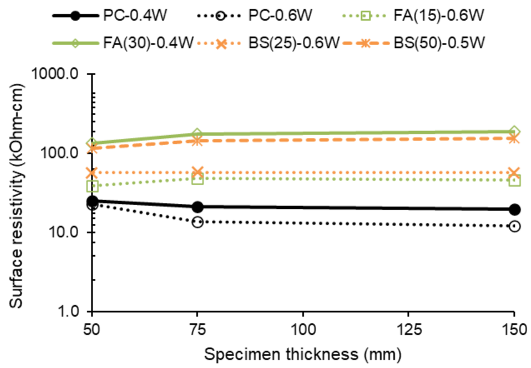

Figure 3. Surface resistivity (on a $\log_{10}$ scale) vs specimen thickness for *wet-cured* specimens

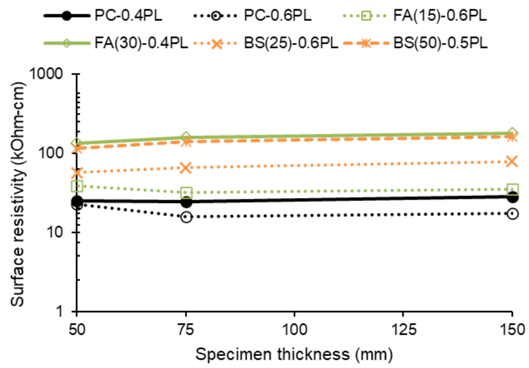

Figure 4. Surface resistivity (on a $\log_{10}$ scale) vs specimen thickness for *plastic-cured* specimens

In order to analyse the effect of decreasing the specimen thickness on SR measurements, the SR results are normalised with respect to the 150 mm thickness results for the corresponding concretes (see Figure 5 and Figure 6). At 75 mm, SR deviates from the base value (at 150 mm) within 5% for wet cured SCM concretes and from 8 to 13% for PC wet cured concretes (Figure 5). On the other hand, at 50 mm, the overall deviation increases to 28% (with only one exception of a very high 91% for PC-0.6). While these deviations are distributed on both sides of the base for wet cured concretes, all plastic cured concretes show reductions in resistivity in the range of 8-16% at 75 mm and up to 30% reduction at 50 mm—PC-0.6 and FA(15)-0.6 are exceptions at this thickness. The general trend of reduction in the resistivities with specimen thickness in case of plastic cured specimens seems to stem from the reduction in the dry area relative to that getting saturated as a result of immersion in lime water. For h/a<3 (specimen thickness-to-probe spacing), the SR is expected to give an overestimate of true resistivity with differences increasing non-linearly as h/a reduces [4], [10], [11]. The results for the control specimens (wet cured concretes) of this study however do not follow that trend.

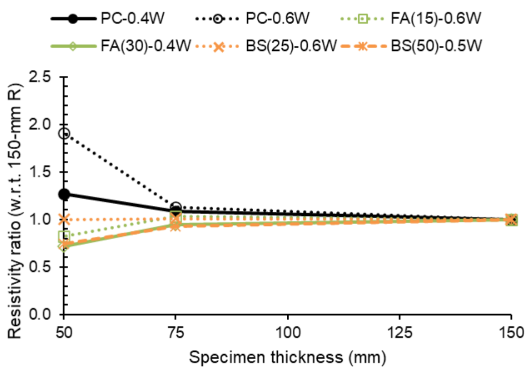

Figure 5. Surface resistivity of *wet cured* concretes at different thicknesses with respect to the surface resistivity at the initial thickness of 150 mm

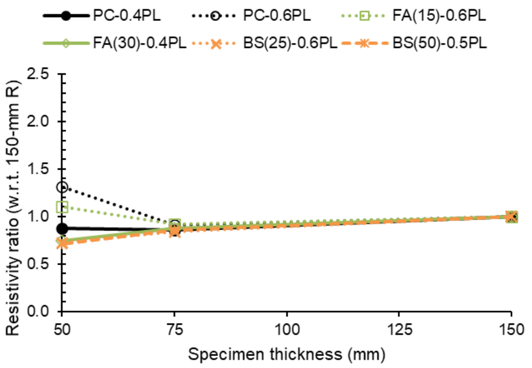

Figure 6. Surface resistivity of *plastic cured* concretes at different thicknesses with respect to the surface resistivity at the initial thickness of 150 mm

The effect of curing and degree of saturation was isolated through normalizing the resistivity results of plastic cured specimens with those of the corresponding wet cured concretes at the same thickness. The resistivity ratios thus obtained are shown in Figure 7. Generally, plastic cured concretes show a reduction in apparent resistivity, in relation to the wet cured concretes, of 7-15% when the thickness is reduced from 150 mm to 50 mm. PC-0.4 and BS(25)-0.6 show even higher reductions in the range 43-52%. At the thickness of 50 mm, all the concretes are below the resistivity ratio of 1 in Figure 7 (PC-0.6 is considered an outlier to this trend). This shows that as the portion of dry concrete reduces from the zone of influence of the 4-probe method, a better picture of the effect of curing on concrete quality emerges.

3.4 Resistivity and porosity of near-surface concrete

Table 3 presents a comparison between the base SR values (150 mm) and the bulk resistivity results on 30-mm thick slices (70-mm diameter). It can be seen that SR overestimates the true resistivity—assuming bulk resistivity as true resistivity—across all concretes although this comparison suffers from the fact that the specimen shapes are different in both cases. However, the focus of this study is to understand the effect of curing on the resistivity measurements. In this regard, bulk resistivity results on 30 mm slices (when normalized with SR results) clearly show the largest differences (from 20 to 40%) between the wet cured and the plastic cured concretes obtained so far in this study. The differences would be exacerbated considering that even 30-mm slices of concrete are often not fully saturated, which is especially the case with low w/b concretes. The differences in the microstructure because of the differences in curing method applied is also confirmed by the porosity results shown in Figure 8.

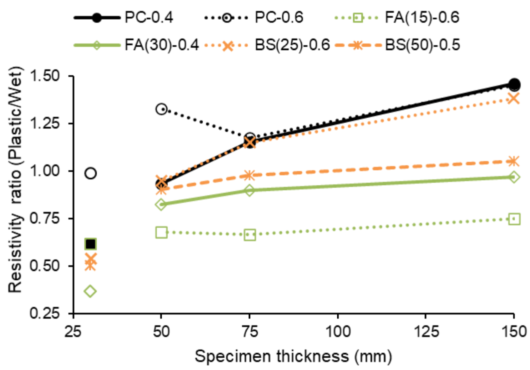

Figure 7. Resistivity ratios of plastic cured with the corresponding wet cured concretes vs specimen thickness [Results corresponding to the specimen thickness of 30 mm represent bulk resistivity measured on 70-mm diameter and 30-mm thick disks. The results for all the other thicknesses represent surface resistivity measured diagonally on 150-mm square surfaces.]

Table 3. Resistivity (kohm.cm) results for 150-mm and 30-mm thick specimens [Results corresponding to the specimen thickness of 30 mm represent bulk resistivity measured on vacuum saturated 70-mm diameter and 30-mm thick disks. The results for the specimen thickness of 150-mm represent surface resistivity measured diagonally on 150-mm square surfaces immersed for 7 days in lime water.]

Mix	150-mm		30-mm		BR/SR	
	W	PL	W	PL	W	PL
PC-0.4	20	29	17	10	0.8	0.4
PC-0.6	12	17	10	10	0.8	0.6
FA(15)-0.6	46	35	20	13	0.4	0.4
FA(30)-0.4	185	178	87	32	0.5	0.2
BS(25)-0.6	57	78	31	17	0.6	0.2
BS(50)-0.5	154	162	81	40	0.5	0.2

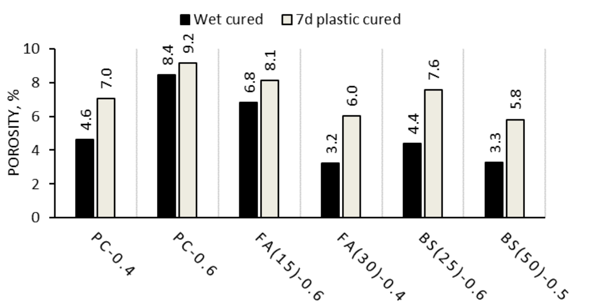

Figure 8. Porosity of the top 5-35 mm thick portion of the cube specimens as measured on 70-mm diameter cored specimens after vacuum saturation

4. Conclusions

The following conclusions can be derived from this experimental study.

1. The surface resistivity is influenced by the drying experienced by concretes subjected to practical curing regimes, which is difficult to eliminate even after 48 hours of immersion in water to get a more accurate estimate of the quality of the concrete.
2. The concretes with higher w/b ratio, and consequently, higher open porosity, absorb water for longer durations than their low w/b counterparts. However, the most significant reduction in SR seems to happen under 24 to 48 hours of immersion.
3. The relative change (w.r.t. 150 mm) in resistivity with reduction in specimen thickness seems to vary with different concrete mixes (binder type, w/b ratio) without showing any preferred direction of change.
4. Notwithstanding the variable effects of thickness reduction on SR measurements, reduced specimen thicknesses seem to provide a better indication of the influence of curing on the concrete properties, although to a limited extent, when normalized with the SR results for the control concretes (wet cured counterparts).
5. The bulk resistivity and porosity measured on smaller specimens (30-mm thick, 70-mm diameter) clearly show the distinction between the two curing methods adopted in this study.
6. It is suggested that this study be replicated at earlier ages, which are more relevant for quality control purposes to make the results more directly relevant for application and avoid the effect of carbonation that may have influenced some of the results in this study.

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