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Electrical Tests for Concrete Penetrability, Part 2

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The resistivity of concrete is evolving as a reliable method to measure the penetrability of water and dissolved chemicals into concrete. In Part 1 of this two-part paper, the results of the bulk and surface resistivity of specimens conditioned by different methods were compared to the results of chloride ion penetrability by ASTM C1202, and the precision of test determinations was reported. In Part 2, the results illustrate how changing the specimen conditioning method can change how concrete mixtures are characterized for chloride ion penetrability or transport properties. For the different mixtures evaluated, specimens subjected to the same curing condition had different degrees of saturation levels at the end of the conditioning period. Correcting the measured resistivity for degree of saturation, however, led to inaccurate mixture classification. The paper recommends a preferred specimen conditioning method for the resistivity test.

Keywords: chloride; curing; degree of saturation; leaching; penetrability; pore solution; rapid chloride permeability (RCP); resistivity; transport.

INTRODUCTION

The improved durability of concrete is most commonly controlled by imposing a maximum limit on the water-cementitious materials ratio (*w*/*cm*) to minimize the penetrability of water and dissolved chemicals into concrete. A performance-based alternative has been to use ASTM C1202 (2019), an electrical method that is referred to as the rapid chloride permeability (RCP) test. More recently, measuring the resistivity of concrete has evolved as a test method to characterize the transport properties of concrete. Table 1 provides a comparison of the chloride ion penetrability for RCP and resistivity test results (ASTM C1202; AASHTO PP 84-17 2017). The factors that impact the measured resistivity of concrete are the resistivity of the solid fraction, the degree of saturation (DOS) of the concrete, the ionic concentration of the pore solution, the degree of hydration/reaction (DOH/DOR) of cementitious materials, and the concrete temperature at the time of measurement (Spragg et al. 2013). These factors are impacted by the procedures used to condition test specimens before measuring resistivity. The following result in an increased measured resistivity of concrete:

- Leaching of alkali ions from the concrete pore solution causing an increase in the resistivity of the pore solution;
- An increase in the DOH/DOR of cementitious materials;
- Lower temperature of the test specimen;
- A test specimen at a lower DOS.

Weiss et al. (2013) proposed a saturation function to account for the impact of the specimen saturation level. This is expressed as the following power-law empirical relationship

$$\frac{R_{sat}}{R_{\mathrm{DOS}}} = \mathrm{DOS}^n \tag{1}$$

Table 1—Chloride ion penetrability based on RCP and resistivity test results (reproduced from ASTM C1202 and AASHTO PP 84 guidance document)

Chloride ion penetrability	RCP, ASTM C1202, Coulombs	Electrical resistivity, Ω·m
High	> 4000	< 50
Moderate	2000 to 4000	50 to 100
Low	1000 to 2000	100 to 200
Very low	100 to 1000	200 to 2000
Negligible	< 100	> 2000

Note: Applicable for saturated specimens.

where R_{DOS} is the resistivity of the specimen at the DOS when measured; R_{sat} is the resistivity of saturated specimens (100% DOS); DOS is the degree of saturation, expressed as a decimal varying from 0 at dry to 1 at saturated; and n is an exponent that varies between 3.0 to 5.0 for non-air-entrained (NAE) concrete and 1.5 to 3.0 for air-entrained (AE) concrete (Bu and Weiss 2014; Qiao et al. 2019; Barrett 2015).

Equation (2) can be used to estimate the resistivity of specimens at different DOS levels

$$\frac{R_{\mathrm{DOS2}}}{R_{\mathrm{DOS1}}} = \left(\frac{\mathrm{DOS}_1}{\mathrm{DOS}_2}\right)^n \tag{2}$$

where R_{DOS1} is the resistivity of the specimen at DOS_1; and R_{DOS2} is the resistivity of the specimen at DOS_2.

There is a considerable difference in how concrete test specimens are conditioned for the electrical tests, and these are summarized in Table 2. Further, electrical test methods permit alternatives for specimen conditioning with limited specificity. Specifying agencies using resistivity test methods invoke different specimen conditioning procedures that impact the results to determine the acceptability of concrete.

ASTM C1202 requires specimens to be vacuum-saturated prior to testing. This will result in specimens prepared from different mixtures to be saturated—that is, have a similar DOS before testing. The resistivity test standards do not require vacuum saturation. As a result, specimens prepared from different mixtures and subjected to the same curing/conditioning method will be at different DOS levels at the end of the curing/conditioning period. The implications for

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Table 2—Differences in curing and conditioning requirements for electrical test methods

	ASTM			AASHTO	
	C1760	C1202	C1876	T 358	TP 119
Measurement	Bulk conductivity	Conductivity measuring charge passed	Bulk or uniaxial resistivity	Surface resistivity	Bulk or uniaxial resistivity
Curing	Moist room or immersion in lime-saturated water	Moist room or immersion in lime-saturated water	Immersion in lime-saturated simulated pore solution	Moist room or immersion in lime-saturated water	Two options: sealed; immersion in lime-saturated simulated pore solution
Conditioning	N/A	Vacuum saturation	N/A	N/A	Vacuum saturation an option
Specimen size	2 in. cylindrical disk	2 in. cylindrical disk	Cylinders	Cylinders	Cylinders

the acceptance of concrete are illustrated in the following scenario. Consider two mixtures of the same cementitious composition, where the *w/cm* of Mixture 1 is 0.50 and that of Mixture 2 is 0.40. Assume that specimens from both mixtures are subjected to the same curing/conditioning method without vacuum saturation. If the conditioning of specimens from Mixture 1 results in a lower DOS than those from Mixture 2, it is likely that the measured resistivity of Mixture 1 will be higher, indicating better chloride penetrability, and will thereby incorrectly classify Mixture 1.

Air content, whether entrained or otherwise, will reduce the DOS of the test specimens (Todak et al. 2015). Based on theoretical calculations and experiments (Todak 2015) showed that a 3% increase in air content can reduce the DOS by approximately 10%. Assuming $n = 2.3$ for AE concrete in Eq. (2), a change in the DOS from 70 to 60% due to a 3% increase in air content predicts a 43% increase in concrete resistivity. This predicted increase in resistivity is due to a reduction in the DOS and not because of a reduction in chloride penetrability. This has implications to the acceptance of concrete because the tolerance for the specified air content for concrete as delivered is ±1.5% (ASTM C94 2019; ACI Committee 301 2020). The typical air content variation permitted can lead to a broad variation in the measured resistivity of concrete test specimens. This increases the risk of complying with the specified resistivity between loads of concrete primarily due to an acceptable variation in air content.

The specific objectives addressed in this paper are listed in the following.

1. Evaluate if different curing/conditioning procedures permitted by the resistivity test methods change the classification of the chloride ion penetrability of mixtures.

2. Quantify the impact of the DOS on measured resistivity, and correct measured resistivity to that for a saturated condition of specimens and evaluate the impact on the classification of mixtures.

3. Evaluate the impact of air content on the DOS of specimens and measured resistivity and compare these results to that predicted by an empirical equation.

4. Suggest a preferred curing/conditioning procedure for the resistivity test.

RESEARCH SIGNIFICANCE

Resistivity tests have several advantages over the RCP test, including a lower testing variation. The resistivity test standards permit different specimen conditioning methods. This paper investigates this impact on the measured resistivity and recommends that specifications invoking requirements for resistivity should state the same specimen conditioning method. This paper investigates if correcting the measured resistivity to represent the resistivity value for saturated concrete improves the classification of mixtures for the expected chloride penetrability. The paper suggests a preferred curing/conditioning procedure for the resistivity test.

EXPERIMENTAL PROGRAM

The materials and mixtures, experimental program, and results of fresh concrete, compressive strength, bulk resistivity (BR), surface resistivity (SR), and rapid chloride permeability (RCP) are reported in Part 1 (Obla and Lobo 2021). In summary, four non air-entrained (NAE) mixtures and five air-entrained (AE) mixtures were evaluated. All mixtures were proportioned with a paste volume of approximately 27%. Target air content for AE mixtures was 5%. The mixture ID for the AE mixtures includes the suffix "-A". One additional AE mixture, designated as 0.40SL, had a target air content of 8% and was identified with suffix "-HA".

- 0.55PC—Portland cement (PC) mixture with a *w/cm* of 0.55
- 0.45FA—Mixture with 25% fly ash (FA) by mass of cementitious materials with a *w/cm* of 0.45
- 0.40SL—Mixture with 50% slag cement by mass of cementitious materials with a *w/cm* of 0.40
- 0.50SL—Mixture with 50% slag cement by mass of cementitious materials with a *w/cm* of 0.50

Specimens of size 4 x 8 in. (100 x 200 mm) were cast and subjected to various curing/conditioning procedures, typically for 56 days before testing for BR, SR, and RCP. The following summarizes the curing/conditioning procedures used with more detail outlined in Part 1:

- LW—Curing in lime-saturated water
- MR—Curing in a moist room
- PS—Cured in a lime-saturated simulated pore solution
- SC—Sealed in molds
- SCB—Sealed in molds followed by curing in a lime-saturated simulated pore solution
- PS2—Cured in a lime-saturated simulated pore solution representative of the type of mixture
- AC—Accelerated curing for 28 days in accordance with ASTM C1202
- ACPS—Accelerated curing for 28 days in the PS solution with temperature in accordance with ASTM C1202

Degree of saturation (DOS)

The DOS of test specimens subjected to conditions LW, MR, SC, PS, and AC was measured at the end of the conditioning period. Two 2 in. (50 mm) thick disks were cut from the top of 4 x 8 in. (100 x 200 mm) cylinders. The surface of the specimen was wiped with a wet cloth, and the mass was measured to represent the saturation level at the end of conditioning. The specimens were placed in an oven at 140°F (60°C) and dried for 7 days. The mass of the dry specimens was measured. The specimens were vacuum-saturated and the mass measured to represent the 100% saturation level. The DOS of the test specimens at the end of the conditioning period was calculated from the following equation

$$\%\text{DOS} = \frac{\left(M_C - M_D\right)}{\left(M_S - M_D\right)} \times 100 \tag{3}$$

where M_C is the mass of the specimen at the end of conditioning; M_D is the mass after drying in the oven; and M_S is the mass of the saturated specimen.

The effect of the DOS on the BR was evaluated for the AE mixtures with specimens subjected to Condition LW. A 4 x 2 in. (100 x 50 mm) thick disk specimen was extracted at 2 to 4 in. (50 to 100 mm) from the cast surface. The mass and bulk resistivity was measured, representing BR at the DOS at the end of 56 days immersion in LW. The disks were placed next to a fan in a room maintained at 70°F (21°C). The mass and bulk resistivity were measured after 1, 2, 6, and 14 days of drying. Before each measurement, the specimens were immersed in water for approximately 2 minutes to moisten the surface, a necessary step to reliably measure bulk resistivity. The intent was to measure the BR as the specimen DOS decreased. These data were used to evaluate the relationship that predicts resistivity based on the change in DOS in Eq. (1).

EXPERIMENTAL RESULTS AND DISCUSSIONS

Overview of electrical test results

Figures 1(a) and (b) illustrate the impact of air entrainment on bulk resistivity and RCP, respectively, for mixtures with specimens subjected to different conditioning methods. While some of the data fall along the line of equality, specimens from mixtures with entrained air had a measured resistivity on average approximately 25% higher and charge passed of approximately 20% lower compared to the equivalent NAE mixture. For bulk resistivity, this is attributed to a lower DOS of AE concrete because entrained air voids are not saturated. The difference cannot be explained for RCP because these specimens were vacuum-saturated, and it is assumed that this saturates the air voids.

Figure 2 compares the measured BR of specimens subjected to the different curing/conditioning methods for all mixtures. The 0.55PC mixtures had the lowest resistivity of all mixtures, representing the highest transport properties. On average, there is a significant difference in the measured BR between the 0.55PC and the 0.45FA mixtures. The mixtures with slag cement had the highest measured BR on average, indicating the lowest transport properties. The higher air content of the 0.40SL-HA mixture compared to the 0.40 SL-A mixture had very little impact on the measured bulk resistivity. This suggests that a change of air content of 2.4% for the same mixture may not have a significant impact on the resistivity test results. The range of air content of the two mixtures is within the acceptable tolerance for specified air content.

Comparing mixtures with slag cement, the measured BR for the mixtures with a *w*/*cm* of 0.40 were only marginally higher than that measured on specimens from the mixtures with a *w*/*cm* of 0.50. For some conditioning methods, the difference was not statistically significant. For the NAE concrete mixtures, the difference was on average 6%. For AE concrete mixtures, the average difference was 13%. In this study, the resistivity was not able to effectively differentiate between mixtures with a *w*/*cm* of 0.40 and 0.50 with the same cementitious materials and at the same paste volume. In contrast, the compressive strength for the AE and NAE slag cement mixtures at a *w*/*cm* of 0.40 were on average 28% higher than mixtures with a *w*/*cm* of 0.50. If the increase in the *w*/*cm* is affected by increasing mixing water content while maintaining the same content of cementitious materials, the resulting higher paste volume would have resulted in a greater reduction in measured resistivity as observed in literature (Obla et al. 2017, 2018). From a quality assurance perspective, resistivity should be able to differentiate between a 0.50 *w*/*cm* and a 0.40 *w*/*cm* mixture if the difference is primarily due to an increase in mixing water content. Mixtures with a higher *w*/*cm* are likely to have a higher porosity with greater pore connectivity, but the resistivity of the pore solution is also likely to be higher because of greater dilution. It is therefore surmised that the net effect is that the higher *w*/*cm* mixture has a smaller decrease in the measured BR than what would be expected from the improvement in a more refined pore structure.

Effect of DOS on resistivity

Figure 3 illustrates the change in the measured BR with the change in the estimated DOS for specimens cured for 56 days in saturated limewater (LW) for four mixtures that were subsequently subjected to drying. A reduction in the DOS resulted in an increase in the measured BR. A power function, Eq. (1), is used to describe the relationship between the BR and DOS. For this evaluation, the estimated value of the exponent *n* of the four supplementary cementitious materials (SCM) mixtures ranged between 2.4 and 3.6 (average of 2.9). This is consistent with that observed in literature referenced earlier. Using the average *n* value in Eq. (2) predicts that a reduction in the DOS from 70 to 55% will double the BR.

From a practical testing perspective, when measuring the BR, if a 4 x 8 in. (100 x 200 mm) specimen is allowed to dry, a decrease in mass of 5 g decreases the specimen DOS by approximately 3%, and Eq. (2) predicts that the measured BR should increase by approximately 12%. Mass loss from specimens depends on the specimen's moisture desorption rates, which in turn depends on the specimen's age, initial DOS, and internal pore structure. Generally, the desorption rate will be low if the initial DOS is low and the specimens are more mature and have a tight internal pore structure due to a low *w*/*cm* and the use of SCMs. A separate evaluation

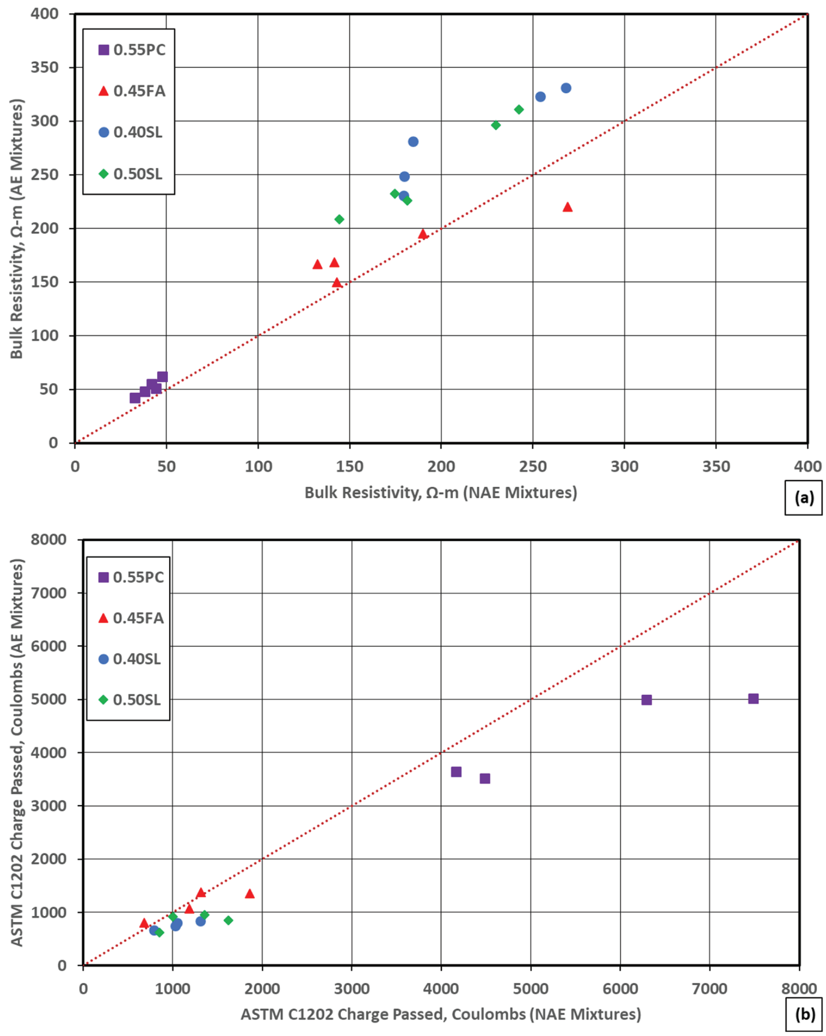

Fig. 1—Impact of entrained air on concrete: (a) bulk resistivity; and (b) RCP.

of 4 x 8 in. (100 x 200 mm) specimens from eight mixtures with 50% slag cement at a 0.40 *w/cm* quantified mass loss over a 30-minute period of approximately 5 g for specimens moist-cured for 28 days, and approximately 2 g for specimens moist-cured for 120 days.

Effect of curing/conditioning on resistivity

As illustrated in Fig. 2, curing/conditioning had a significant effect on the measured bulk resistivity for the mixtures containing SCMs. These data are reported in Table 4 of Part 1. Table 3 classifies mixtures for chloride penetrability for different specimen conditioning based on the measured bulk resistivity (BR), surface resistivity (SR), and rapid chloride permeability (RCP).

For the BR, the chloride penetrability was mostly "High" for the 0.55PC mixture and split between "Moderate" and "High" for the 0.55PC-A mixture depending on how the specimens were conditioned. The AE slag cement mixtures—0.40SL-A, 0.40SL-HA, and 0.50SL-A—are classified based on the BR as "Very Low" chloride penetrability regardless of how the specimens were conditioned. For mixtures 0.45FA-A, 0.40SL, and 0.50SL, classification based on BR is split between "Very Low" and "Low" depending upon how the specimens were conditioned. For the 0.45FA mixture, the chloride penetrability classification is "Low" except for Condition AC, which is classified as "Very Low," more likely due to the increased degree of reaction of fly ash resulting from accelerated curing.

The mixture classifications for SR and RCP that differ from the classification based on BR are highlighted in Table 3. For SR, the mixture classification is consistent with that indicated by BR in 75% of the cases. As indicated in Part 1, the measured SR was consistently lower than the measured BR, and in 25% of the cases, the chloride penetrability classification based on SR diminished one level compared to that based on BR. For RCP, the mixture classification is consistent with that indicated by BR in almost all cases except for specimens subjected to Condition SC. Specimens subjected to Condition SC had the lowest degree of saturation after conditioning, resulting in a higher measured BR; RCP was measured after vacuum-saturating these specimens before the test.

To summarize, depending on the curing/conditioning of test specimens permitted for resistivity tests, the same mixture could be classified differently for chloride penetrability. It is thereby recommended that one standardized specimen conditioning method be adopted by all specifying agencies. The same curing/conditioning method of test

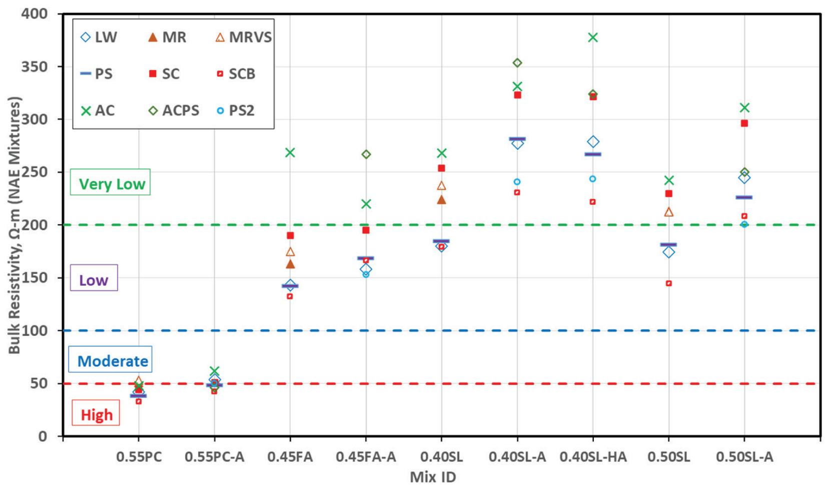

Fig. 2—Bulk resistivity of various conditions and mixtures. (Note: Data comes from Table 4 of Part 1.)

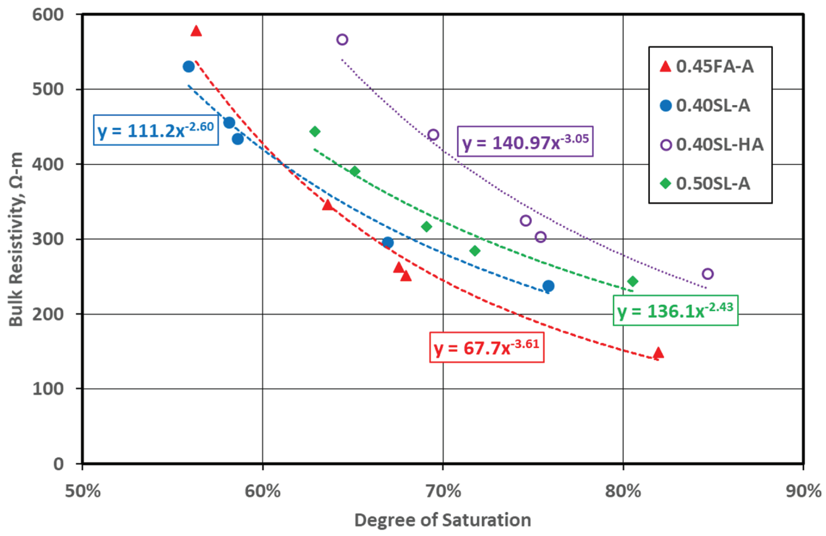

Fig. 3—Impact of drying on measured DOS and bulk resistivity. Specimens dried after 56 days of limewater curing.

Table 3—Chloride penetrability level for mixtures and specimen conditions based on bulk resistivity, surface resistivity, and RCP

Specimen condition	Chloride penetrability level for BR/SR/RCP																										
	0.55PC-A			0.45FA-A			0.40SL-A			0.40SL-HA			0.50SL-A			0.55PC			0.45FA			0.40SL			0.50SL		
Method	B	S	R	B	S	R	B	S	R	B	S	R	B	S	R	B	S	R	B	S	R	B	S	R	B	S	R
LW	M	***H***	M	L	L	L	V	V	V	V	V	V	V	***L***	V	H	H	H	L	L	L	L	L	L	L	L	L
MR	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	M	***H***	M	L	L	L	V	***L***	V	V	***L***	***L***
PS	H	H	—	L	L	—	V	V	V	V	V	V	V	***L***	V	H	H	H	L	L	L	L	L	L	L	L	L
PS2	H	H	—	L	L	—	V	***L***	V	V	V	V	V	***L***	V	—	—	—	—	—	—	—	—	—	—	—	—
SC	M	***H***	***H***	L	L	L	V	V	V	V	V	***L***	V	V	V	H	H	H	L	L	L	V	V	***L***	V	***L***	***L***
SCB	H	H	H	L	L	L	V	V	V	V	V	V	V	***L***	V	H	H	H	L	L	L	L	L	L	L	L	L
AC	M	M	M	V	***L***	V	V	V	V	V	V	V	V	V	V	H	H	H	V	V	V	V	V	V	V	V	V
ACPS	H	H	—	V	V	—	V	V	V	V	V	V	V	V	V	—	—	—	—	—	—	—	—	—	—	—	—

Note: H is high; M is moderate; L is low; and V is very low, based on criteria in Table 1; B is BR; S is SR; and R is RCP.

specimens should be used when comparing the mixtures and for pre-qualification and acceptance of concrete.

For a given mixture, the curing/conditioning of test specimens have an impact on the DOS, ion leaching from the specimens, and the DOH/DOR of cementitious materials, thus affecting the measured BR. For different mixtures, the same curing/conditioning procedure would impact the DOS, ion leaching from specimens, and DOH/DOR differently as a result of differences in the cementitious material reactivity, the pore solution composition, and the pore structure.

Table 4—Effect of curing/conditioning on bulk resistivity normalized to Condition LW

Specimen condition	BR condition/BR (LW)									Average (SCM mixtures)	
	0.55PC		0.45FA		0.40SL			0.50SL			
	N	A	N	A	N	A	HA	N	A	N	A
LW	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	**1.00**	**1.00**
MR	1.21	—	1.14	—	1.25	—	—	1.22	—	**1.20**	**—**
PS	0.91	0.91	0.99	1.01	1.03	0.92	0.89	1.04	0.88	**1.02**	**0.92**
SC	1.06	0.92	1.33	1.30	1.41	1.30	1.24	1.32	1.27	**1.35**	**1.28**
SCB	0.78	0.77	0.93	1.11	1.00	0.93	0.86	0.83	0.90	**0.92**	**0.95**
AC	1.14	1.12	1.88	1.47	1.49	1.33	1.46	1.39	1.34	**1.59**	**1.40**
ACPS	—	0.89	—	1.60	—	1.16	1.08	—	0.97	**—**	**1.20**
PS2	—	0.91	—	1.02	—	0.97	0.94	—	0.86	**—**	**0.95**

Note: N is non-air-entrained concrete mixture; A is air-entrained concrete mixture; and HA is high-air-content concrete mixture.

This ultimately affects the measured BR. To compare these effects, measured BR results are normalized to the LW curing/conditioning procedure for each mixture in Table 4.

A general ranking of the BR results in terms of classification for chloride penetrability for the SCM mixtures subjected to different curing/conditioning procedures is SCB = LW = PS < MR < ACPS < SC < AC. Condition AC consistently gave the highest BR for the SCM mixtures and more significantly for the fly ash mixture. Accelerated curing increases the DOR of the SCMs, especially that of fly ash. This phenomenon is well understood (Ozyildirim 1998). Table 3 shows that the 0.45FA and 0.45FA-A mixtures had the same "Very Low" chloride penetrability as the 0.40SL and 0.40SL-A mixtures for specimens subjected to any of the accelerated conditions (AC and ACPS), but it was one level lower for specimens subjected to the other conditions.

For the NAE mixtures, specimens subjected to Condition MR had a higher average measured BR by approximately 20% compared to those subjected to Condition LW. This can be attributed to increased leaching of alkali ions from specimens in Condition MR, which was confirmed by pore solution composition analysis on specimens from this study by the Federal Highway Administration (FHWA) (Tanesi et al. 2019). The differences in measured resistivity are recognized in AASHTO T 358-17 (2017), where it is recommended to multiply the measured surface resistivity by a correction factor of 1.1 for specimens cured in saturated limewater when comparing to specimens cured in a moist room. The difference between the measured BR of specimens in Condition PS relative to those subjected to LW was within 10%, and for practical purposes, not significant. The classification of mixtures for chloride penetrability based on BR (Table 3) was the same for Conditions LW and PS. However, pore solution expressed from the specimens subjected to Condition PS was more conductive (indicative of less specimen leaching) than that expressed from the specimens in Condition LW. The pore solution resistivity of specimens belonging to SCM mixtures and subjected to Condition LW was on average 60% higher than that for specimens subjected to Condition PS (Tanesi et al. 2020). It is surmised from the similarly measured resistivity for specimens subjected to Conditions LW and PS that the difference in pore solution resistivity is offset by a better paste microstructure in specimens subjected to Condition PS than that developed in specimens subjected to Conditions MR and LW (Tanesi et al. 2019).

The LW curing/conditioning option is recommended for the evaluation of concrete on projects. The resistivity measurements of specimens in Condition LW were more stable with time than those in Condition PS (refer to Part 1). Additionally, curing in LW is consistent with current practice for strength testing, and these specimens can be subsequently used to measure strength. Additionally, testing agencies are familiar with this curing method and will find it easier to adopt. Preparing the simulated pore solutions as prescribed in ASTM C1876 (2019) requires precise measurements, added expense in chemicals and storing the buckets, and leads to challenges in disposing of the simulated pore solution after the test. If specimens need to be conditioned in simulated pore solutions, it is recommended that specimens be washed under running tap water for 45 seconds before the measurements. This is because of drifting measurements for specimens immersed in PS and is discussed in Part 1.

Effect of curing/conditioning on DOS

Table 5 reports the estimated DOS of test specimens at the end of the conditioning period for all mixtures. For perspective, a difference in mass of about 0.4 g in the 2 in. (50 mm) disk specimen represents a difference in DOS of 1%. Such small differences should not be considered significant.

For the NAE concrete mixtures, the DOS is close to 100% for most of the conditions, with the exception of specimens in Condition SC. Specimens in Condition SC had the lowest DOS; these specimens were not immersed in solution for the duration of the curing/conditioning process, and water within the specimen was likely consumed by hydration reactions. Excluding Condition SC, the DOS of specimens at the end of the conditioning period for the AE mixtures averaged approximately 77%, compared to 97% for the NAE mixtures. Using the average exponent $n = 2.9$, derived from Fig. 3, in Eq. (2), a change in the DOS from 97 to 77% predicts an increase in the resistivity by approximately 95%. However, as observed in Fig. 1(a), the average BR of the AE

Table 5—Estimated degree of saturation of specimens subjected to curing/condition

Specimen condition	DOS, %									Average (SCM mixtures)	
	0.55PC		0.45FA		0.40SL			0.50SL			
	N	A	N	A	N	A	HA	N	A	N	A
MR	99	—	98	—	97	—	—	94	—	**96**	**—**
LW	100	88	100	83	98	78	76	97	84	**99**	**80**
PS	100	82	100	75	96	73	62	94	84	**97**	**73**
SC	81	72	81	65	75	63	62	80	71	**78**	**65**
SCB	—	82	90	69	—	77	75	—	76	**90**	**74**
AC	100	92	100	78	92	72	70	100	83	**97**	**76**
ACPS	—	84	—	78	—	85	68	—	84	**—**	**79**
PS2	—	81	—	75	—	74	75	—	81	**—**	**76**

Note: N is non-air-entrained concrete mixture; A is air-entrained concrete mixture; and HA is high-air-content concrete mixture.

concrete mixtures was approximately 25% higher than the equivalent NAE concrete mixtures.

The air content of the 0.40SL-HA mixture was 2.4% higher than the 0.40SL-A mixture. Conceptually, the higher air content should have caused specimens from the 0.40SL-HA mixture to be at a lower DOS and an associated higher measured BR compared to the 0.40SL-A mixture. Table 5 indicates that the DOS of the 0.40SL-HA was on average approximately 5% lower than the 0.40SL-A mixture. However, the changes in the DOS resulting from different conditioning methods did not result in significant changes to the measured BR between the two mixtures, as shown in Fig. 2.

Corrections were applied to the measured BR for each condition to normalize results to a reference temperature of 23°C (296K) (Spragg et al. 2013) and DOS of 100%. Measured resistivity was corrected for specimen temperature to a reference temperature based on the following Arrhenius equation

$$\rho_{t-Ref} = \rho_t.exp\left[\frac{E_{A-Cond}}{R}\left(\frac{1}{T}-\frac{1}{T_{Ref}}\right)\right] \qquad (4)$$

where ρ_{t-Ref} is the resistivity, Ω·m, at a reference temperature, T_{Ref}, K; ρ_t is the measured resistivity, Ω·m, at the testing temperature, T, K; E_{A-Cond} is the activation energy of conduction, kJ/mol; and R is the universal gas constant, 8.314 J/ mol·K.

E_{A-Cond} was assumed to be equal to 33.3 – (16.3 × DOS) (Coyle 2017). Based on the measured DOS in this project, the E_{A-Cond} varied between 17 and 23.2 kJ/mol.

Measured resistivity decreases with the increase in specimen temperature. The temperature of the specimens at the time of the BR measurements varied between 72 and 77°F (22 and 25°C). When corrected to a reference temperature of 73°F (23°C) the corrected BR varied between 2% lower and 5% higher than the measured BR. For measured resistivity on test specimens at temperatures between 70 and 77°F, the correction for temperature is relatively small and can be ignored. The temperature dependency of electrical resistivity or conductivity is recognized in ASTM C1876, where it is required to perform all tests on concrete specimens conditioned between 21 and 25°C. No temperature correction is required in ASTM C1876.

Measured resistivity was corrected for specimen DOS to a reference DOS of 100% using Eq. (1) with assumed exponent $n = 2.9$. This correction resulted in a greater difference. The measured BR and BR corrected for DOS and temperature are compared in Fig. 4(a) for NAE mixtures 0.40SL and 0.50 SL; and in Fig. 4(b) for AE mixtures 0.40SL-A and 0.50SL-A. The measured BR indicates a clearer difference between the mixtures, with a *w/cm* of 0.40 consistently higher than that for the mixtures with a *w/cm* of 0.50. The corrected BR considerably reduces this difference and makes it harder to distinguish between mixtures with the different *w/cm*. In some cases, the corrected BR was higher for the mixtures with a *w/cm* of 0.50. Table 6 classifies mixtures for chloride penetrability for different specimen conditioning based on the corrected BR. These can be compared to the classification based on the measured BR in Table 3. In Table 6, the conditions where the rankings differed from Table 3 are highlighted. In most of the cases, the classification for chloride penetrability based on BR corrected to 100% DOS changed by one or two levels worse than the classification based on the measured BR. Based on the BR and RCP results, the 0.40SL-A mixture had a classification of "Very Low" (Table 3), but was classified as "Moderate," "Low," or "Very Low" based on the corrected BR (Table 6). The general expectation for the 0.40SL-A mixture is also "Very Low." As shown in Fig. 3, the value of the exponent n varies between mixtures. Using a mixture-specific n value could be a better option, but is difficult to implement in practice. Therefore, it is suggested that a correction for DOS not be made to assess the quality of concrete mixtures for chloride penetrability.

Effect of vacuum saturation on resistivity

The measured BR of specimens that were vacuum-saturated after the end of the curing/conditioning process is reported in Table 7. The ratio of the measured BR for specimens in each condition to that of the specimens subjected to Condition LW (and vacuum-saturated) is indicated. For a given mixture, assuming that the vacuum-saturated specimens are at 100% saturation, the differences in BR between

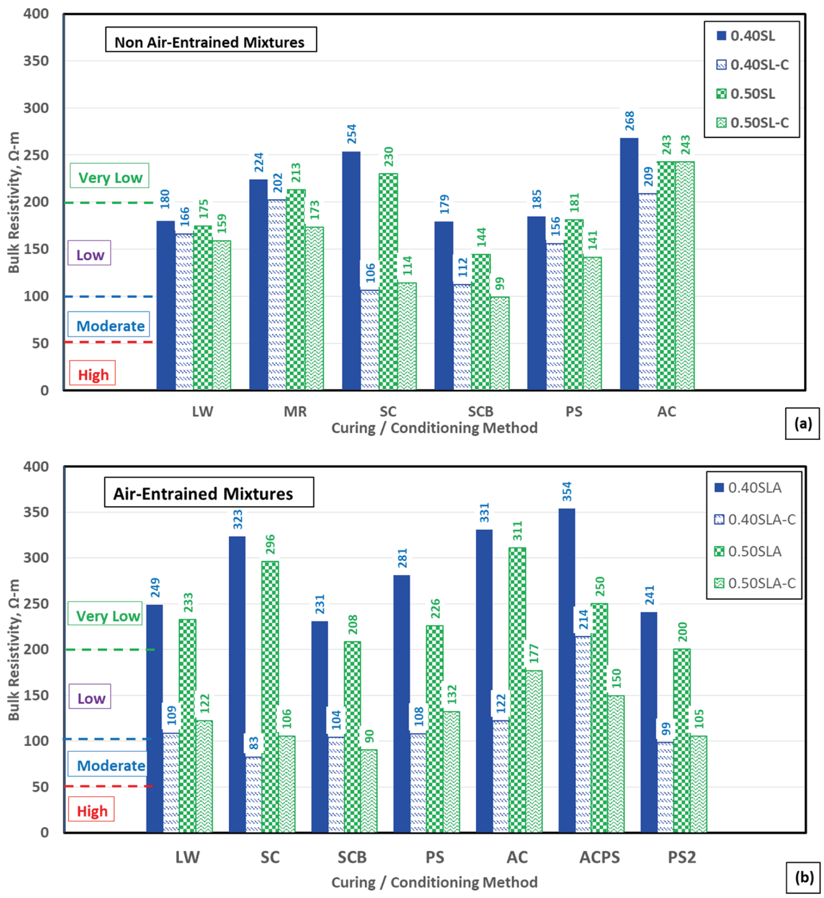

Fig. 4—Measured and corrected (C) bulk resistivity for mixtures with slag cement with w/cm *0.40 and 0.50: (a) non-air-entrained; and (b) air-entrained.*

Table 6—Chloride penetrability level based on bulk resistivity corrected for DOS

Specimen condition	Air-entrained mixtures					Non-air-entrained mixtures			
	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	0.55PC	0.45FA	0.40SL	0.50SL
LW	***H***	***M***	***L***	***L***	***L***	H	L	L	L
MR	—	—	—	—	—	M	L	V	***L***
PS	H	***M***	***L***	***M***	***L***	H	L	L	L
PS2	H	***M***	***M***	***L***	***L***	—	—	—	—
SC	***H***	***M***	***M***	***M***	***L***	H	L	***L***	***L***
SCB	H	***M***	***L***	***M***	***M***	H	L	L	***M***
AC	***H***	***L***	***L***	***L***	***L***	H	V	V	V
ACPS	H	***L***	***V***	***L***	***L***	—	—	—	—

the conditions should be primarily due to differences in leaching and the DOH/DOR of the cementitious materials resulting from the conditioning method. For the SCM mixtures, as observed earlier, Condition AC had a significant impact on the measured BR, particularly for the fly ash mixture. For the SCM mixtures, specimens subjected to Condition MR had a measured BR on average 13% higher than those subjected to Condition LW, which was attributed to a higher level of alkali leaching in Condition MR, as observed earlier. The measured BR on the vacuum-saturated specimens subjected to Condition SC was considerably lower for NAE mixtures and marginally lower for AE mixtures than those subjected to Condition LW.

Effect of Condition SC on specimens

Sealed curing (SC) of specimens is considered a preferred option because the pore solution in the specimen is not impacted by the exchange of ions caused by other methods for curing/conditioning. The question arises, however, whether specimens subjected to sealed curing will self-desiccate as water is consumed by hydration reactions and the rate of hydration reduces with age. This is more of a concern with higher-performance concrete mixtures with a lower *w/cm*. Additionally, it is very likely that the degree of reaction of SCMs, especially those that react at a slower rate like fly ash, is curtailed, and the typical benefit they provide

Table 7—Bulk resistivity of specimens vacuum-saturated after conditioning

Specimen condition	Measured BR, Ω·m (relative BR*)					Avg. relative BR (SCM mixtures)
NAE mixtures	0.55PC	0.45FA	0.40SL		0.50SL	—
AC	46 (1.10)	267 (1.88)	242 (1.30)		223 (1.28)	1.49
MR	55 (1.31)	161 (1.13)	218 (1.17)		190 (1.09)	1.13
LW	**42 (1.00)**	**142 (1.00)**	**186 (1.00)**		**174 (1.00)**	**1.00**
SC	37 (0.88)	99 (0.70)	134 (0.72)		105 (0.60)	0.67
AE mixtures	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	—
AC	62 (1.09)	210 (1.60)	NA	304 (1.38)	279 (1.42)	1.47
LW	**57 (1.00)**	**132 (1.00)**	**236(1.00)**	**221 (1.00)**	**217 (1.00)**	**1.00**
SC	46 (0.81)	135 (1.03)	220 (0.93)	187 (0.85)	211 (0.98)	0.95

*BR condition / BR (LW).

for durable concrete in actual structures is not recognized by this conditioning method.

For the NAE mixtures, specimens subjected to Condition SC and subsequently vacuum-saturated (Table 7) had substantially lower measured BR compared to those subjected to Condition LW. The difference is more significant for mixtures containing SCMs. Pore solution composition analysis showed (Tanesi et al. 2019) that specimens subjected to Condition SC had less leaching and lower pore solution resistivity than specimens conditioned to LW. It was surmised that in Condition SC, the reduction of available water due to initial hydration reduced the DOH/DOR of the cementitious systems, more so for the mixtures containing SCMs. This effect was experimentally confirmed (Tanesi et al. 2019). It is recognized that the rate of hydration decreases when the internal relative humidity gets below 90% and ceases below 80% (Wyrzykowski and Lura 2016).

Considering that specimens subjected to Condition SC prevents the effective reaction of SCMs, it is suggested that this option not be used for acceptance testing of concrete mixtures. Interestingly, for the mixtures evaluated in this study, the mixture classification based on specimens subjected to Condition SCB and Condition LW was similar, while those subjected to Condition SC resulted in a better classification ranking for some of the mixtures (Table 3). This is because specimens in Conditions SC and SCB had a lower DOS compared to those in Condition LW, thereby resulting in a higher measured BR. When the BR was corrected for measured DOS, the mixture classification based on specimens subjected to Conditions SCB and SC were equal to or worse than specimens subjected to Condition LW (Table 6).

For the AE mixtures, specimens subjected to Condition SC and subsequently vacuum-saturated (Table 7) did not have a substantially lower measured BR compared to those subjected to Condition LW. This was determined to be due to inadequate sealing of these specimens from intrusion of moisture when placed in the moist room (Obla et al. 2020).

CONCLUSIONS

The following conclusions are drawn from this study:

1. Depending on the curing and conditioning procedures used and the measured resistivity, the same mixture could be classified in different categories for chloride penetrability based on criteria stated in Table 1. It is thereby important that a single curing/conditioning method be established by agencies using this test for determining acceptance of concrete and for appropriately comparing the potential permeability characteristics of different mixtures. This is consistent with the way compressive strength is specified, where all specifications require the strength test specimens be standard-cured in accordance with ASTM C31 (2019).

2. For the different mixtures evaluated, specimens subjected to the same curing condition had different degree of saturation (DOS) levels at the end of the conditioning period. Resistivity measurements, however, classified concrete for chloride penetrability consistent with rapid chloride permeability (RCP) results and typical expectations.

3. The measured DOS of air-entrained (AE) concrete mixtures was on average 20% lower compared to equivalent non-air-entrained (NAE) concrete mixtures. The measured bulk resistivity of AE concrete mixtures was 25% higher, and the RCP results were 20% lower compared to equivalent NAE concrete mixtures. For one set of AE mixtures evaluated, a 2.4% higher air content decreased the measured DOS and did not impact the measured resistivity.

4. The measured resistivity of test specimens increased with a decrease in the DOS affected by drying the specimens. The applicability of the power function used to describe the relationship between bulk resistivity (BR) and DOS was evaluated. The estimated value of the exponent n in Eq. (1) for the four AE mixtures containing supplementary cementitious material (SCM) ranged between 2.4 and 3.6 (average of 2.9).

5. Correcting the measured BR to represent the BR value for saturated concrete based on the power function relationship resulted in an incorrect classification of mixtures for the expected chloride penetrability. Based on this, it is recommended that for mixture classification purposes, the measured BR should not be corrected for the DOS to represent a saturated condition. For specimens measured in a controlled laboratory environment, the correction for specimen temperature is small and can be ignored.

6. Contradictory observations are noted for specimens that are sealed cured. For mixtures containing SCMs, it is surmised that the hydration reaction causes self-desiccation that prevents

the effective degree of hydration/reaction (DOH/DOR) of SCMs. The lower DOS of sealed cured specimens, however, resulted in a higher measured resistivity compared to specimens subjected to other conditions. It was observed that the specimen sealing process is likely to be inconsistent and is a potential source of testing error.

7. Specimens immersed in lime-saturated pore solution had a measured resistivity within 10% of that of specimens immersed in limewater. Bulk resistivity measurements on specimens immersed in lime-saturated pore solution did not stabilize over a reasonable time, while those immersed in limewater were stable and less prone to recording error. Limewater immersion is easier and more practical for technicians and testing agencies. Based on all the curing conditions evaluated in this research project, it is recommended that test specimens be immersed in limewater for 56 days after casting. If test results are desired at an earlier age, the specimens can be subjected to accelerated curing—immersion in saturated limewater at 73°F (22°C) for 7 days followed by 21 days at 100°F (38°C) in accordance with the accelerated curing methods of ASTM C1202. If specimens need to be conditioned in simulated pore solutions, as observed in Part 1, it is recommended that those specimens be washed under running tap water for 45 seconds before the measurements. This helped attain BR measurements that were stable over the measurement duration.

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