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Electrical Resistivity Measurements on Hardened Concrete Exposed to Various Curing Conditions

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Abstract. *Evaluating concrete quality and performance, especially determining the resistance of concrete to fluid and ion ingress, is fundamental to estimating concrete's durability and predicting the service life of concrete structures. Both bulk and surface electrical resistivity tests have gained increasing interest as rapid and repeatable indicators of concrete's resistance to fluid ingress. In this study, concrete electrical resistivity was measured at the ages of 56 and 91 days on specimens from five concrete mixtures exposed to different curing environments and storage solutions. Both bulk and surface resistivity of concrete in each curing condition are compared, and the effect of curing methods on electrical resistivity is discussed. The results show that conditioning in a highly-conductive storage solution, such as a simulated pore solution, led to a lower concrete resistivity measurement than when stored in saturated limewater. The effect of mixture compositions on measured resistivity revealed that for the same cementitious materials, the electrical resistivity increased as the w/cm ratio decreased, and a linear correlation between the w/cm ratio and concrete electrical resistivity was obtained.*

Keywords: *Concrete Bulk Resistivity, Concrete Surface Resistivity, Curing/Storage Conditions, Chloride Penetrability, Concrete Pore Solution.*

1 Introduction

Measuring the transport properties of concrete, especially its resistance to fluid and ion ingress, plays a significant role in understanding concrete performance and durability. To accelerate testing, electrical resistivity tests have been widely applied as rapid and non-destructive indicator for quantifying concrete transport properties.

Concrete is a composite material made up of cement, aggregate and water, and when hardened, has three phases including a solid phase (i.e., aggregate and cementitious materials), a liquid phase (i.e., pore solution) and a vapour phase (air). Since pore solution conductivity is exceptionally high relative to other two phases, the applied electric current is primarily transferred through the ion-intensive pore solution in the concrete pore system, so the electrical resistivity measurements rely on the current conducted through concrete pore solution (Spragg et al., 2012; Chen et al., 2014). Thus, electrical resistivity can be used to reflect a concrete's pore volume and pore connectivity, which relates to a concrete's resistance to fluid penetration.

In general, concrete with a more porous microstructure has a lower resistivity and a higher chloride and fluid penetrability (Chen et al., 2014).

The Nernst-Einstein relationship is used to relate concrete bulk resistivity (BR) to transport properties, such as ion diffusion, as shown in Equation 1 (McCarter et al., 2000; Nokken & Hooton, 2007; Bu & Weiss, 2014; Spragg et al., 2017):

$$\frac{\rho_T}{\rho_o} = \frac{D_o}{D} = F = \frac{1}{\beta\phi} \tag{1}$$

where, ρ_T is concrete bulk resistivity, ρ_o is the pore solution resistivity, D_o is the self-diffusion coefficient describing how various ionic species (e.g., Na^+, K^+, OH^-) move though a liquid, D is the effective diffusion coefficient, and F is the formation factor of concrete which is a material property describing the concrete pore structure. ϕ is the porosity of saturated cementitious system, and β is the connectivity of pores inside the concrete.

The concrete bulk resistivity test has been standardized as ASTM C1876 and CSA A23.2-26C, and is used as a rapid indicator as concrete's resistance to fluid ingress. However, in ASTM C1876, specimens are stored in a fixed simulated pore solution, while in CSA A23.2-26C, specimens are stored in lime-saturated water. Table 1 lists different BR ranges and their corresponding chloride ion penetrability level, suggested by CSA A23.2-26C.

Table 1. Chloride ion penetrability and bulk electrical resistivity

Chloride ion penetrability	Bulk electrical resistivity (Ω-m)
High	<50
Moderate	50-100
Low	100-200
Very Low	200-2000
Negligible	>2000

However, electrical resistivity measurements are affected by several factors. This paper aims to address the effect of specimen curing and storage conditions on concrete electrical resistivity measurements. The role of supplementary cementitious materials and water to cementitious material ratio (w/cm) is explained as well. Meanwhile, the concrete bulk and surface resistivities are compared and discussed.

2 Experimental Program

2.1 Material and Mix Designs

Canadian CSA A3001 Type GU – general use Portland cement was used to prepare concrete specimens for all mixtures; ground granulated blast furnace slag (GGBFS) and low-calcium fly ash were used as a partial replacement of Type GU Portland cement. The coarse aggregate was 19-mm crushed limestone with a specific gravity of 2.88 and a bulk density of 1750 kg/m^3. The fine aggregate was natural river sand with a specific gravity of 2.65 and fineness modulus of 2.45. A liquid polycarboxylate admixture was applied as a high range water reducer (HRWR). The mix proportions for the five concrete mixtures are presented in Table 2. Three mixtures are

Type GU Portland cement concretes with water to cementitious material (w/cm) ratios of 0.3, 0.4, and 0.6, designated as Mix 0.3PC, Mix 0.4PC and Mix 0.6PC, respectively. The other two mixtures are Portland cement concrete of 0.4 w/cm ratio with either 25% slag or 15% fly ash as the partial replacement of Portland cement, denoted as Mix 25SL and Mix 15FA.

Concrete was mixed in a 60-L capacity concrete mixer at room temperature of 23 ± 2°C and cast in cylindrical molds of 100 mm diameter and height of 200 mm. Caps were placed on the cylinder molds and then covered with wet burlap and plastic sheet to prevent moisture loss prior to demolding. Concrete specimens were demolded after 24 hours and immediately stored into the different curing environments.

Table 2. Concrete Mix Proportions

Mix ID	0.3PC	0.4PC	0.6PC	25SL	15FA
w/cm	0.3	0.4	0.6	0.4	0.4
Coarse aggregate (kg/m^3)	1041	1040	1039	1040	1040
Fine aggregate (kg/m^3)	753	800	753	800	800
Portland cement (kg/m^3)	466	400	380	300	340
Slag (kg/m^3)	/	/	/	100	/
Fly ash (kg/m^3)	/	/	/	/	60
Water (kg/m^3)	140	160	228	160	160
HRWR (kg/m^3)	9.3	8	7.6	8	8

2.2 Curing and Storage Conditions

Table 3. Compositions of different storage solutions

Proportions (g/L)	Saturated limewater	Pore solution (ASTM C1876)	Synthetic pore solution specific to each mix				
			0.3PC	0.4PC	0.6PC	25SL	15FA
NaOH	/	7.6	50.4	32.5	19.0	24.6	34.7
KOH	/	10.64	12.4	8.0	4.8	6.0	8.0
$Ca(OH)_2$	3	2.0	2.0	2.0	2.0	2.0	2.0
Conductivity (mS/cm)	9.75	79.8	223	154.4	98.6	123.5	162.2

Concrete specimens after demolding were submerged in three alkaline solutions at 23.0 ± 2.0 °C, including saturated limewater, simulated pore solution suggested by ASTM C1876, and synthetic pore solutions specific to mix proportions, designated as LW, APS and SPS, respectively. The solution compositions and conductivities are shown in Table 3. Since different concretes have pore solutions with different ion concentrations, the synthetic pore solution proportions for each mix were determined on the basis of mix design of each mixture and chemical analysis of the cementitious materials used; the main components in this solution are potassium hydroxide, sodium hydroxide and calcium hydroxide. The concentrations of K^+ and Na^+ were calculated using an online pore solution simulation model developed by National Institute of Standards and Technology (NIST), available at https://www.nist.gov/el/materials-and-structural-systems-division-73100/inorganic-materials-group-73103/estimation-pore. In addition to curing specimens in these solutions, concrete samples were also subjected to sealed-curing condition; specimens were double sealed in plastic bags with duct tape, with air eliminated from the bags before sealing to minimize moisture loss, designated as SC.

2.3 Electrical Resistivity Tests

The electrical tests involved in this study were bulk resistivity test (BR) and surface resistivity test (SR). Both tests were conducted on ø100 x 200 mm concrete cylinders using the Resipod resistivity meter from Proceq SA. The Resipod resistivity meter is a four-point Wenner probe resistivity meter with a fixed probe spacing of 38 mm for surface resistivity measurements; it operated with a 40 Hz alternating current. To measure concrete bulk resistivity using the Resipod meter, a bulk resistivity accessory kit from Proceq was used together, consisting of two stainless steel plate electrodes and cables for the connection between electrodes and the Resipod meter.

Before testing, the ends of concrete cylinders were ground to obtain plane end surface perpendicular to the longitudinal axis. After end grinding, the average diameter and length of each specimen were measured for resistivity. At each test age (e.g., 56 and 91 days), three cylinders of each mixture were removed from each curing environment and tested both electrical resistivities, then samples were placed back into their curing regimes immediately after testing. Tests were completed within 5 minutes.

Concrete surface resistivity was measured in accordance with AASHTO T358. Four surface resistivity readings were collected from each concrete cylinder by placing the probes at 0^o, 90^o, 180^o, and 270^o of the circumference on the longitudinal side of each cylinder and the average of SR was calculated.

To measure bulk resistivity, two plate electrodes were connected to the Resipod meter using cables. Two plate electrodes were placed on the end faces of concrete cylinders. Sponges soaked with the conductive fluid (e.g., the simulated pore solution) were inserted between cylinder end faces and the electrodes to ensure a good electrical contact; a 5-kg weight was also placed on the top plate to provide sufficient pressure for firm contact between samples and electrodes. Generally, the concrete bulk resistivity, ρ was determined using Equation 2:

$$\rho = \frac{V}{I} \cdot \frac{A}{L} \quad (2)$$

where, V is voltage, I is current, L is average specimen length and A is specimen cross-sectional area.

3 Results and Discussions

3.1 Effect of Curing/storage Conditions

Figure 1 shows the bulk resistivity of five concrete mixtures in different curing/storage environments measured at 56 and 91 days. It is seen that curing or storage methods have a significant impact on concrete bulk resistivity measurements because it affects the degree of saturation, degree of hydration, pore solution compositions and microstructure of concrete. For a given concrete mixture, different conditioning procedures led to different bulk electrical resistivity values, resulting in different evaluations of chloride penetrability of concrete, as shown in Figure 1. For example, the chloride penetrability of Mix 03PC was defined as "moderate" for sealed curing (SC) condition, but "low" for other curing regimes based on its BR data measured at 56 days. The Mix 25SL concrete had either low chloride penetrability or very low penetrability depending on how it was conditioned.

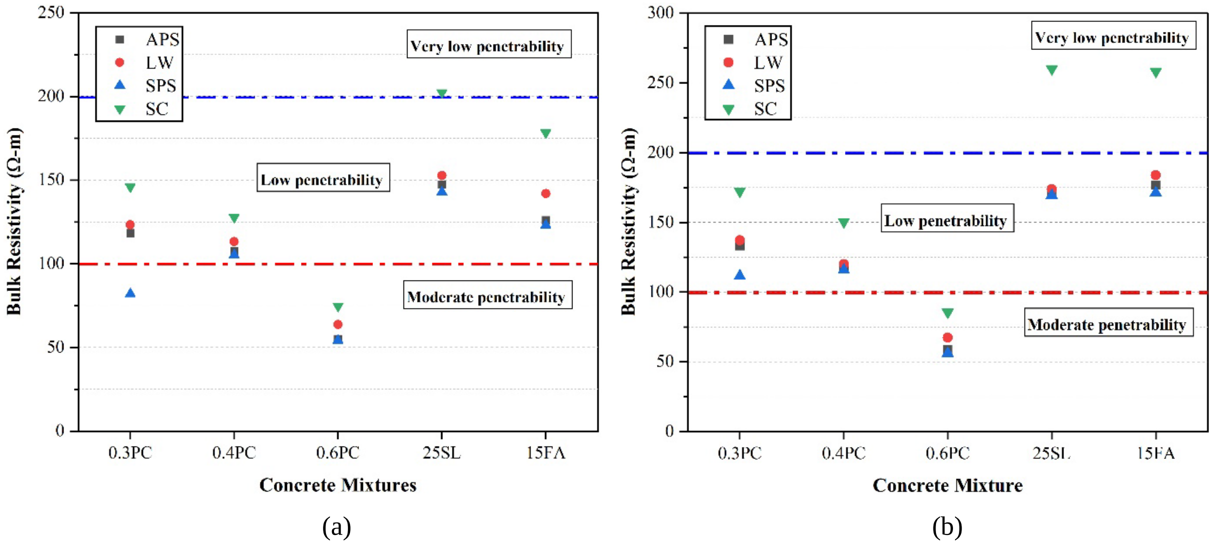

Figure 1. Concrete bulk resistivity in curing/storage conditions at 56 (a) and 91 (b) days

The sealed curing state (SC) always resulted in the highest bulk resistivity for all concretes among all curing conditions, explained by their lowest degree of saturation, which made the concrete less electrically conductive. In addition, what can be clearly seen from Figure 1 is that the difference between the bulk resistivity of concrete in Condition SC and in other curing conditions increased with the test age for all concretes except for Mix 0.6PC. Hydration reactions continuously consumed water in concrete over time and the sealed curing method did not provide specimens with additional moisture as compared with other storage conditions. Thus, the degree of saturation in SC specimens gradually decreased with age, leading to a relatively higher increase in BR. For Mix 0.6PC, its BR from Condition SC was not significantly higher than other conditions, likely resulting from a higher water content for Mix 0.6PC.

Immersing concrete specimens in alkaline solutions provides concrete specimens with sufficient moisture to keep them saturated. Thus, concretes submerged in fluids always had relatively lower electrical resistivity due to their higher degree of saturation. However, unless stored in matched pore solutions, submerging concrete can cause leaching of ions from its pore solution, due to concentration gradients between concrete pore solution and storage solution. Once ionic species leach out from concrete pore solution, ionic concentrations in pore solution decrease and pore solution resistivity increases, as a result, concrete bulk resistivity values go up (Spragg et al., 2017).

Leaching can be observed from BR values of concretes stored in different solutions. The bulk resistivity ratios of concretes in either saturated limewater (LW) or mix-specific synthetic pore solutions (SPS) to the ASTM C1876-suggested fixed pore solution (APS) are listed in Table 4. For all concretes, the BR in LW condition was on average 1.06 times higher than the BR in APS condition; while the BR in SPS condition was on average 0.94 times lower than the

BR in APS condition. For a given concrete, storing in saturated limewater resulted in the highest BR among these three solutions because the limewater has no potassium and sodium species and more alkalis were leached out from pore solution caused by the higher alkali concentration difference between concrete pore solution and limewater. The pore solution specific to each mix led to the lowest BR readings because of its high alkali concentrations that minimized the leaching of ions. Based on the Table 4 results, on average, bulk resistivity values measured using CSA A23.2-26C (i.e., LW storage) would be expected to be about 6% higher than those determined using ASTM C1876 (i.e., APS storage).

Table 4. Ratios of Concrete BR in either LW or SPS conditions to APS condition

Mix ID	LW/APS (56 days)	LW/APS (91 days)	SPS/APS (56 days)	SPS/APS (91 days)
0.3PC	1.04	1.02	0.69	0.84
0.4PC	1.05	1.02	0.99	0.98
0.6PC	1.15	1.14	0.99	0.98
25SL	1.04	1.02	0.97	0.99
15FA	1.12	1.04	0.97	0.97
Average	1.06		0.94	

3.2 Effect of Mix Proportions

Figure 2 plots the change in measured bulk resistivity of concretes immersed in the fixed simulated ASTM C1876 pore solution with curing age. It is shown that the bulk resistivity of all concrete mixtures increased with age, due to increased level of hydration affecting both the concrete pore structure and pore solution (Xue et al., 2021).

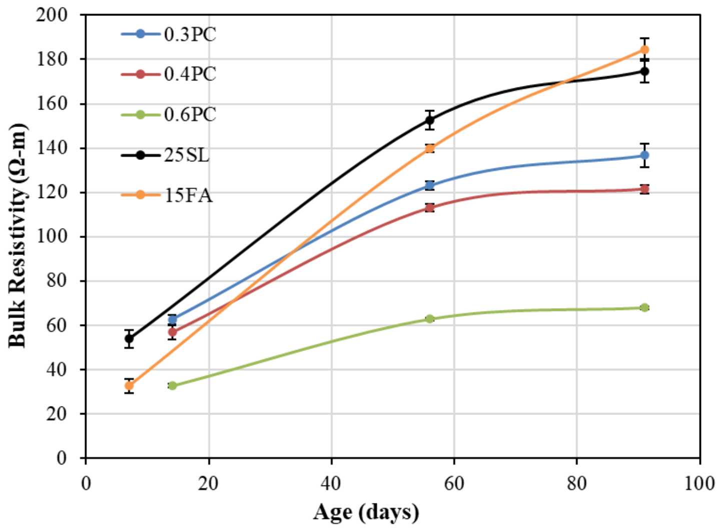

Figure 2. Bulk Resistivity of concrete mixtures with age stored in the ASTM C1876 simulated pore solution

3.2.1 Supplementary cementitious materials

As displayed in both Figures 1 and 2, concretes with either slag (Mix 25SL) and fly ash (Mix 15FA) had higher bulk resistivity than that of the pure Portland cement concrete at w/cm ratio of 0.4 (Mix 0.4PC) at 56 and 91 days in each curing condition. It is attributed to the additional reaction with $Ca(OH)_2$. Figure 2 shows that the fly ash concrete (Mix 15FA) had lower resistivity than the slag concrete (Mix 25SL) at 56 curing days but higher resistivity at 91 days. However, at early ages (i.e., less than 28 days) the BR of the fly ash concrete was even lower than that of Mix 0.4PC concrete, resulting from its slower rate of hydration but it improved the long-term resistivity value.

3.2.2 Water to cementitious material ratio

Figure 3 compares the measured bulk resistivity of concretes with different w/cm ratios cured in the ASTM C 1876 simulated pore solution at ages of 56 and 91 days. As expected, increased w/cm ratio led to a decrease in concrete bulk resistivity due to higher porosity and increases the amount of connected pores in concrete. It can be seen in Figure 3 that there is a strongly linear correlation between w/cm ratio and bulk resistivity of concrete at each age, with a R^2 of 0.97.

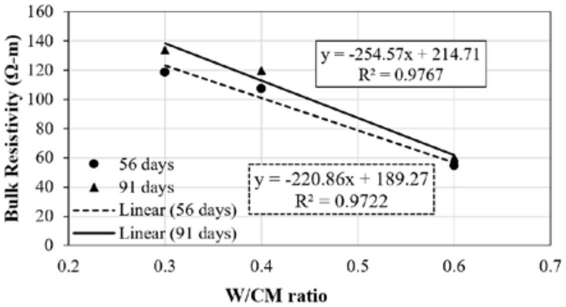

Figure 3. Correlation between w/cm ratios and BR of concrete in the ASTM C1876 simulated pore solution

3.3 Concrete Bulk Resistivity and Surface Resistivity

Figure 4 is a plot of concrete surface resistivity against bulk resistivity for all concrete mixtures in all curing environments at 56 and 91 days. There is a strong linear relationship with a slope of approximately 1.0 and a R^2 value of 0.9985 between concrete surface and bulk resistivity values, with measured values being essentially the same.

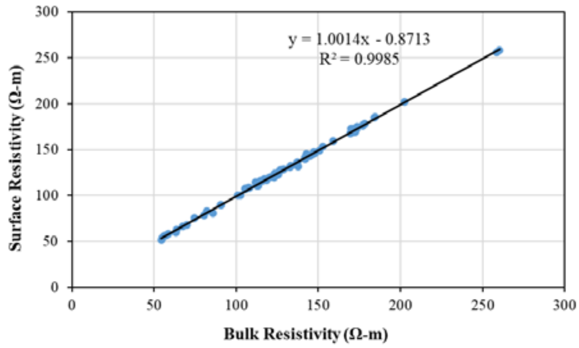

Figure 4. Correlation between bulk and surface resistivities for all five concrete mixtures

4 Conclusions

In this study, the effect of curing and storage conditions and effect of mix design on concrete electrical resistivity was analyzed and the surface and bulk resistivity measurements were compared. The following main conclusions are drawn:

(1). Different curing conditions result in differences in measured concrete resistivity since they affect the degree of saturation, degree of hydration, concrete microstructure and pore solution characteristics. Immersing concrete in solutions, other than ones that simulate the internal pore solution, causes leaching of ions from concrete pore solution which in turn modifies concrete's pore solution resistivity. Storage in higher alkali solution (i.e., simulated pore solution) led to lower measured resistivity since fewer ions were leached out. The ASTM C1876-suggested simulated pore solution may reduce the leaching of ions but does not eliminate this issue because each concrete has a different pore solution composition.

(2). The concrete bulk resistivity decreased as the w/cm ratio increased. A potential linear correlation was observed between w/cm ratio and concrete bulk resistivity. Inclusion of slag and fly ash in concrete mixtures enhanced the later-age electrical resistivity compared with the pure Portland cement concrete, but the fly ash did not improve the resistivity at early ages.

(3). It is shown that the surface and bulk resistivities from concrete specimens of all mixtures in all curing conditions had a strong linear correlation and gave similar values.

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