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Electrical Tests for Concrete Penetrability, Part 1

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The resistivity of concrete is gaining acceptance as an easier and more reliable method to measure the penetrability of water and dissolved chemicals into concrete. This study evaluates the surface and bulk resistivity of concrete specimens prepared from mixtures with varying levels of penetrability or transport properties. Test specimens were conditioned by different methods as permitted by the standards. In Part 1, the results indicate that, based on measured resistivity, concrete mixtures are classified for transport properties similar to ASTM C1202. Resistivity measurements were less variable. Changes in the resistivity of specimens placed in simulated service conditions for 1 year are also evaluated. Comparisons were also made on resistivity measured on smaller specimens obtained from different locations of a cylindrical specimen. In Part 2, the impact of various specimen conditioning techniques allowed by the standards on the degree of saturation, resistivity, and characterization of concrete for transport properties are discussed.

Keywords: chloride; condition; curing; penetrability; pore solution; rapid chloride permeability (RCP); resistivity; transport.

INTRODUCTION

There is an increased emphasis on developing performance-based tests and criteria to address requirements for durable concrete. One of the primary properties of concrete that impact durability is the penetrability of water or ionic species such as chlorides and sulfate into the concrete. Currently, industry standards (ACI 318-19 [ACI Committee 318 2019] and ACI 301-20 [ACI Committee 301 2020]) rely on specifying the maximum water-cementitious materials ratio (w/cm) for concrete mixtures used in members that require low transport properties, commonly referred to as low penetrability, based on anticipated exposure that impacts durability. It is well recognized that the transport properties of concrete are best improved by a lower w/cm and the use of supplementary cementitious materials (SCMs). Different mixtures at the same w/cm can have widely ranging transport properties. Further, w/cm cannot be reliably measured and verified in the field.

Previous research (Berke and Hicks 1992; Thomas 2013; Obla et al. 2016; Obla 2019) has shown a good correlation between the apparent chloride diffusion coefficient, determined in accordance with ASTM C1556, and the results from ASTM C1202 referred to as rapid chloride permeability (RCP). Some issues related to the use of RCP are that the test method is complex, requiring laboratory proficiency; has high variability; and is relatively expensive. The RCP test primarily measures the conductivity of concrete. Measuring the electrical resistivity of concrete, the inverse of its conductivity, has evolved more recently (Nokken and Hooton 2007; Paredes et al. 2012; Gudimetla and Crawford 2016). Lower penetrability (better transport properties)

is indicated by lower RCP/conductivity or higher resistivity values. Table 1 provides a comparison of the chloride ion penetrability for RCP and resistivity test results (ASTM C1202; AASHTO PP 84 2017). A theoretical relationship between RCP and resistivity (Weiss et al. 2017) is

$$\rho = \frac{206,830}{Q} \quad (1)$$

where Q is the RCP in coulombs; and ρ is the resistivity in $\Omega \cdot m$.

Table 1 criteria are applicable for saturated specimens and are consistent with the aforementioned theoretical relationship. Specifications would thereby state a minimum resistivity for qualifying concrete mixtures with low penetrability. In this paper, the RCP and resistivity test methods are referred to as electrical test methods.

State highway agencies have been moving towards using the resistivity test AASHTO T 358 (2017), measuring surface resistivity, and provisional standard AASHTO TP 119 (2017) for measuring bulk or uniaxial resistivity. ASTM C1876 also measures the bulk electrical resistivity of concrete. Resistivity is one of the methods included in AASHTO PP 84 for evaluating the transport characteristics of concrete mixtures used for pavements. The resistivity measurement is easier to perform and has better precision than ASTM C1202 (Rupnow and Icenogle 2011; Spragg et al. 2011).

The specific objectives addressed in this paper are listed as follows:

1. Compare the categorization of mixtures based on resistivity and RCP for transport properties.
2. Compare surface and bulk resistivity results for different mixtures with a wide range of chloride penetrability.
3. Determine the single-operator precision of the evaluated electrical test methods.
4. Compare bulk resistivity measurements on 2 in. (50 mm) disk specimens to that on 4 x 8 in. (100 x 200 mm) cylindrical specimens.
5. Compare the resistivity of specimens kept in simulated service conditions to those maintained in standardized laboratory conditions.

Additional details of the research on factors impacting resistivity measurements are discussed in Part 2.

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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 per 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.

RESEARCH SIGNIFICANCE

The RCP test has been widely used as an indicator test to select mixtures for low chloride penetrability. The resistivity test is relatively new. The resistivity test standards permit different specimen conditioning methods, and specimens need not be vacuum-saturated, such as the RCP test before testing. This paper addresses several issues about the resistivity test, which will improve confidence in the use of the test. The paper also suggests improvements to the ASTM C1876 specimen conditioning.

EXPERIMENTAL PROGRAM

Material and mixtures

The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (PC)
- ASTM C618 Class F fly ash (FA)
- ASTM C989 slag cement (SL)
- ASTM C33 No. 57 crushed limestone coarse aggregate
- ASTM C33 natural sand with a fineness modulus (FM) of 2.67
- ASTM C494 Type A water-reducing admixture (WRA)
- ASTM C494 Type F high-range water-reducing admixture (HRWRA)
- ASTM C260 air-entraining admixture

The cementitious materials used were a Type II cement with equivalent alkali ($\text{Na}_2\text{O}_{\text{eq}}$) of 0.54%; Class F fly ash with CaO content of 4.0% and $\text{Na}_2\text{O}_{\text{eq}}$ of 1.64%; and a Grade 120 slag cement with a $\text{Na}_2\text{O}_{\text{eq}}$ of 0.6%. Details of the chemical composition are available in Obla et al. (2020). The concrete mixtures evaluated in this study are summarized in Tables 2(a), (b), and (c). Also listed are the fresh concrete properties and strength test results. Mixtures were selected to cover a broad range of expected transport properties by varying the w/cm and supplementary cementitious material (SCM) type and content. The paste volume, defined as the volume of cementitious materials and mixing water as a percent of the total concrete volume, was maintained at approximately 27% for all the mixtures. Four non-air-entrained (NAE) concrete mixtures (Table 2(a)) and five air-entrained (AE) concrete mixtures (Table 2(b)) of similar paste composition were used. The target air content for the AE mixtures was 5%, with a higher air content at 8% targeted for one mixture with 50% slag cement at a w/cm of 0.40. Replicate AE mixtures (Table 2(c)) were prepared for additional evaluation of specimen conditioning.

Table 2(a)—Mixture proportions and test results for non-air-entrained concrete mixtures

Mixture designation	0.55PC	0.45FA	0.40SL	0.50SL
Yield-adjusted proportions				
Total cementitious, lb/yd ³	527	583	627	554
Portland cement, lb/yd ³	527	438	313	277
Fly ash, lb/yd ³	0	146	0	0
Slag cement, lb/yd ³	0	0	313	277
Coarse aggregate (No. 57), lb/yd ³	1995	2000	1993	2001
Fine aggregate, lb/yd ³	1179	1178	1177	1181
Mixing water, lb/yd ³	290	262	247	277
WRA, oz/cwt	4.00	4.00	4.00	4.00
HRWRA, oz/cwt	0.00	3.50	4.50	1.58
w/cm	0.550	0.450	0.395	0.500
% paste volume	27.1	27.3	26.9	27.2
Fresh concrete properties				
ASTM C1064, temperature, °F	73	73	74	73
ASTM C143, slump, in.	7-1/2	8	6-3/4	7-3/4
ASTM C138, density, lb/ft ³	147.8	149.0	149.8	148.6
ASTM C138, gravimetric air content, %	1.6	1.4	1.7	1.3
ASTM C231, pressure air content, %	1.7	1.8	1.8	1.9
Strength, psi (ASTM C39)				
28-day	5715	5860	8020	5790
56-day	6160	6795	8690	6885

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/cwt = 65.3 mL/100 kg; 1 in. = 25 mm; 1 lb/ft³ = 16.02 kg/m³; 1 psi = 0.0069 MPa.

Mixture designations are indicated in Table 2. Designations use the w/cm followed by the SCM type. Mixtures without SCMs use “PC”. AE mixtures use the suffix “-A” and the mixture with the higher air content is denoted with “-HA”. Fly ash was used at 25% and slag cement at 50% by mass of cementitious materials. Replicate AE mixtures include a suffix “R”. Batch quantities are calculated based on actual yield determined from the measured density of fresh concrete. An ASTM C494 Type A water-reducing admixture at a dosage of 4 oz/cwt of cementitious material was generally used for all the mixtures. Type F admixture dosage was varied to achieve a slump within the target range of 6 to 8 in. (150 to 200 mm).

Experimental procedures

Concrete mixtures were mixed in a revolving drum mixer in accordance with ASTM C192. Fresh concrete was tested for slump (ASTM C143), temperature (ASTM C1064), air content by the pressure method (ASTM C231), and density (ASTM C138). The gravimetric air content was calculated in accordance with ASTM C138. This was followed by casting 4 x 8 in. (100 x 200 mm) cylindrical specimens that were consolidated in two layers on a vibration table. Specimens were cast for compressive strength and electrical tests.

Table 2(b)—Mixture proportions and test results for air-entrained concrete mixtures

Mixture designation	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A
Yield-adjusted proportions					
Total cementitious	521	572	621	623	543
Portland cement, lb/yd ³	521	429	311	312	272
Fly ash, lb/yd ³	0	143	0	0	0
Slag, lb/yd ³	0	0	311	312	272
Coarse aggregate, lb/yd ³	1973	1961	1976	1983	1964
Fine aggregate, lb/yd ³	1035	1025	1037	909	1029
Mixing water, lb/yd ³	278	249	248	249	271
Air entrainer, oz/cwt	0.70	1.00	2.10	1.73	0.85
WRA, oz/cwt	0.00	4.00	4.00	4.00	4.00
HRWRA, oz/cwt	0.00	1.00	3.66	3.70	0.75
w/cm	0.53	0.44	0.40	0.40	0.50
% paste volume	26.3	26.2	26.9	27.0	26.7
Fresh concrete properties					
ASTM C1064, temperature, °F	68	70	70	70	72
ASTM C143, slump, in.	8	6-3/4	5	7-3/4	5-3/4
ASTM C138, density, lb/ft ³	141.0	141.0	143.8	139.4	141.0
ASTM C138, gravimetric air content, %	5.7	6.3	5.5	8.2	6.2
ASTM C231, pressure air content, %	5.8	6.8	5.9	8.3	6.5
Strength, psi (ASTM C39)					
56-day	4125	4610	6480	6440	5465

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/cwt = 65.3 mL/100 kg; 1 in. = 25 mm; 1 lb/ft³ = 16.02 kg/m³; 1 psi = 0.0069 MPa.

Curing/conditioning procedures for electrical tests

Specimen conditioning procedures maintained in a laboratory environment are listed as follows:

- MR (NAE mixtures)—56-day curing in the moist room conforming to ASTM C511.
- MRVS (NAE mixtures)—56-day curing in the moist room followed by vacuum saturation of the cylinder in accordance with ASTM C1202.
- LW—56-day curing in saturated limewater in a solution to specimen volume ratio of 2:1 to minimize leaching of alkalis (Spragg et al. 2013). Three 4 x 8 in. (100 x 200 mm) cylinders were placed in a 5 gal. (19 L) bucket.
- SC—Specimens were sealed in the molds for 56 days. For the NAE mixtures, specimens were retained in the molds with lids taped and the molds were double-wrapped in plastic bags and sealed with duct tape. For the AE mixtures, the specimens were retained in the molds with the lids taped. The sealed specimens were placed in the moist room.

Table 2(c)—Mixture proportions and test results for replicate air-entrained concrete mixtures

Mixture designation	0.55PCR-A	0.45FAR-A	0.40SLR-A	0.40SLR-HA	0.50SLR-A
Yield-adjusted proportions					
Total cementitious	527	574	621	621	545
Portland cement, lb/yd ³	527	430	311	311	272
Fly ash, lb/yd ³	0	143	0	0	0
Slag, lb/yd ³	0	0	311	311	272
Coarse aggregate, lb/yd ³	1995	1967	1975	1976	1968
Fine aggregate, lb/yd ³	1047	1028	1036	906	1031
Mixing water, lb/yd ³	281	249	248	248	272
Air entrainer, oz/cwt	0.70	1.24	2.20	1.72	0.50
WRA, oz/cwt	0.00	5.19	4.00	4.00	4.00
HRWRA, oz/cwt	0.00	1.00	3.60	3.70	0.75
w/cm	0.53	0.44	0.40	0.40	0.50
% paste volume	26.6	26.3	26.9	26.9	26.8
Fresh concrete properties					
ASTM C1064, temperature, °F	71	72	70	70	71
ASTM C143, slump, in.	8	8	5	7-3/4	6-1/2
ASTM C138, density, lb/ft ³	142.6	141.4	143.7	138.9	141.3
ASTM C138, gravimetric air content, %	4.6	6.0	5.6	8.5	5.9
ASTM C231, pressure air content, %	5.5	7.5	5.9	8.3	5.5

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/cwt = 65.3 mL/100 kg; 1 in. = 25 mm; 1 lb/ft³ = 16.02 kg/m³; 1 psi = 0.0069 MPa.

The specimens were weighed when molded and before demolding at 56 days.

5. SCB—After 56 days in condition SC, the specimens were demolded and immersed in lime-saturated simulated pore solution (PS) for 7 days. The solution-specimen volume ratio was 4:1.

6. PS—Specimens were immersed in lime-saturated simulated pore solution, prepared in accordance with ASTM C1876, for 56 days. The solution composition is indicated in Table 3. The solution-specimen volume ratio was 4:1.

7. AC—Specimens were subjected to accelerated curing through an age of 28 days in accordance with ASTM C1202. This involves immersion in saturated limewater at 73°F (23°C) for 7 days followed by 21 days at 100°F (38°C).

8. ACPS (AE mixtures)—Specimens were subjected to condition AC for 28 days, except that specimens were immersed in lime-saturated simulated pore solution (PS) instead of saturated limewater.

Table 3—Composition of pore solution used in conditions PS, ACPS, and PS2

Mixture designation	PS* (ASTM C1876)	Solutions for condition PS2			
		0.55PC-A	0.45FA-A	0.40SL-A/HA	0.50SL-A
NaOH, mol/L	0.19	0.07	0.06	0.06	0.05
KOH, mol/L	0.19	0.26	0.23	0.17	0.12
Ca(OH) ₂ , mol/L	0.03	0.03	0.03	0.03	0.03
Measured resistivity, Ω·m	0.127	0.140	0.157	0.197	0.266

*Same pore solution composition was used for Condition ACPS and SCB.

9. PS2 (AE mixtures)—Specimens were immersed in lime-saturated simulated pore solution (PS) with composition estimated based on mixture proportions and materials using a modified version of the NIST model (Tanesi et al. 2019). Solution composition and the measured resistivity is indicated in Table 3. The solution-specimen volume ratio was 4:1.

Test measurements

The electrical tests evaluated included surface resistivity (SR) AASHTO T 358, bulk resistivity (BR) ASTM C1876, and RCP ASTM C1202. Bulk resistivity measurements were made on 4 x 8 in. (100 x 200 mm) concrete cylinders, or on 2 in. (50 mm) disks sawed from cylinders, for each condition. Surface resistivity was measured on 4 x 8 in. (100 x 200 mm) cylinders. Unless otherwise stated, the cylindrical specimens were demolded 1 day after casting, placed in the applicable curing/conditioning method, and tested at the stated age. The results of electrical tests reported are the average of measurements on three specimens.

Strength tests were measured in accordance with ASTM C39/C39M at ages of 28 and 56 days. The strength reported is the average of two 4 x 8 in. (100 x 200 mm) cylinders tested at each age. For the AE mixtures, strength was measured at 56 days.

The surface resistivity was measured in accordance with AASHTO T 358 using a four-point Wenner probe with an electrode spacing of 1.5 in. (38.1 mm). However, the curing condition correction was not used. SR in accordance with AASHTO T 358 applies to semi-infinite specimens where the measured response is not constrained by specimen dimensions, such as on a soil surface. Cylindrical specimens used in this study are not semi-infinite. So, the SR values were divided by a correction factor of 1.85, which was determined based on the specimen diameter and electrode spacing (ASTM Committee C09 WK 37880; Morris et al. 1996).

The same equipment was adapted for measuring bulk or uniaxial resistivity in accordance with ASTM C1876. To measure bulk resistivity, thin sponges dampened in saturated limewater were placed between the electrode plates and the specimen surfaces to establish electrical contact. An 11 lb (5 kg) weight was placed on the top plate to improve the contact of the plates with the specimen. Poor contact results in a higher measured resistance.

The surface resistivity of each specimen was measured before the bulk resistivity. To minimize surface drying when measuring resistivity, specimens from each curing/conditioning procedure were removed in sets of three. Specimens subjected to condition SC were rolled on a wet towel before

the measurements, while the other specimens were blotted as stated in ASTM C1876. For specimens that were immersed in the simulated pore solution (PS, ACPS, SCB, PS2), the BR measurements continued to drift upwards and did not reach a stable value with time. Therefore, in this study, BR readings were recorded within 10 seconds of placing the specimen between the plates. A potential resolution to this issue is discussed later. Resistivity readings were stable for specimens subjected to conditions LW, MR, SC, and AC.

Chloride penetrability (RCP) was measured on 2 x 4 in. (50 x 100 mm) disks in accordance with ASTM C1202.

For the NAE and AE concrete mixtures, after resistivity was measured at the end of the conditioning period, a 2 in. (50 mm) thick disk, referred to as S1, was cut from the top of the cylinder and the mass and BR were measured. For the AE mixtures, disk S1 was then vacuum saturated and mass, BR, and RCP were measured. For the NAE mixtures, disk S1 was not vacuum saturated before the RCP test; an additional disk, S2, was extracted at 2 to 4 in. (50 to 100 mm) from the surface. Disk S2 was weighed and the BR measured. Disk S2 was vacuum saturated, following which the mass, BR, and RCP were measured. For all mixtures, specimens immersed in lime-saturated pore solution were not vacuum saturated to minimize solution exchange, and RCP was measured on disk S1. Results for RCP reported in Tables 4(a) and (b) indicate where measurements were made on S1, which were not vacuum saturated.

Additionally, two cylindrical specimens from each mixture were used to evaluate the effect on measured BR with exposure to the environment to simulate service conditions. Specimens from each mixture were cured in the moist room for 56 days. Disks of height 2 in. (50 mm) were cut from the top of the cylinders. Two disks from two cylinders with the top surface facing upwards were exposed to the environment. These were placed in an undisturbed outdoor location on a raised platform exposed to the sun and precipitation at the NRMCA laboratory in College Park, MD. This was referred to as Exterior exposure. Two disks from two cylinders with the top surface facing upwards were placed in a room maintained at 50% relative humidity and 73°F (23°C). This was referred to as Interior exposure. The disk specimens were placed on a grid 1 in. (25.4 mm) thick to permit air circulation around the specimens. Towards the end of the 1-year exposure period, the specimens were immersed for 7 days in limewater, following which the final mass and BR measurements were made.

The results of most electrical tests are reported in Tables 4(a) and (b). The SR and BR measurements were made on the 4 x 8 in. (100 x 200 mm) specimens at the end

Table 4(a)—Resistivity and RCP test results for non-air-entrained mixtures

Cond.	0.55PC			0.45FA			0.40SL			0.50SL		
	SR, $\Omega\cdot\text{m}$	BR, $\Omega\cdot\text{m}$	RCP, C									
MRVS	—	52.9	4499	#N/A	175.2	1230	199.5	237.6	925	178.4	212.7	1301
LW	39.0	41.9	4486	124.3	142.9	1313	156.2	179.8	1047	153.5	174.6	1000
MR	44.1	50.6	3521	140.2	163.2	1205	183.6	224.1	924	177.5	213.1	1027
SC	40.9	44.4	7487	164.3	190.2	1859	215.9	253.9	1308	187.3	229.8	1623
SCB	31.8	32.6	6289	123.5	132.3	1187	157.8	179.4	1025	128.4	144.3	1359
PS	35.4	38.0	5408	122.5	141.8	1230	168.6	184.5	1031	156.5	181.4	1201
AC	42.3	47.6	4164	246.8	268.9	680	233.8	268.0	789	211.8	242.5	852

Note: Shaded cells indicate specimens were not vacuum saturated.

Table 4(b)—Resistivity and RCP test results for air-entrained mixtures

Cond.	0.55PC-A			0.45FA-A			0.40SL-A			0.40SL-HA			0.50SL-HA		
	SR, $\Omega\cdot\text{m}$	BR, $\Omega\cdot\text{m}$	RCP, C												
LW	47.6	55.1	3522	143.6	149.9	1375	217.2	248.9	807	234.4	258.5	888	207.8	232.7	921
SC	46.9	50.9	5017	172.9	195.3	1349	287.0	323.3	839	274.1	321.5	1114	249.9	296.2	854
SCB	38.5	42.4	4995	150.8	166.5	1070	210.1	230.8	749	223.1	221.5	896	171.4	208.5	956
AC	59.1	62.0	3650	202.1	219.9	810	273.2	331.1	662	298.2	377.7	683	277.8	311.2	626
PS2	43.5	50.0	—	137.1	152.7	—	204.2	240.6	—	215.4	243.5	—	192.3	200.4	—

The following results were obtained from specimens made from the replicate AE mixtures (Table 2(c))

LW(R)	46.8	52.3	4023	154.7	167.0	1048	286.1	305.5	603	274.3	299.8	685	226.0	256.8	846
PS	42.4	47.8	—	153.4	168.4	—	251.9	281.2	—	257.3	266.8	—	207.7	225.8	—
ACPS	40.3	46.4	—	238.8	267.3	—	313.7	353.7	—	304.2	324.0	—	229.2	250.2	—

Note: Shaded cells indicate specimens were not vacuum saturated.

of the conditioning period. For most conditions, the age of the specimens was 56 days. The specimen age for the AC condition was 28 days. Specimen age for SCB was 56 + 7 days immersion in the simulated pore solution. The RCP tests were on 2 in. (50 mm) disks that were vacuum saturated after the conditioning period, except for specimens immersed in lime-saturated simulated pore solution. The age of these specimens at the time of testing includes two additional days after the conditioning period for vacuum saturation.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Overview of electrical test results

Figure 1 plots the bulk resistivity and RCP for all mixtures and conditions. These data are compared to the theoretical relationship between charge passed and resistivity from Eq. (1) and includes zones for levels of chloride penetrability from Table 1. Except for specimens subjected to condition SC, the data for different mixtures fall in the same zones and are consistent with this relationship. This observation is relevant because the specimen size and conditioning for BR is different from that used for the RCP test. 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.

Figure 2 plots bulk resistivity and surface resistivity along a line of equality. These values should be similar when specimen geometry is considered to convert measured resistance to resistivity. The transmission of electrical signals is different in these two modes of measurement. In this study, the measured SR was generally less than the measured BR. The ratio of SR to BR ranged between 0.80 and 1.01. No clear trend can be observed between the mixtures or the curing conditions. For specimens from the AE mixtures, BR was measured before and after the SR measurement for some of the conditions. For the specimens conditioned in the lime-saturated simulated pore solution, the BR measured before the SR measurements were lower than that measured after. If these BR values are used, the ratio of SR to BR increased on average from approximately 0.91 to 0.98 for specimens in SCB and PS conditions. BR measurements made on specimens immersed in simulated pore solution were more sensitive to elapsed time prior to taking the measurement than specimens subjected to other conditions. To maintain consistency with the NAE mixtures, the BR measurement obtained after the SR measurement is reported. An SR/BR ratio less than 1 can also be due to specimen inhomogeneity and/or localized leaching of alkalis from near the specimen surface (Spragg et al. 2017).

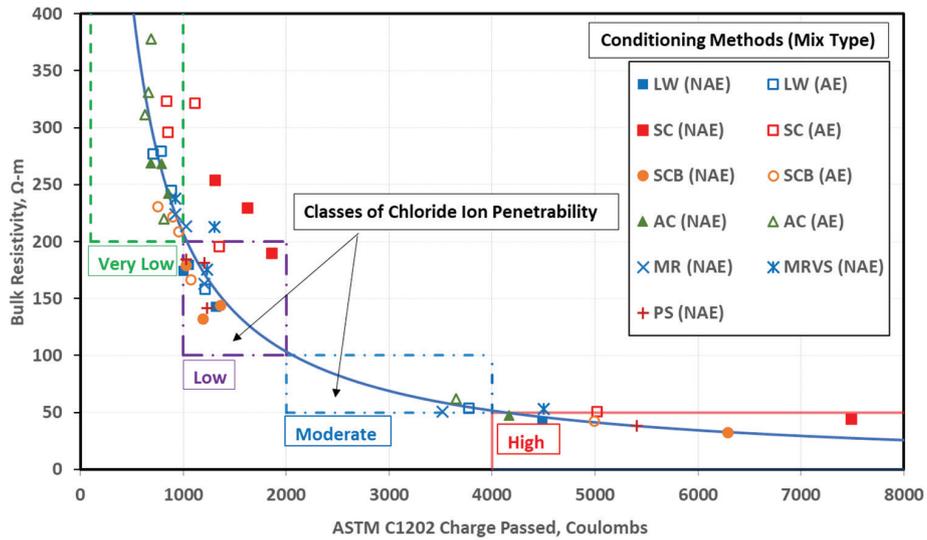


Fig. 1—RCP versus bulk resistivity for all conditions and concrete mixtures. Zones for chloride ion penetrability classification are based on Table 1.

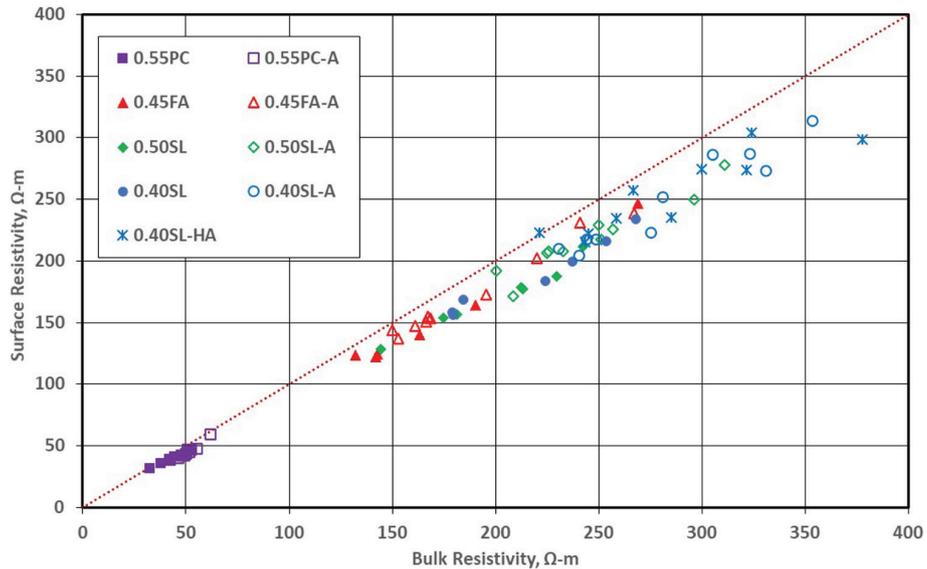


Fig. 2—Bulk resistivity versus surface resistivity for all conditions and concrete mixtures.

Variability of electrical test methods

Table 5 reports the single-operator coefficient of variation (COV) from measurements on three replicate specimens for all mixtures. Each value for a specific specimen condition is the average COV from four NAE and five AE concrete mixtures. The average single-operator COV for a test method across all the specimen conditions is also reported. BR (S1) is the COV of measured BR on a 2 in. (50 mm) thick disk specimen cut from the top of the 4 x 8 in. (100 x 200 mm) cylinder at the end of the conditioning period. The BR on the cylinders and disk S1 was measured before specimens were vacuum saturated, except for condition MRVS for the NAE mixtures. Ranking the precision of the test methods in this study are as follows: BR < SR < BR (S1) < RCP. The precision of the BR test is considerably better than ASTM C1202 and marginally better than the SR test. The average COV of 3.1% for BR measurements is similar to the single-operator COV for compressive strength tests in ASTM C39. This evaluation suggests that the precision of BR measured

on 4 x 8 in. (100 x 200 mm) cylinders is better than that measured on 2 in. (50 mm) disk specimens.

Figures 3 and 4 illustrate the single-operator COV for bulk resistivity for the NAE and AE mixtures, respectively. Each bar represents the COV from measurements of three replicate specimens. Specimens subjected to condition SCB resulted in a higher variability. Also, vacuum saturating the test specimens did not improve the precision of BR measurements (Obla et al. 2020).

Specimen effects on bulk resistivity

The BR of disk S1 obtained from a cylinder after conditioning was measured and compared to BR measured on the 4 x 8 in. (100 x 200 mm) cylindrical specimen. The ratio of disk to cylinder BR for all mixtures is plotted in Fig. 5. In general, the measured BR of the disks is slightly lower than that measured on the cylinder. Disk specimens subjected to conditions ACPS and PS resulted in a measured BR that was less than 80% of that measured on whole cylinders. BR

Table 5—Single-operator precision of results of electrical tests

Condition	Mixture	Single-operator precision, COV			
		SR	BR	BR (S1)	RCP
MR	NAE	3.1%	2.0%	4.7%	13.4%
MRVS	NAE	2.4%	3.1%	3.9%	9.0%
LW	NAE	3.5%	2.3%	3.0%	8.6%
	AE	3.7%	2.4%	3.7%	6.1%
SC	NAE	4.1%	1.8%	4.3%	7.7%
	AE	3.4%	3.3%	5.9%	17.2%
PS	NAE	2.2%	2.5%	4.6%	9.0%
	AE	3.2%	1.8%	—	—
SCB	NAE	5.8%	2.5%	10.4%	13.3%
	AE	9.0%	9.5%	9.2%	7.6%
AC	NAE	4.9%	3.0%	5.5%	9.6%
	AE	5.3%	2.4%	2.9%	7.3%
ACPS	AE	4.4%	4.0%	—	—
PS2	AE	2.8%	2.6%	—	—
Average		4.1%	3.1%	5.3%	9.9%

Note: Each value is the average of measurements from four mixtures for NAE and five mixtures AE.

measured on whole cylinders classified mixtures for chloride penetrability the same as RCP results. Further, as shown in Table 5, the precision of BR measured on 4 x 8 in. (100 x 200 mm) cylinders is better than that measured on 2 in. (50 mm) disk specimens. It is recommended that BR be measured on whole cylinders. If disk specimens are prepared for RCP or if disks are obtained as cores, BR may be measured on these specimens. If comparisons need to be made to results from whole cylinders, based on a limited evaluation, it is recommended that the disk specimens be immersed in limewater and not in lime-saturated simulated pore solution.

The difference of BR between the top 2 in. (50 mm) disk (S1) and that obtained between 2 and 4 in. (50 and 100 mm) from the top (S2) is compared in Table 6. No significant difference was observed between these two specimen locations. A significant difference may be observed if there is segregation through the depth of the cylindrical specimen.

Effect of simulated service conditions on BR

Table 7 reports the initial bulk resistivity of specimens before exposure after 56-day moist curing and at 1 year in the simulated exposure.

After 12 months of exterior exposure, followed by 7 days of limewater conditioning:

1. The BR of specimens from the SCM mixtures was on average 2 to 2.8 times higher than the initial BR before exposure. The BR of specimens from the PC mixture were considerably lower before exposure and changed to approximately 3.2 times higher.

2. The BR of specimens from the SCM mixtures was on average 2.1 to 3.3 times higher than that of the corresponding air-entrained or non-air-entrained PC mixture.

Table 6—Ratio of measured BR of Disk S2 (2 to 4 in. [50 to 100 mm] from top) to Disk S1 (top 2 in. [50 mm])

Specimen condition	Mixture				Average (SCM mixtures)
	0.55PC	0.45FA	0.40SL	0.50SL	
LW	N/A	1.00	0.96	1.05	1.00
MR	0.95	0.95	0.96	0.97	0.96
SC	0.99	1.04	0.97	1.03	1.01
AC	0.92	1.06	1.01	1.01	1.00

After 12 months of interior exposure, followed by 7 days of limewater conditioning:

1. For the NAE mixtures, the BR of specimens from the SCM mixtures was on average 1.5 to 2.0 times higher than the initial BR before exposure. For the AE mixtures, the BR at 1 year was 1.1 to 1.7 times, suggesting that the saturation level of AE mixtures might have been impacted more. The BR of specimens from the PC mixture was approximately 2.8 times higher.

2. The BR of specimens from the SCM mixtures was on average 1.4 to 2.6 times higher than that of the corresponding air-entrained or non-air-entrained PC mixture.

Exterior exposure did not significantly reduce the degree of saturation of specimens based on the measured change in mass (Obla et al. 2020). The average degree of saturation (DOS) of specimens for all mixtures was 89% before being placed in exterior exposure and changed to approximately 72% on average at the end of the 1-year period in exterior exposure. The average DOS of specimens at the end of interior exposure was approximately 63%.

The BR of specimens in exterior exposure was higher. This suggests that a reduced DOS of specimens in interior exposure (Obla et al. 2020) curtailed the improvement in transport properties for the SCM mixtures, relative to those in exterior exposure.

Suggested revision to ASTM C1876

ASTM C1876 requires that measurements should be recorded after allowing the readings to stabilize for 2 to 5 seconds. However, it was observed that the bulk resistivity readings for specimens conditioned in pore solution do not stabilize and continue to increase with time. More recent work (Obla et al. 2020) verified that bulk resistivity of three different mixtures (three specimens per mixture) increased between 8 and 20% (average 14%) when measured at 2 minutes relative to the measurement at 5 seconds (Table 8). The specimens were blotted after being removed from the pore solution in accordance with ASTM C1876 and were maintained between the plates over the 2-minute duration.

As part of the evaluation, specimens conditioned in pore solution were washed under tap water for 45 seconds before the measurement. After this washing, the bulk resistivity measurements were stable and did not show the drifting trend over a 2-minute duration. Measurement variability based on the range of three specimens reduced from 13% before washing to 4% after washing. After washing, the bulk resistivity of specimens conditioned in pore solution increased

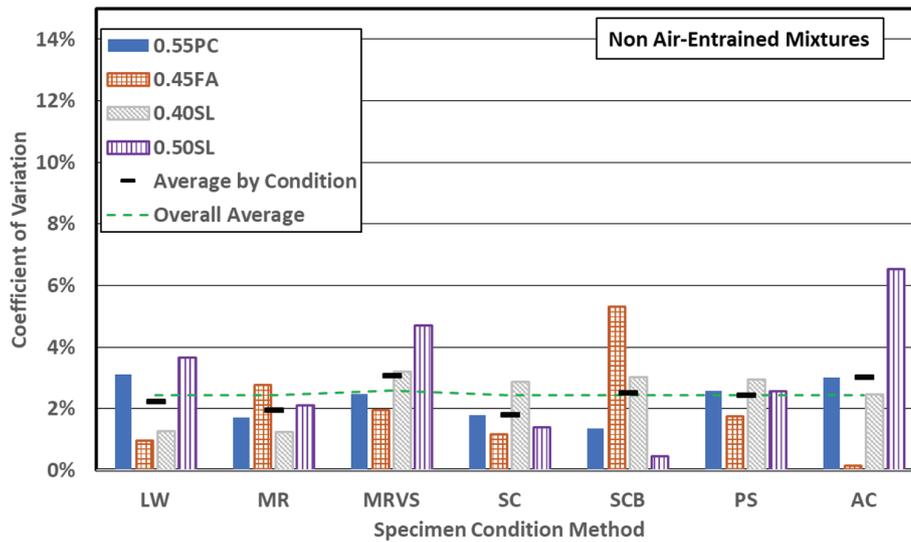


Fig. 3—Coefficient of variation of bulk resistivity test specimens subjected to different conditions for NAE mixtures.

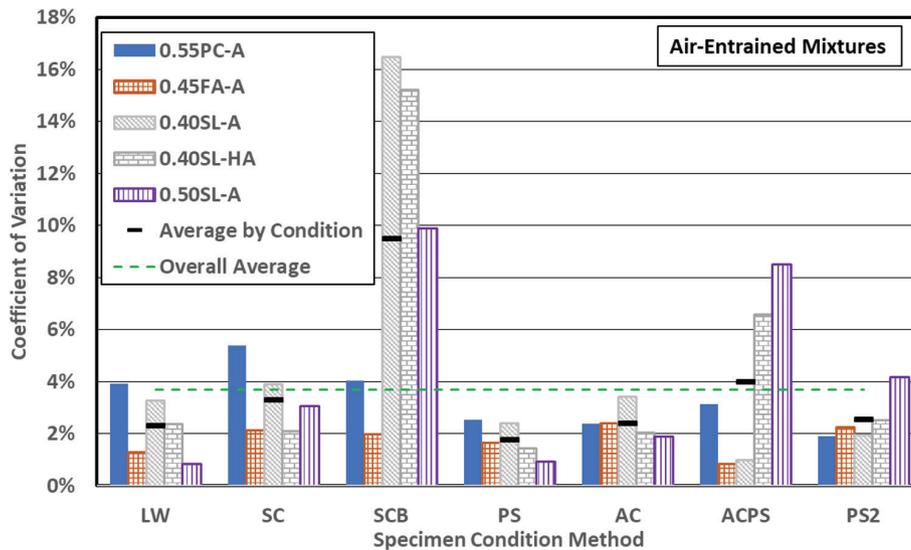


Fig. 4—Coefficient of variation of bulk resistivity test specimens subjected to different conditions for AE mixtures.

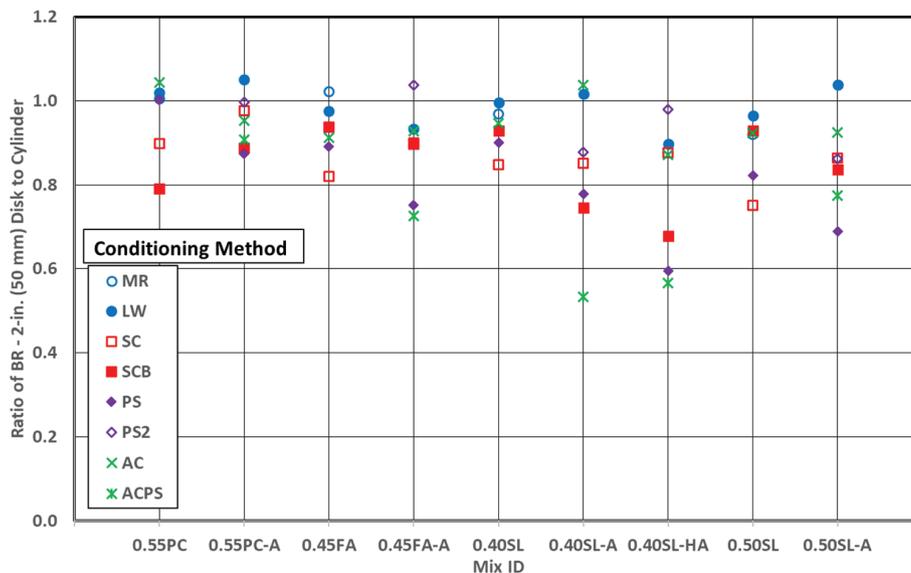


Fig. 5—Ratio of bulk resistivity of top 2 in. (50 mm) disk to whole specimen of various conditions and concrete mixtures.

Table 7—Impact of long-term exposure on BR of 2 in. (50 mm) disk specimens

Mixture	Initial BR before exposure*, $\Omega\cdot\text{m}$		BR at 1 year, $\Omega\cdot\text{m}$		Ratio of BR at 1 year to initial	
	Exterior exposure	Interior exposure	Exterior exposure	Interior exposure	Exterior	Interior
0.55PC	58.4	59.5	186.4	167.6	3.2	2.8
0.45FA	165.9	147.8	463.5	240.8	2.8	1.6
0.40SL	215.0	209.6	421.5	427.6	2.0	2.0
0.50SL	193.8	196.5	425.2	299.9	2.2	1.5
0.55PC-A	72.6	71.9	223.7	194.1	3.1	2.7
0.45FA-A	188.1	181.4	474.9	301.0	2.5	1.7
0.40SL-A	313.0	297.6	621.4	457.5	2.0	1.5
0.40SL-HA HAHA	358.7	336.6	738.3	430.6	2.1	1.3
0.50SL-A	294.2	268.7	584.4	305.7	2.0	1.1

*Cylinders were cured in moist room for 56 days, after which disk specimens were cut.

Table 8—Stability of measured resistivities (Obla et al. 2020)

Mixture ID	BR LW		BR PS		BR LW (AW)		BR PS (AW)	
	5 seconds	2 minutes	5 seconds	2 minutes	5 seconds	2 minutes	5 seconds	2 minutes
Mixture 1	142.2	143.1	94.2	107.8	139.9	139.9	113.9	113.7
Mixture 2	373.2	381.6	173.2	208.4	366.0	366.0	249.4	244.2
Mixture 3	102.2	102.8	63.6	68.3	100.8	100.8	76.0	75.4

Note: Reported results are average of three specimens; AW refers to after washing.

between 20 and 44% (average 28%) for the three mixtures. However, the bulk resistivity was lower than that measured on specimens conditioned in limewater. It is postulated that the presence of the pore solution on the surface impacts the bulk resistivity measurements. Specimens conditioned in limewater did not drift with time, and the measurements were more repeatable between specimens.

The following is a recommended revision to ASTM C1876. After removing specimens from the pore solution, rinse them under running tap water for 45 seconds while lightly wiping the specimens with the palm. Blot off the excess liquid and obtain the BR measurement.

CONCLUSIONS

The following conclusions are drawn from this study:

1. Mixture classification for chloride penetrability based on criteria stated in Table 1 is consistent for measured bulk resistivity (BR) and rapid chloride permeability (RCP) as long as the same specimen curing/conditioning procedure is used. The exception is for specimens subjected to condition SC. This observation was valid even though RCP specimens were vacuum saturated prior to testing while resistivity specimens were not.

2. Surface resistivity results were, on average, approximately 10% lower than the measured bulk resistivity on the same test specimens in this study. As a result, there were some cases where the chloride penetrability classification based on surface resistivity (SR) diminished one level from the classification based on measured BR.

3. The single-operator precision of the BR test is considerably better than ASTM C1202 and marginally better than the SR test. BR measured on the 4 x 8 in. (100 x 200 mm) cylinder is less variable than that measured on the top

2 in. (50 mm) thick disk. Conditioning specimens by SCB resulted in higher variability of measured bulk resistivity. Vacuum saturation of test specimens after the curing/conditioning process had little impact on the variability of the resistivity test results.

4. If BR is measured on disk specimens and comparisons need to be made to results from whole cylinders, based on a limited evaluation, it is recommended that the disk specimens be immersed in limewater and not in simulated pore solution. There was no difference in measured BR of the top and middle disk specimens cut from cylinders.

5. Measurements made after 12 months show that exterior exposure did not adversely impact the development of improved transport properties for the supplementary cementitious material (SCM) mixtures. Companion specimens from the SCM mixtures stored at a constant 50% relative humidity and 73°F (23°C) environment did not have a similar level of improvement in transport properties.

6. For specimens that were immersed in the simulated pore solution, the BR measurements continued to drift upwards and did not reach a stable value with time. To avoid this drift, it is recommended that ASTM C1876 be modified to require that specimens be washed under running tap water for 45 seconds before the measurements.

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