Improving the Reliability of Resistivity Tests of Concrete

FINAL REPORT

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EXECUTIVE SUMMARY

The evolution towards performance-based specifications that is beneficial to the ready mixed concrete industry is constrained to some extent with the availability of a reliable test method that is an indicator of the permeability of concrete. This requirement is important for concrete subject to exposure conditions that can cause deterioration due to penetration of water and dissolved chemicals that impact the durability and prolonged service life of concrete. The current way of specifying for durability is to impose a maximum w/cm limit on concrete. This is not verifiable and does not recognize the significant benefit provided by supplementary cementitious materials (SCMs). A commonly used electrical test, referred to as the rapid chloride permeability (ASTM C1202) is more expensive, has deficiencies, and subject to error by less proficient testing agencies. The risk of rejecting acceptable concrete is high.

A promising electrical test method that predicts the permeability of concrete is to measure the resistivity of concrete and is gaining increased acceptance. The method is easy to perform, non-destructive, and can be measured on strength test specimens before those are broken. However, there are significant differences in the measured resistivity depending on how the specimens are cured and conditioned before measurements are obtained. The primary factors that impact resistivity include the resistivity of the solid portion, the resistivity of the pore solution that depends on the chemical species dissolved, and the degree of saturation of the test specimen. Another important requirement for the use of this method is that it should characterize concrete mixtures consistently with our understanding of reduced permeability.

In this research study, four types of air-entrained and non-air-entrained concrete mixtures with different SCMs – fly ash and slag cement – and at varying w/cm were evaluated. Test specimens were cured and conditioned, typically for 56 days, by several different methods that included sealing specimens without exposure to external moisture, immersion in saturated lime water, immersion in a solution that mimics the composition of typical concrete pore solutions, and several other variations. Two types of resistivity measurements were performed – surface resistivity measured along the circumference of cylindrical test specimens, and bulk resistivity measured parallel to the axis of the cylinders. Test specimens included typical 4 by 8-in cylinders and 2 by 4-in slices from cylinders. The degree of saturation of test specimens was determined to evaluate its impact on resistivity measurements.

This study indicates that measuring the resistivity of concrete is a reliable test method to predict its permeability property and potential durability. Characterization of mixtures is similar to expectations of reduced permeability. The variability of the test is considerably lower than that seen for RCPT. The bulk resistivity is the more robust measurement with reduced variability compared to measuring surface resistivity. It is recommended that a single curing/conditioning method and test age be established by agencies using this test for determining the acceptance of concrete. While the preference in the currently written standards is to cure/condition test specimens in a carefully composed simulated pore solution, this research identified some potential problems with this option. These include a lower measured resistivity (indicating a higher level of permeability), difficulties with obtaining a stable reading, and potential problems with preparing this solution to the required accuracy by testing agencies. The research also observed a significant effect of saturation of concrete in providing an incorrect assessment of concrete and could potentially accept unacceptable concrete. The final suggestion of this work is to cure

and condition test specimens in saturated lime water for 56 days. This method has been traditionally used for strength specimens and testing agencies are familiar with it. It also recognizes that the test age may need to be extended for some of the slower reacting SCMs or an accelerated curing procedure could be used. It also indicates that the resistivity of test specimens conditioned in simulated pore solution will be unstable and more variable and suggests a wash process of test specimens before measurement to achieve stable and consistent results. The results of this research can be used to develop improved testing protocols for improved reliability of results to predict the potential durability of concrete and can be used as an alternative to w/cm in industry codes and standards for more optimized concrete mixtures.

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 impacts durability is permeability and the transport of ionic species through concrete. Currently, industry standards (ACI 318-19, ACI 301-16) rely on specifying the maximum water-to-cementitious materials ratio (*w/cm*) for concrete mixtures used in members that require low transport properties, commonly referred to as low permeability, due to exposure conditions. It is well recognized that the transport properties of concrete are best improved by a lower *w/cm* and use of supplementary cementitious materials (SCMs). Specifying solely a maximum *w/cm* may not necessarily result in the best performance for low permeability and could prevent concrete mixtures from being optimized for improved durability. Different mixtures at the same *w/cm* can have widely ranging permeability and other performance characteristics. Further, *w/cm* cannot be reliably measured and verified in the field.

Previous research (Berke and Hicks 1992; Thomas 2013; and Obla et al. 2016) has shown a good correlation between apparent chloride diffusion coefficient, determined in accordance with ASTM C1556, and the results from ASTM C1202, Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (RCPT). However, the RCPT result, like all electrical tests, is impacted by the pore solution conductivity. The use of high amounts of more reactive SCMs like slag cement and silica fume, in combination with reduced quantity of portland cement reduces the ionic concentration of the pore solution and reduces its conductivity. This lowers the measured RCPT result, thus indicating that mixtures with high *w/cm* (>0.60) and high dosages of reactive SCMs like slag cement or silica fume have a low permeability. For this reason, the study (Obla et al. 2016) recommended that specification criteria for measured coulombs by the RCPT method be combined with a minimum specified compressive strength to reliably select mixtures for low chloride ion penetrability. The strength requirement could prevent the high *w/cm* mixtures that meet the RCPT criteria from being used. This is similar to the current ACI 318 requirements where a minimum specified compressive strength is combined with a maximum *w/cm*.

More recent work (Archie 1942; Weiss et al. 2017) has promulgated the concept of the formation factor (FF) as an indicator of the transport properties of concrete. The FF is demonstrated to be a scientifically sound principle that characterizes a material property of concrete, as opposed to an indicator type test. The use of FF addresses the impact of the pore solution conductivity on electrical measurements. This evolution permits the use of FF as the sole specification requirement without including the specified strength as the basis for selecting concrete mixtures for low chloride-ion penetrability (Obla, 2019). FF has also been correlated with concrete sorptivity (Moradllo 2018) and it can thereby be used to specify requirements for concrete mixtures that will be resistant to cycles of freezing and thawing from the perspective of the rate at which saturation may be achieved (Todak et al. 2015). Mixtures with low transport properties are important when sulfate resistance is required, along with criteria for a sulfate resistant cementitious system.

There are several factors that impact the measured result with RCPT; the test method is complex and requires a high level of laboratory proficiency; has a high variability; and is relatively expensive. RCPT 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 RCPT/conductivity or higher resistivity values. Table 1 provides a qualitative interpretation of the chloride ion penetrability based on the RCPT and resistivity test results and is reproduced from ASTM C1202 and the AASHTO PP84, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures guidance document. A theoretical relationship between RCPT and resistivity has been derived (Weiss et al. 2017) as:

$$\rho=\frac{206830}{Q} \quad (1)$$

Where:
Q is the RCPT test result in coulombs measured in accordance with AASHTO T 277, and
ρ is the resistivity of the concrete.

The values shown in Table 1 are consistent with the above theoretical relationship and is applicable for saturated specimens. The specifications would thereby state a minimum resistivity for qualifying concrete mixtures with low penetrability. In this report, the RCPT, conductivity, and resistivity test methods together are referred to as electrical test methods.

State highway agencies have more recently been moving towards using the resistivity test, AASHTO T 358 measuring surface resistivity, and provisional standard AASHTO TP 119 for measuring bulk or uniaxial resistivity. ASTM C1876, released in 2019, also measures bulk electrical resistivity of concrete. Resistivity is one of the methods included in AASHTO PP 84 for evaluating the durability 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).

Important 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). Even though the focus here is on electrical resistivity, these factors will also impact the measured electrical conductivity and RCPT results of concrete.

Leaching of alkali ions from the pore solution in the concrete increases the resistivity of the pore solution and thereby increases the measured resistivity of concrete. An increase in DOR/DOH of cementitious materials and/or a reduction in concrete specimen temperature at the time of measurement will increase the measured resistivity.

A specimen that is at a lower saturation level (i.e. with a lower DOS) will have a higher measured resistivity than a saturated specimen of the same concrete. Weiss et al. (2013) proposed a correction, or a saturation function, that would allow for the resistivity of a test specimen at any degree of saturation to be corrected to represent the resistivity of the specimen in a saturated condition. This is a power law relationship, shown here as:

$$\frac{\mathrm{R_{sat}}}{\mathrm{R_{DOS}}}=\mathrm{DOS^n} \quad (2)$$

Where:
R_{DOS} is the resistivity of the specimen at the DOS when measured
R_{sat} is the resistivity at 100% DOS
DOS is the degree of saturation, expressed as a decimal varying from 0 at dry to 1 at saturated, and
n = an exponent of the empirical relationship

The value of n has been shown to vary 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 modified as Equation 3 to estimate the resistivity of specimens at different degrees of saturation.

$$\frac{R_{DOS2}}{R_{DOS1}} = \left(\frac{DOS_1}{DOS_2}\right)^n \qquad (3)$$

Where:
R_{DOS1} is the resistivity of the specimen at degree of saturation DOS_1, and
R_{DOS2} is the resistivity of the specimen at degree of saturation DOS_2

Using Equation 3 and assuming n=4, a reduction in DOS from 70% to 60% estimates that the resistivity increases by 85%.

Air content, whether entrained or otherwise, will reduce the DOS of the test specimens (Todak et al. 2015). The tolerance on air content for concrete delivered to the jobsite is ±1.5% (ASTM C94, ACI 301). Based on theoretical calculations and experiments Todak (2015) showed that a 3% increase in air content (corresponding to the allowed tolerance) can reduce the DOS determined after about five days of immersion in water (when the concrete matrix pores are filled with water with the entrapped/entrained air voids empty) by about 10%. Assuming n=2.3 for AE concrete, which is the average value observed for AE concrete, a change in DOS from 70% to 60% (due to a 3% increase in air content) can be calculated to result in a 43% increase in concrete resistivity. This predicted increase in resistivity is due to a reduction in the estimated DOS and not due to a reduction in chloride penetrability. What is of concern though is that the typical air content variation observed in the field can lead to a broad variation in the measured resistivity values. This increases the risk of complying with the specified resistivity between loads of concrete primarily due to a variation in air content and not due to any variation in the chloride penetrability of concrete.

BACKGROUND ON RESISTIVITY TEST STANDARDS

There is considerable difference in how concrete test specimens are conditioned for the electrical tests and these are summarized in Table 2. The RCP test, ASTM C1202, requires test specimens to be vacuum-saturated after a water curing period that can be accelerated by immersion in water at a higher temperature. The bulk resistivity method, AASHTO TP 119, allows vacuum saturation after curing/conditioning in lime-saturated simulated pore solution or maintaining the specimens sealed in molds. The surface resistivity (AASHTO T 358) and the bulk conductivity (ASTM C1760) test method require moist curing, which could be either curing in a moist room or immersion in saturated lime water. ASTM

C1876 requires curing/conditioning in lime-saturated simulated pore solution. As currently written, resistivity and conductivity test methods permit alternatives for specimen conditioning with limited specificity. The surface resistivity test method being standardized by ASTM permits moist curing, vacuum saturation, or storing specimens in a sealed condition in the molds. The specifying agencies using the resistivity test methods invoke a wide range of specimen conditioning procedures.

Test specimens from the same concrete mixture cured and conditioned in the various options permitted by the standards could have widely different degree of saturation (DOS), leaching of alkali ions from concrete, and DOH/DOR of cementitious materials; all of which impact the measured resistivity. So, all specifications should preferably state the same specimen conditioning method for the resistivity test. 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. Using different options allowed by the standards makes the development of mixtures difficult and acceptance testing by different entities uncertain and unreliable.

ASTM C1202 requires specimens to be vacuum-saturated that will result in specimens prepared from different mixtures to have similar DOS. For all the other tests listed in Table 2, however, the same curing/conditioning method will result in varying DOS of specimens prepared from different mixtures. As discussed earlier, a 10% decrease in DOS is predicted to increase the concrete resistivity by 85%. Conditioning procedures that causes different mixtures resulting in different levels of DOS makes comparisons between mixtures for permeability characteristics questionable. Consider, for example, two mixtures of the same cementitious composition, where *w/cm* of mixture 1 is 0.50 and that of mixture 2 is 0.40. If conditioning of specimens from mixture 1 result 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. Therefore, concrete mixtures characterized for low penetrability in accordance with ASTM C1202 (RCPT) with considerable history of use may be inconsistently classified by the resistivity criteria.

OBJECTIVE

Electrical tests were performed on test specimens prepared from nine concrete mixtures with varying compositions. Test specimens were subjected to the different curing and conditioning procedures required or permitted by the test methods. The following questions were raised and are addressed in this report:

1. Does the resistivity test classify concrete mixtures for chloride penetrability similarly to ASTM C1202 (RCPT)?
2. Will the different curing/conditioning procedures required or permitted by the resistivity test methods change the classification of specific mixtures?
3. How do the surface and bulk resistivity results compare for mixtures over a wide range of chloride penetrability? How does the bulk conductivity results compare with ASTM C 1202?
4. What is the single-operator precision of the various electrical test methods?
    a. Will vacuum saturation of test specimens improve precision of resistivity measurements?

5. What is the impact of DOS on measured resistivity?
    a. Due to variation in DOS at the end of curing/conditioning between mixtures should the resistivity results be normalized to the saturated condition? Would this better facilitate comparing and classifying mixtures for low chloride penetrability?
6. What is the impact of air content on DOS of specimens and how does this affect measured resistivity? Does measured resistivity vary as much for variations within accepted air content tolerances as predicted by Equation 2?
7. Is there an impact of type of specimen used?
    a. bulk resistivity measured on the cylinder or a 2-inch disk cut from the cylinder?
    b. bulk resistivity measured on disks from different locations of a cylinder?
8. What is the preferred curing/conditioning procedure? Consideration should include simplicity for technicians and laboratories.
9. How does the DOS and resistivity of concrete specimens kept in simulated service conditions compare with the DOS and resistivity of concrete test specimens maintained in standardized laboratory conditions?

EXPERIMENTAL PROGRAM

MATERIALS AND MIXTURES

Table 3 summarizes the chemical characteristics of the cementitious materials used in this project as reported by the supplier. The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (PC), Lot # 9116
- ASTM C989 slag cement (SL), Lot # 9270
- ASTM C618 Class F fly ash (FA), Lot # 9152
- ASTM C33 No. 57 crushed limestone coarse aggregate, Lot # 9100
- ASTM C33 natural sand with an FM of2.67, Lot # 9101
- ASTM C494 Type A water-reducing admixture, Lot # 9102
- ASTM C494 Type F high-range water-reducing admixture, Lot # 9103
- ASTM C260 Air entraining admixture, Lot #9104

Table 4 lists the concrete mixtures and assigned mixture designations evaluated in this study. The table includes expected transport properties (as indicated by ASTM C1202) to cover a broad range by varying the *w/cm* and supplementary cementitious materials (SCM) type and content. Since transport properties and electrical measurements are impacted by the paste volume (volume of cementitious materials and mixing water as a percent of the total concrete volume), this was maintained at about 27% for all the mixtures. Four non-air-entrained concrete mixtures were evaluated in Phase A. Five air-entrained concrete mixtures were evaluated in Phase B. Four of the AE mixtures, the same as the mixtures from Phase A, had a target air content of 5%. One mixture with 50% slag cement at a *w/cm* of 0.40 was targeted at a higher air content of 8%. It was anticipated that air entrainment will result in a lower DOS at the end of conditioning and its impact on measured resistivity was of interest.

Mixture designations were assigned by the *w/cm* followed by the SCM type used in the mixture. Mixtures without SCM use the designation "PC". Mixtures with entrained air use the suffix "– A". The AE concrete mixtures with the higher air content is denoted by the suffix "– HA". Fly ash was used at 25% and slag cement was used at 50% by mass of cementitious materials. The 0.40SL mixture (NAE) and all the AE concrete mixtures were repeated, and these include a suffix "R" in the mixture designation. The 0.40SL mixture was repeated to evaluate the batch-to-batch variation of the test results. The AE concrete mixtures were repeated due to an error in preparing the simulated pore solution used for conditioning the specimens and is discussed later. Calculated mixture proportions, properties of fresh concrete, and strength test results for NAE, AE, and repeated AE concrete mixtures are provided in Tables 5a, 5b, and 5c, respectively. Batch quantities are calculated based on actual yield determined from the measured density of fresh concrete. A higher slump in the range of 6-8 in. was targeted for the mixtures to ensure adequate workability for casting the test specimens. An ASTM C494 Type A water reducing admixture at a dosage of 4 oz/cwt. of cementitious materials was generally used for all the mixtures. Type F admixture dosage was varied to achieve slump within the target range.

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 by 8 in. cylindrical specimens which were consolidated in two layers on a vibration table. Specimens were cast for compressive strength, electrical tests, and DOS measurements. Fifteen additional cylinders were cast for supplementary testing by the Federal Highway Administration (FHWA).

Supplementary tests by FHWA included independent resistivity measurements, non-evaporable water as a measure of degree of hydration/reaction, total pore volume, sorptivity, and DOS measured by a different method. FHWA measurements provided insight into alkali leaching from specimens and DOH/DOR of cementitious materials subjected to various curing conditions. The FHWA specimens were conditioned at the NRMCA laboratory and transported to their facilities at the end of the conditioning period. Additionally, samples of immersion solutions of saturated lime water and lime-saturated pore solution before and after specimen immersion were provided to evaluate alkali leaching. Portions of the specimens tested by NRMCA were provided to FHWA for extraction of pore solution to measure composition and conductivity (resistivity).

Curing/Conditioning Procedures for the Electrical Tests

Specimen conditioning procedures in a laboratory environment (70-76 °F) are listed below.

1. MRVS (NAE mixtures only) – 56 day curing in the moist room followed by vacuum saturation of the whole cylinder in accordance with ASTM C1202. This conditioning is expected to attain the highest DOS level. Alkali leaching is expected during the moist room curing but not much additional leaching is expected during the subsequent limited duration of vacuum saturation (VS).

2. LW – 56 day curing in saturated lime water in a solution-to-specimen ratio by volume of 2:1 (three 4 by 8 in. cylinders in a 5-gal bucket) to minimize leaching (Spragg et al. 2013). Alkali leaching is expected.
3. MR (NAE mixtures only) – 56 day curing in the moist room that conforms to ASTM C511. Alkali leaching is expected.
4. 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 which were sealed with duct tape. Considering the extensive effort required, for the AE mixtures, the specimens were retained in the molds with the lids taped. The sealed specimens were placed in the moist room. The specimens were weighed in the sealed molds when molded and before demolding at 56 days. It is expected that this conditioning process will result in the lowest DOS level and alkali leaching will be negligible. There is concern whether this condition will support continued hydration of cementitious materials, especially with lower *w/cm* and for mixtures containing SCMs, and whether the benefits provided by SCMs will be realized in the measured results. It is expected that this condition will have the lowest DOH/DOR compared to the other methods.
5. SCB – specimens were conditioned as described in SC for 56 days following which they were demolded and immersed in lime-saturated simulated pore solution, as used in condition PS, for seven days. The solution to specimen volume ratio was maintained at 4:1. It is expected that DOS and DOH/DOR will be higher than that for specimens subjected to the SC condition. It is expected that leaching would be negligible but may occur if the pore solution composition is not similar to that of the immersion solution.
6. PS – specimens were immersed in lime-saturated simulated pore solution for 56 days. The solution to specimen volume ratio was maintained at 4:1. The solution was prepared in accordance with ASTM C1876 by dissolving 153.9 g sodium hydroxide, 215.9 g potassium hydroxide, and 40.5 g calcium hydroxide in 19,880 g water. The solution is intended to simulate an average pore solution composition to minimize alkali leaching from test specimens. It is expected that leaching would be negligible but may occur if the pore solution composition is not similar to that of the immersion solution. The level of DOS and DOH/DOR are likely to be higher than that for specimens subjected to the SCB condition.
7. AC – specimens were subjected to an accelerated curing process through an age of 28 days in accordance with ASTM C1202. This involves immersion in saturated lime water at 73°F for seven days followed by 21 days at 100°F. It is expected that the DOH/DOR of cementitious materials will be higher than the LW condition. The accelerated curing process is intended to accelerate the reactions of SCMs to realize their beneficial impact on reduced permeability. Specimens were stabilized to room temperature by conditioning them for 16h in lime water at 73°F before the measurements.
8. ACPS (for AE mixtures) – specimens were subjected to an accelerated curing process through an age of 28 days. Specimens were demolded at one day and placed in 73°F simulated pore solution described for Condition PS for seven days followed by 21 days in 100°F simulated pore solution. This condition is similar to Condition AC except for the conditioning in simulated pore solution.

Specimens were stabilized to room temperature by conditioning them for 16h in simulated pore solution at 73°F before the measurements.

9. PS1 (for AE mixtures) – specimens were immersed in lime-saturated simulated pore solution for 56 days. The solution-to-specimen volume ratio was maintained at 4:1. The solution was prepared by dissolving 215.9 g sodium hydroxide, 153.9 g potassium hydroxide, and 40.5 g calcium hydroxide in 19,880 g water. While the original intent was to make a solution for Condition PS the sodium and potassium hydroxide concentrations were switched resulting in Condition PS1.
10. ACPS1 (for AE mixtures) – specimens were subjected to an accelerated curing process through an age of 28 days. Specimens were demolded at 1 day and placed in 73°F simulated pore solution described for Condition PS1 for seven days followed by 21 days in 100°F simulated pore solution. While the original intent was to make a solution for Condition ACPS, the sodium and potassium hydroxide concentrations were switched resulting in Condition ACPS1.
11. PS2 (for AE mixtures) – specimens were immersed in lime-saturated simulated pore solution with composition estimated based on mixture proportions and materials (volume of solution to specimen ratio 4:1) using a modified version of the NIST model (NIST 2018) as follows:
    a. Mixture 0.55PC-A - 0.07 mol/L of NaOH, 0.26 mol/L of KOH and 0.03 mol/L of $Ca(OH)_2$. The resistivity of this solution was 0.140 Ohm-m.
    b. Mixture 0.45FA-A - 0.06 mol/L of NaOH, 0.23 mol/L of KOH and 0.03 mol/L of $Ca(OH)_2$. The resistivity of this solution was 0.157 Ohm-m.
    c. Mixture 0.40SL-A and 0.40SL-HA - 0.06 mol/L of NaOH, 0.17 mol/L of KOH and 0.03 mol/L of $Ca(OH)_2$. The resistivity of this solution was 0.197 Ohm-m.
    d. Mixture 0.50SL-A - 0.05 mol/L of NaOH, 0.12 mol/L of KOH and 0.03 mol/L of $Ca(OH)_2$. The resistivity of this solution was 0.266 Ohm-m.

Condition PS and SCB are intended to minimize leaching of alkali ions from the pore solution of test specimens and achieve equilibrium between the pore solution and the immersion solution. In this case, the resistivity of the immersion solution can be measured to calculate the formation factor that will provide a better estimation of the apparent diffusion coefficient of the concrete, which can be used in service life models (Weiss et al. 2018).

Test Measurements

The electrical tests evaluated included surface resistivity (SR) AASHTO T 358, bulk resistivity (BR) ASTM C1876 and AASHTO TP 119, RCP ASTM C1202, and modified bulk conductivity (BC), ASTM C1760. Measurements were made on 4 by 8 in. concrete cylinders, or on 2-in. disks sawed from cylinders, for each condition. 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. 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 by 8 in. cylinders tested at each age. For the air-entrained mixtures, strength was measured only at an age of 56 days. Strength was not measured for the repeated air-entrained mixtures. Strength results are reported in Tables 5a and 5b.

The resistivity was measured using a 4-point Wenner probe. The equipment was wired to perform surface resistivity with the probes and connected to plates for measuring bulk or uniaxial resistivity. The equipment included a standardization device to verify resistivity measured by the device at different levels. Verification of the measuring equipment was performed before the measurements for any condition were made.

To measure surface resistivity, the specimens were marked along the circumference with four lines orthogonal to each other. Surface resistivity was measured along these lines in duplicate for eight readings that were averaged for the result on the specimen. The electrical resistance of a hardened concrete cylindrical specimen is measured using four linearly aligned, equally spaced electrodes applied on the surface of the concrete. An alternating current (AC) is applied between the outer two electrodes, and the voltage is measured between the inner two electrodes. The resistance is calculated from the ratio of the measured voltage to the applied current. Surface resistivity is calculated from the following equation:

$$SR = \frac{2\pi}{1.95} aR \qquad (4)$$

Where:
a=spacing between the electrodes;
R=resistance,
2π is the original geometry correction factor that is applicable where the specimen surface is flat, and the specimen being measured is many times larger than the electrode spacing such as in the case of soils.

The factor 1.95 accounts for the specimen's cylindrical shape and varies depending on the specimen dimensions, and the spacing between the electrodes.

AASHTO T 358 does not incorporate the 1.95 factor in the calculation. So, the SR results reported in this project should be multiplied by 1.95 for comparisons with SR determined in accordance with AASHTO T 358.

To measure bulk resistivity, thin sponges dampened with saturated lime water were placed between the plates and the specimen surfaces to establish electrical contact. A 5 lb. weight was placed on the top plate to improve the contact of the plates with the specimen. If a weight is not used, the imperfect contact increases the measured resistance.

The surface resistivity of each specimen was measured before the bulk resistivity; this applies to measurements performed on the 4 by 8 in. cylindrical specimens. To minimize surface drying when measuring resistivity, specimens from each curing/conditioning procedure were removed one at a time. Specimens subject to condition SC were rolled on a wet towel before the measurements, while the other specimens were wiped with a clean damp cloth to remove surface moisture. For specimens subjected to conditions SCB and PS, specimens were initially wiped with a cloth dampened in the simulated pore solution, but resistivity measurements were not stable, and this process was replaced by wiping specimens with a clean damp cloth.

Resistivity readings were stable for specimens subjected to conditions LW, MR, SC, and AC. However, for specimens conditioned in simulated pore solution, the BR readings did not stabilize and increased by 10% or more over a two-minute period when the specimens were maintained between the plates. Therefore, in this study, BR readings were recorded within 10 seconds of placing the specimen between the plates. Since this can be a source of testing error, this needs to be resolved before using this condition for acceptance purposes. ASTM C1876 requires that the readings be recorded after they stabilize for 2 to 5s.

Chloride penetrability (RCP) was measured on 2 by 4 in. discs in accordance with ASTM C1202. For the BC test, the current passed in the RCPT at five minutes was measured to calculate the conductivity. ASTM C1760 requires NaCl in both the cells; specimens need not be vacuum saturated; during the test the specimen sides need not be sealed; and the measurements are made at one minute. These represent the modifications to procedures described in ASTM C1760.

For the NAE and AE concrete mixtures, after resistivity of the 4 by 8 in. specimens were measured at the end of the conditioning period, a 2-in. thick disk, referred to as S1, was cut from the top of the specimen. For the NAE mixtures, the mass, BR, RCP, and BC were measured on the S1 disk. The specimens were not vacuum saturated before the RCP and BC test. An additional disk, S2, was extracted at 2-4 in. from the surface. Disk S2 was weighed and the BR measured. Disk S2 was vacuum saturated following which the mass, BR, RCP, and BC were measured. The RCP and BC results reported in Table 6a are for vacuum saturated S2 specimens for conditions LW, MR, SC and AC. For specimens that were conditioned in pore solution, SCB and PS, the results reported for RCP and BC in Table 6a are from disk S1 that were not vacuum saturated.

For the AE mixtures for conditions LW, SC, and AC, the mass, and BR, were measured on the S1 disk. Disk S1 was then vacuum saturated and mass, BR, RCP and BC were measured. Disk specimens from conditions PS, PS1, PS2, ACPS, and ACPS1 were not vacuum saturated before performing the RCP and BC tests as indicated in Table 6b.

The effect of DOS on BR was evaluated for the AE mixtures with specimens subjected to condition LW. Disk S2 was cut from the cylinders and mass and bulk resistivity were 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. The mass and bulk resistivity was measured at ages of 57, 58, 62, 70 days (1, 2, 6, and 14 days of drying). Before each measurement, the specimens were immersed in water for about two minutes so that the surface became moist and bulk resistivity could be measured. The intent was to measure BR as the specimen dried and the DOS decreased at a constant temperature. These data were used to estimate the exponent “n” in Eqn. 3.

Additionally, four cylindrical specimens from each mixture were used to evaluate the effect on DOS and measured BR with exposure to environment to simulate service conditions. Specimens from each mixture were cured in the moist room for 56 days. Disks of height 2-in. were cut from top and from bottom of the cylinders. Four disks from 2 cylinders with the top and bottom 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, Maryland. Four disks from two cylinders were placed in a room maintained at 50% relative humidity and 70°F. The cut faces of the disk specimens were placed on a grid of thickness 1 in. to permit air circulation around the specimens. Periodically the specimens were weighed to estimate DOS and the bulk resistivity (BR) was measured. These data were used to estimate the change in DOS and the impact on measured resistivity of the different mixtures. The surfaces were lightly cleaned. Prior to each mass and BR reading the specimens were immersed for five minutes in 73°F water. This was done to stabilize the specimen temperature and moisten the specimen surface in order to get a valid and comparable BR measurement. Mixtures with lower permeability are expected to absorb less water in service conditions. However, this may be offset by a lower drying rate. The periodic measurements should shed light on how these effects impact the change in DOS and resistivity. Prior to the last mass and BR readings, the specimens were immersed for seven days in lime water.

Results of most electrical tests are reported in Tables 6a and 6b. The SR and BR are measurements on the 4 by 8 in. specimens at the end of the conditioning period. For most conditions the age of the specimens was 56 days. 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 and BC are measurements on 2 in. disks that were vacuum saturated after the conditioning period. The age of these specimens at time of test include two additional days after the conditioning period for vacuum saturation. Exceptions are specimens immersed in simulated pore solutions in which case specimens were not vacuum saturated before measuring RCP and BC.

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. The top 2 in. slice was cut from two 4 by 8 in. 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 and dried for seven days. The mass of the dry specimens was measured. The specimens were vacuum saturated in accordance with ASTM C1202 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:

$$\%DOS = \frac{(M_C - M_D)}{(M_S - M_D)} X100 \qquad (5)$$

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 saturated specimen after vacuum saturation

For specimens subjected to MRVS, the mass of the specimens was obtained after 56 days in the moist room and again after vacuum saturation. Because these specimens were not dried, the DOS for specimens at the end of the conditioning period was estimated from the mass change of companion specimens from condition MR that were subjected to drying and subsequently vacuum saturated. For specimens in condition SCB, the mass of the specimens was measured after the cylinders were removed from the molds at 56 days and after immersion in the pore solution seven days later. Because these specimens were not dried, the DOS for specimens at the end of the conditioning period was estimated from the mass change of companion specimens from condition SC that were subjected to drying and subsequently vacuum saturated.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Overview of Electrical Test Results

Figs. 1a and 1b plot the bulk resistivity measured on 4 by 8 in. specimens and RCP for all mixtures and conditions. These data are compared to the theoretical relationship between charge passed and resistivity from Equation 1 and includes zones for levels of chloride penetrability from Table 1. With the exception of specimens subjected to condition SC, the experimental data fall in the zones and are consistent with this relationship. Specimens subjected to condition SC had the lowest DOS after conditioning, resulting in a higher measured BR; RCP was measured after vacuum saturating the specimens that had been subject to Condition SC. This is discussed in more detail later in the report. This observation is relevant because the specimen size and conditioning for BR is different from that of RCP.

Figs. 2a and 2b plot bulk resistivity and surface resistivity measured on the 4 by 8 in. cylinders 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 measurements. In this study, the measured SR was generally less than the measured BR. **The ratio of SR to BR ranged between 0.80 and 0.90.** No clear trend can be observed between the mixtures or the curing conditions. It is possible that the two-to-three minutes that it takes to perform the SR measurements caused some drying of the specimens resulting in a higher measured BR. In Phase B, BR was measured before and after the SR measurement. The BR measured before the SR measurements was lower than that measured after. The ratio of SR to BR, however, was not affected for specimens in LW and SC conditions; whereas it increased on average from about 0.86 to 0.93 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 after the SR measurement was used. SR/BR ratio less than 1 can be due to specimen inhomogeneity and/or localized leaching of alkalis from near the specimen surface.

Figs. 3a and 3b compare bulk conductivity and RCP, respectively, for all mixtures and conditions for the NAE and AE mixtures. A good correlation between BC and RCP is expected as these data are derived from the same test. This is true for mixtures with lower chloride penetrability with RCP < 2000 coulombs representing the mixtures containing SCMs. For the PC mixtures with higher chloride penetrability, RCP results increase primarily due to the increase in temperature of the specimens during the 6-hour measurement period. Thereby, the RCP results for PC mixtures with charge passed around 4000 coulombs are higher relative to the correlation line.

Figs. 4a and 4b illustrate the impact of air-entrainment on bulk resistivity and RCPT, respectively, for mixtures with specimens subjected to conditions LW, SC, SCB, PS, and AC. **While some of the data fall**

along the line of equality, on average, specimens from mixtures with entrained air had a measured resistivity on average about 25% higher and charge passed of about 20% lower compared to the equivalent NAE mixture. For the BR comparison, this is attributed to a lower DOS of air-entrained concrete where the air voids are not saturated and reduce the conduction of electricity, thereby increasing the measured resistivity. However, this does not explain why the RCP of AE concrete was lower since the vacuum saturation process is assumed to saturate the air voids.

Figs. 5a and 5b compare the measured BR of specimens subjected to the different curing/conditioning methods for non-air-entrained and air-entrained mixtures, respectively. The 0.55PC and 0.55PC-A mixtures had the lowest resistivity among all mixtures, representing the highest transport properties. On average there is a significant difference in measured BR between the 0.55PC and the 0.45FA mixture. 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 bulk resistivity of the 0.40SL mixture. **This suggests that the typical air content variation of 2-3% that may be observed for different loads of concrete may not have a significant impact on the resistivity test results.**

Comparing mixtures with slag cement, the measured BR for the mixtures with *w/cm* of 0.40 were only marginally higher than that measured on specimens from the mixtures with *w/cm* of 0.50. For the NAE concrete mixtures, the difference was on average 6% and ranged between 2% and 12% higher with the different conditions. One exception is for the specimens subjected to condition SCB where the difference was 24%. For AE concrete mixtures, the average difference was 13% and ranged between 6% and 25%. One exception is for specimens subjected to condition ACPS where the difference was 41%. These results suggest that, in this study, 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. The compressive strength for the AE and NAE slag cement mixtures at *w/cm* of 0.40 were on average about 28% higher than the similar mixtures with a *w/cm* of 0.50. If the increase in *w/cm* is affected by increasing mixing water content while maintaining the same content of cementitious materials, the resulting higher paste volume would have reduced the resistivity further as observed in literature (Obla et al. 2017; Obla et al. 2018). Therefore, 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.

Effect of Degree of Saturation on Corrected Resistivity

Fig. 6 illustrates the change in measured BR with change in the estimated DOS for specimens cured in saturated lime water (LW) for four mixtures that were subjected to drying after the 56 day conditioning period. Reduction in DOS resulted in an increase in the measured BR. A power function was used to describe the relationship between BR and DOS. **The estimated value of the exponent "n" of the four SCM mixtures ranged between 2.4 and 3.6 (average of 2.9)**. This is consistent with that observed in the literature and reported earlier. Using the average "n" value in Equation 3 predicts that a reduction in DOS from 70 to 55% will double the BR.

From a practical testing perspective, when measuring the BR, if a 4 by 8 in. specimen is allowed to dry and the mass is reduced by 5 g, it reduces the specimen DOS by about 3% and can increase the measured BR by about 12%. Mass loss from specimens depend on the specimen's desorption rates, which in turn depends on the specimen's age, initial DOS, and internal pore structure. Generally, desorption will be low if the initial DOS is low and the specimens are more mature and have a tight internal pore structure due to low *w/cm* and the use of SCMs. A separate evaluation of 4 by 8 in. specimens from eight 50% slag cement mixtures with 0.40 *w/cm* quantified mass loss over a 30-minute period of about 5 g for specimens moist cured for 28 days and about 2 g for specimens moist cured for 120 days. However, for specimens subject to pore solution conditioning the rapid increase in the measured resistivity even within a two minute period suggests that there are factors other than reduction in DOS that impact the results.

Effect of Curing/Conditioning on Resistivity

As illustrated in Fig 5a and 5b, curing/conditioning had a significant effect on the measured bulk resistivity for the mixtures containing SCMs. The chloride penetrability level for all the mixtures in this study was assigned based on measured BR, RCPT, and SR respectively according to Table 1. This is summarized in Tables 7a through 7c.

Table 7a classifies mixtures and specimen conditioning based on measured bulk resistivity. The chloride penetrability was mostly "High" for the 0.55PC mixture and equally split between "Moderate" and "High" for the 0.55PC-A mixture depending on the condition. The air-entrained slag cement mixtures, 0.40SL-A, 0.40SL-HA and the 0.50SL-A, are classified as "Very Low" chloride penetrability regardless of how the specimens were conditioned. For mixtures 0.45FA-A, 0.40SL, and 0.50SL chloride penetrability classification 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.

Table 7b classifies mixtures and specimen conditioning based on RCP. The classification is mostly consistent with Table 7a. An exception is for specimens subjected to condition SC and in cases where the BR and RCPT values were close to the criteria borderline that change the classification. The classification differences from Table 7a are highlighted in Table 7b and 7c. The mixture classification in Table 7c based on measured SR is consistent with Table 7a in many of the cases. But there were several cases where the chloride penetrability classification based on SR diminished one level from the classification based on measured BR. As discussed earlier, in this study, SR was consistently lower than BR which impacted the mixture classification.

Depending on the curing/conditioning of specimens adopted for the resistivity test, 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 specimens should be used when comparing the mixtures and for pre-qualification and acceptance of concrete.

For a given mixture, the curing/conditioning procedure would have an impact on the DOS, ion leaching from the specimens, and 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, thus ultimately affecting the measured BR. To compare these effects, measured BR results are normalized to the LW curing/conditioning procedure for each mixture in Table 8a for the non-air-entrained mixtures and in Table 8b for the air-entrained mixtures. The measured BR for any condition is divided by the measured BR of specimens conditioned in saturated lime water.

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=MRVS < ACPS < SC < AC. Condition AC consistently gave the highest BR for the SCM mixtures and more significantly for the fly ash mixture. It is expected that the accelerated curing at a higher temperature at early ages increases the DOR of the SCMs to reduce the chloride penetrability of the concrete, as indicated by the higher BR results. Owing to the slower rate of reaction of fly ash and slag cement at 73°F for 56 days, the other curing/conditioning methods do not recognize the benefit of SCMs that will be provided at later ages – both on strength and chloride penetrability. This phenomenon is well understood (Ozyildirim 1998). Table 7 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, ACPS, ACPS1); but it was one level lower for specimens subjected to the other conditions. Fly ash typically reacts slower than slag cement and it is surmised that accelerated curing beneficially impacts the fly ash mixture more.

For the non-air-entrained mixtures, specimens subjected to condition MR had a higher average measured BR by about 20% compared to those subjected to condition LW. This is likely due to greater leaching from specimens in condition MR, which was confirmed by pore solution chemistry measurements on specimens from this study by FHWA (Tanesi et al. 2019). The differences in measured resistivity is recognized in AASHTO T 358 where it is recommended to multiply the measured resistivity by a correction factor of 1.1 for specimens cured in saturated lime water when comparing to specimens cured in a moist room. The difference between the measured BR of specimens in conditions PS relative to those subjected to LW were within 10%, and for practical purposes, not significant. The classification of mixtures for chloride penetrability based on BR (Table 7a) 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. It is surmised from the similar measured resistivity for specimens subjected to condition 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). **Since the measured resistivity of specimens subjected to LW and PS is similar, using the LW curing/conditioning option is recommended for evaluation of concrete on projects. The resistivity measurements appear to be less sensitive and due to similarity with current practice for strength testing, testing agencies will find it**

easier to adopt. Making up the simulated pore solutions as prescribed in ASTM C1876 needs some precise measurements and attention to detail.

Effect of Curing/Conditioning on Degree of Saturation

Tables 9a and 9b report the estimated degree of saturation (DOS) of test specimens at the end of the conditioning period for the non-air-entrained and the air-entrained mixtures, respectively. For perspective, a difference in mass of about 0.4 g in the 2 in. disk specimen represents a difference in DOS of 1%. So small differences should not be considered significant.

For the NAE concrete mixtures, DOS is close to 100% for most of the conditions with the exception of specimens in Condition SC. Excluding Condition SC, the DOS of specimens at the end of the conditioning period for the AE mixtures averaged about 77%, compared to the 97% for the NAE mixtures. Using the average exponent n=2.9, derived from Fig. 6, in Equation 3 the reduction in DOS from 97% to 77% predicts an increase in resistivity by about 95% for the AE concrete mixtures compared to the equivalent NAE concrete mixtures. However, as observed in Figure 4a, the average resistivity of the AE concrete mixtures was only about 25% higher compared to the equivalent NAE concrete mixtures. This suggests that the value of exponent “n” should be closer to 1.0. A higher value of “n” may still be applicable if specimens from a given mixture subjected to certain conditions are allowed to dry, as discussed earlier. 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.

Table 5b reports that the air content of the 0.40SL-HA mixture was 2.4% more than the 0.40SL-A mixture. Theoretically, 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. However, Table 9b reports that the DOS of the 0.40SL-HA and the 0.40SL-A mixtures were similar. Further, the changes in DOS resulting from different conditioning methods did not result in significant changes to measured BR between the two mixtures as seen in Fig. 5b.

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

$$\rho_{t-Ref} = \rho_t . exp\left[\frac{E_{A-Cond}}{R}\left(\frac{1}{T} - \frac{1}{T_{Ref}}\right)\right] \quad (6)$$

Where:
ρ_{t-Ref} is the resistivity, Ω·m, at a reference temperature, T_{Ref}, °K,
ρ_t (Ω ·m) is the measured resistivity 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 x 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 an increase in specimen temperature. The temperature of the specimens at the time of the BR measurements varied between 71.7°F and 77.1°F. When corrected to a reference temperature of 23°C (73.4°F), the corrected BR varied between 2% lower and 5% higher than the measured BR. For measured resistivity on test specimens at temperature between 70°F 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 Equation 2 with exponent n=3. Correction for DOS resulted in a greater difference. The measured BR and BR corrected for DOS and temperature are compared in Fig. 7a for NAE mixtures 0.40SL and 0.50 SL; and in Fig. 7b for AE mixtures 0.40SL-A and 0.50SL-A. The measured BR indicates a clearer difference between the mixtures with *w/cm* of 0.40 that are 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* ratios. In some cases, the corrected BR was higher for the mixtures with a *w/cm* of 0.50. The mixture classification for chloride penetrability based on the corrected BR is indicated in Table 10. These can be compared to the classification based on measured BR in Table 7a. The conditions where the rankings differed from Table 7a are highlighted. In most of the cases the classification for chloride penetrability based on corrected BR changed by one or two levels worse than the classification based on measured BR. Based on general expectations and RCP results, the 0.40 SL-A mixture should have a classification of “Very Low”, but was classified as “Moderate” or “Low” or “Very Low” chloride penetrability based on corrected BR depending on the specimen conditions. Based on this assessment, it is suggested that these corrections for DOS and temperature not be made to assess the quality of concrete mixtures for chloride penetrability.

The same curing condition caused the DOS at the end of conditioning to vary considerably between the mixtures. Correcting BR for temperature and DOS resulted in an incorrect classification of mixtures for the expected chloride penetrability. It is thereby recommended that when comparing mixtures for the purpose of mixture classification that the BR not be corrected for DOS. If the BR measurements are made in a standard laboratory environment (70°F to 77°F) correcting BR to a reference temperature results in a small difference and can be ignored.

Effect of Vacuum Saturation on Resistivity

The measured BR of specimens that were vacuum saturated after the end of the curing/conditioning process are reported in Table 11a for NAE mixtures and Table 11b for AE mixtures, respectively. The ratio of 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 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. It is anticipated that while the

DOH/DOR of specimens subjected to conditions MR and LW are similar, there was higher level of alkali leaching in condition MR reducing the pore solution conductivity. This was confirmed by composition of expressed pore solution (Tanesi et al. 2019). 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 desirable as the pore solution in the specimen is not impacted by 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, the question arises as to whether the degree of reaction of SCMs, especially those that react at a slower rate like fly ash, is curtailed to realize the typical benefit they provide for durable concrete.

For the non-air-entrained mixtures, specimens subjected to condition SC and subsequently vacuum saturated (Table 11a) 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 rate of hydration decreases when the internal relative humidity gets below 90% and ceases below 80% (Wyrzykowski and Lura 2016).

Considering 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 7a). This is because Conditions SC and SCB lowered the DOS when compared to Condition LW which increases the measured BR. When the BR was corrected for measured DOS, the mixture classification based on specimens subjected to Condition SCB and SC where equal to or worse than specimens subjected to Condition LW (Table 10). As discussed earlier, correcting BR for DOS for various conditions is not recommended.

For the air-entrained mixtures, specimens subjected to condition SC and subsequently vacuum saturated (Table 11b) did not have a substantially lower measured BR compared to those subjected to condition LW. As discussed earlier these specimens were sealed by taping lids on the molds, while a more extensive sealing process was used for specimens from the NAE mixtures. Sealed specimens were stored in the moist room for 56 days. The sealed-cured (SC) specimens were weighed in the sealed molds when molded and before demolding at 56 days. Fig. 8 shows that for the AE mixtures after 56 days in the moist room the sealed specimens had water present under the seals whereas no water was present for the NAE mixtures. Table 12 shows the change in mass of a 4 by 8 in. cylindrical specimen over the 56 day conditioning period for each of the mixtures. For the NAE mixtures, the average mass gain was 0.3 g. For the AE mixtures, the average mass gain was 14 g. Sealing specimens for the AE mixtures resulted in moisture intrusion into the specimens that might have improved the DOH/DOR of the cementitious materials. Thereby, for the AE mixtures, the measured BR for specimens subjected to condition SC was not significantly different than the measured BR of specimens subjected to condition LW (Table 11b). **Therefore, it appears that the specimen sealing process is likely to be inconsistent and can be another source of testing error.**

In Table 13, the change in mass of 2 in. disk specimens on vacuum saturation is reported. Disk specimens were cut from 4 by 8 in. specimens subjected to Condition SC and LW and their initial mass was measured. Some of these specimens were vacuum saturated and the gain in mass is indicated as "not dried" in Table 13. The BR of these specimens were measured after vacuum saturation. Additional disk specimens were dried for seven days at 140°F and subsequently vacuum saturated. The gain in mass is indicated as "dried" in Table 13. The gain in mass is based on this initial mass of the disk specimens cut at the end of the conditioning period. For AE mixtures, the gain in mass on vacuum saturation of "not dried" specimens was less than those that were dried. This indicates that vacuum saturation of "not dried" specimens is less effective. The measured BR is expected to be higher on a specimen at a lower DOS. This may explain the higher relative BR of specimens subjected to Condition SC for the AE mixtures (Table 11b). However, for the NAE mixtures, the gain in mass on vacuum saturation of "not dried" specimens was similar to those that were dried.

Specimens subjected to Condition SC that were dried and not dried before vacuum saturation had greater gain in mass than specimens subject to condition LW. This is as expected because specimens subject to Condition SC were at a lower DOS at the end of the conditioning period. For the dried specimens, a greater mass gain is observed for the AE mixtures. This is attributed to filling of air voids with water in AE concrete due to vacuum saturation. This effect has been indirectly confirmed in past research (Obla et al. 2015) where AE concrete prisms that had performed well in freezing and thawing failed in a few cycles when subject to vacuum saturation.

For the S2 disk specimens, the ratio of measured BR after VS to before VS is plotted in Fig. 9a for the NAE mixtures and in Fig. 9b for the AE mixtures. Vacuum saturation (VS) increases DOS and should decrease the measured BR. For NAE mixtures, this ratio is close to 1 because the specimens at the end of conditioning was close to saturation. The saturation level of specimens at the end of conditioning is reported in Table 9a. The exception for a considerably lower BR ratio is for specimens subjected to condition SC, more significantly for mixtures containing SCMs. For the AE mixtures, as indicated in Table 9b, the DOS of specimens subjected to LW and AC at the end of the conditioning period was about 75-80%. Vacuum saturating these specimens changed the measured BR by less than 10% in Fig. 9b. This contradicts the corrections suggested to BR for DOS by Equation 2 that resulted in reduction of BR exceeding 50% as illustrated in Fig. 7. However, as already noted, the vacuum saturation of the AE mixtures may not have been effective in saturating the specimens.

Variability of the Electrical Test Methods

Table 14a and Table 14b reports the single-operator coefficient of variation (COV) from measurements on three replicate specimens for non-air-entrained and air-entrained mixtures, respectively. Each value for a specific specimen condition is the average COV from four NAE mixtures and five AE mixtures, respectively. The average for a test method across all the specimen conditions is also reported. BR (S1) is the COV measured on a 2-in. thick disk specimen cut from the top of the 4 by 8 in. cylinder at the end of the conditioning period. The BR on 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) < BC < RCP. The average COV of 2.4% for NAE mixtures and 3.7% for the AE mixtures for BR measurements is similar to the single-operator COV for compressive strength tests in ASTM C39. **The precision of the BR test is considerably better than ASTM C1202 (RCPT) and marginally better than the SR test. This evaluation suggests that the precision of BR measured on 4 by 8 in. cylinders is better than that measured on 2 in. disk specimens.**

Figs. 10a and 10b illustrate the single-operator COV of surface resistivity and bulk resistivity for each of the NAE mixtures. Figs. 11a and 11b illustrate the same for the AE mixtures. Each bar represents the COV from measurements of three replicate specimens. **Specimens subjected to condition SCB resulted in a higher variability.**

Tables 15a and 15b report the effect of vacuum saturation of 2 in. disk specimens on the single operator precision for specimens subjected to various curing conditions. These data suggest that vacuum saturating the test specimens did not improve the precision of the BR measurements.

Specimen Effects on Bulk Resistivity

The BR can be measured on a 2 in. thick specimen or on a 4 by 8 in. cylindrical specimen. SR cannot be performed on a 2 in. specimen. The BR of disk S1 obtained from a cylinder after conditioning was measured and compared to BR measured on the 4 by 8 in. cylindrical specimen. The ratio of disk-to-cylinder BR is plotted in Fig. 12a for NAE mixtures and Fig. 12b for AE mixtures, respectively. In general, the measured BR of the disks are slightly lower than that measured on the cylinder. Disk specimens subjected to conditions ACPS, ACPS1, and PS resulted in a measured BR that was less than 80% of that measured on whole cylinders. BR measured on whole cylinders classified mixtures for chloride penetrability the same as RCPT results. Further, as shown in Tables 14a and 14b, the precision of BR measured on 4 by 8 in. cylinders is better than that measured on 2 in. disk specimens. **It is recommended that BR be measured on whole cylinders. If disk specimens are prepared for RCPT 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 lime water and not in simulated pore solution.**

The difference of BR between the top 2 in. disk (S1) and that obtained between 2-4 inches from the top (S2) is compared in Table 16. 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.

Batch to Batch Variation

The 0.40SL NAE mixture and the AE mixtures were repeated and specimens were subjected to limited conditions. The bulk resistivity of specimens from the two batches subjected to condition LW are compared in Fig. 13. For the replicate batches, the BR measured on specimens subjected to condition LW (r), was 18% higher for the SCM mixtures. The compressive strength of the replicate batch was measured only for the 0.40SL mixture. The BR of this replicate batch was 18% higher while the compressive strength was 5.4% higher. No clear conclusion can be made on batch-to-batch effects from these limited data.

Effect of Simulated Service Conditions on DOS and BR

NAE Concrete Mixtures

As discussed earlier, disk specimens from some mixtures were placed in simulated exterior and interior exposure to evaluate the effect on DOS and bulk resistivity with time. Two types of disk specimens were used: the top surface of a cast cylinder (referred to as T) and the bottom cast surface (B). One set were subjected to exterior exposure (referred to as E) and another set to interior exposure (I) in a room that maintains constant temperature and relative humidity. The mixtures were cast one week apart and subject to exposure after 56 days of curing in the moist room. The exposure started between July 25 and August 15, 2018, and continued for one year. The specimens were placed elevated from the ground on a plastic grid. Figs. 14a and Fig 14b show the changes in DOS of the disk specimens for the exterior and interior exposure, respectively. While not shown, similar trends of DOS were observed for the air-entrained mixtures. A replicate set of air-entrained mixtures was cast at a later time and specimens were subjected only to exterior exposure. These specimens were cured by immersion in lime water for seven days before subjecting them to exterior exposure.

Before each mass and bulk resistivity measurement, the specimens were immersed for five minutes in saturated lime water at 73°F. This was done to stabilize the specimen temperature and moisten the specimen surface to get comparable BR measurements. Towards the end of the 1-year exposure period, the specimens were immersed for seven days in lime water following which the final mass and BR measurements were made. As expected, DOS of specimens subjected to exterior exposure for all mixtures tends to vary, whereas that of specimens in interior exposure shows a steady decrease as the specimens dried. The final DOS of the disk specimens after immersion in lime water was about 100%.

The DOS of all NAE mixtures was between 94% and 99% at 56 days when the exposure was started. For the 0.55 PC mixture specimens subjected to exterior exposure, the DOS reduced to about 50%; that of the slag cement mixtures reduced to about 75%; and that of the fly ash mixture reduced to about 67%. For the specimens subjected to interior exposure, the change in DOS were similar. For the PC and the FA mixture, the DOS reduced to below 50% while for the slag cement mixtures, the DOS reduced to about 68%. It is surmised that the mixtures with slag cement achieved a refined pore structure that retained moisture better and was less prone to drying.

Tables 17a and 17b report the bulk resistivity at 56 day and one year for the non-air-entrained and air-entrained mixtures, respectively. Table 17c reports the bulk resistivity at 7-day and 1-year for the replicate air-entrained mixtures subjected only to exterior exposure. For all mixtures, BR increased with age. For both the interior and the exterior exposures, for the NAE and AE mixtures the BR of "B" specimens was consistently higher than that of the "T" specimens.

For the NAE mixtures after 12 months of exterior exposure, followed by seven days of lime water conditioning:

1. The BR of specimens from the SCM mixtures was on average 2 to 2.8 times higher than that measured after 56 days of curing in the moist room. The BR of specimens from the PC mixture was 3.2 times higher.
2. The BR of specimens from the SCM mixtures was on average 2.4 to 2.8 times higher than that of the PC mixture. The average BR after one year for the mixtures was: 0.55PC (182 Ω-m), 0.45FA (513 Ω-m), 0.40SL (438 Ω-m) and 0.50SL (462 Ω-m).
3. Exterior exposure did not significantly reduce DOS of specimens to impact continued hydration reactions and improvement of transport properties was observed for the SCM mixtures.
4. The resistivity of "B" specimens was on average 11% higher than the "T" specimens. The corresponding value after 56 days of moist curing was 13% higher.

After 12 months of interior exposure, followed by seven days of lime water conditioning:

1. The BR of specimens from the SCM mixtures was on average 1.6 to 2.1 times higher than that measured after 56 days of curing in the moist room. The BR of specimens from the PC mixture was 3.3 times higher.
2. The BR of specimens from the SCM mixtures was on average 1.6 to 2.5 times higher than the PC mixture. The average BR after one year for the mixtures was: 0.55PC (186 Ω-m), 0.45FA (301 Ω-m), 0.40SL (468 Ω-m) and 0.50SL (346 Ω-m).
3. The ratio of the BR of specimens in the exterior exposure to those in interior exposure was close to 1 for the 0.55 PC and 0.40SL mixtures. For the 0.45FA and 0.50SL mixtures, the BR of specimens in exterior exposure was considerably higher. This suggests that lower DOS resulting from specimens in interior exposure reduced continued reaction of SCMs and did not result in improvement in transport properties.
4. The resistivity of "B" specimens was on average 30% higher than the "T" specimens. The corresponding value after 56 days of moist curing was 15% higher.

AE Concrete Mixtures

The mixtures were cast one week apart and subjected to exposure after 56 days of curing in the moist room. The exposure started between April 10 and May 15, 2019 and continued for one year.

After 12 months of exterior exposure, followed by seven days of lime water conditioning:

1. The BR of specimens from the SCM mixtures was on average 2 to 2.5 times higher than that measured after 56 days of curing in the moist room. The BR of specimens from the PC mixture was 2.8 times higher.

2. The BR of specimens from the SCM mixtures was 2.2 to 3 times higher than the PC mixture. The average BR after one year for the mixtures was: 0.55PC-A (255 Ω-m), 0.45FA-A (555 Ω-m), 0.40SL-A (657 Ω-m), 0.40SL-HA (768 Ω-m) and 0.50SL-A (621 Ω-m).
3. Exterior exposure did not significantly reduce DOS of specimens to impact continued hydration reactions and improvement of transport properties was observed for the SCM mixtures.
4. The resistivity of "B" specimens was on average 19% higher than the "T" specimens. The corresponding value after 56 days of moist curing was 22% higher.

After 12 months of interior exposure, followed by seven days of lime water conditioning:

1. The BR of specimens from the SCM mixtures was on average 1.1 to 1.5 times higher than that measured after 56 days of curing in the moist room. The BR of specimens from the PC mixture was 2.6 times higher.
2. The BR of specimens from the SCM mixtures was 1.4 to 2.3 times higher than the PC mixture. The average BR after one year for the mixtures was: 0.55PC-A (232 Ω-m), 0.45FA-A (337 Ω-m), 0.40SL-A (528 Ω-m), 0.40SL-HA (489 Ω-m) and 0.50SL-A (324 Ω-m).
3. The decreased DOS of specimens during interior exposure resulted in reduced improvement in transport properties for the SCM mixtures, relative to those in exterior exposure.
4. The resistivity of "B" specimens was on average 26% higher than the "T" specimens. The corresponding value after 56 days of moist curing was 37% higher.

AE Concrete Mixtures (replicate)

These batches of mixtures were cast on three consecutive days and subjected to exposure after seven days of curing in lime water. The exposure started between May 13 and May 15, 2019 and continued for 11 months.

After 11 months of exterior exposure, followed by seven days of lime water conditioning:

1. The BR of specimens from all mixtures was 5.2 to 10.4 times higher than that measured after seven days of curing in the lime water.
2. The BR of specimens from the SCM mixtures was 2.1 to 2.9 times higher than the PC mixture. The average BR after one year for the mixtures was: 0.55PC-A (271 Ω-m), 0.45FA-A (583 Ω-m), 0.40SL-A (782 Ω-m), 0.40SL-HA (744 Ω-m) and 0.50SL-A (585 Ω-m).
3. Exterior exposure did not significantly reduce DOS of specimens to impact continued hydration reactions for improvement of transport properties for all mixtures.
4. The resistivity of "B" specimens was on average 24% higher than the "T" specimens. The corresponding value after seven days of moist curing was 39% higher.

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 and RCP as long as the same specimen curing/conditioning procedure is used. The exception is for specimens subjected to condition SC.
2. Depending on curing and conditioning procedures used and the measured resistivity, the same mixture could be classified in two different categories for chloride penetrability based on criteria stated in Table 1. It is thereby important that a single curing/conditioning method and test age be established by agencies using this test for determining acceptance of concrete and for appropriately comparing the potential permeability characteristics of different mixtures.
3. Surface resistivity results were about 10-20% lower than the measured bulk resistivity on the same test specimens in this study. As a result, there were several cases where the chloride penetrability classification based on SR diminished one level from the classification based on measured BR.
4. Bulk conductivity results correlated well with RCP results.
5. The measured DOS of air-entrained concrete mixtures was on average 20% lower compared to equivalent non-air-entrained concrete mixtures. The measured bulk resistivity of air-entrained concrete mixtures was 25% higher and the RCP results were 20% lower compared to equivalent non-air-entrained concrete mixtures. For one air-entrained concrete mixture evaluated, an increase of 2-3% air content (representing an acceptable tolerance) slightly decreased the measured DOS and did not impact the measured resistivity.
6. For all concrete mixtures evaluated, drying of the specimen reduced its degree of saturation and increased the measured resistivity. A power function (Eqn. 2) was used to describe the relationship between BR and DOS. The estimated value of the exponent “n” of the four SCM mixtures ranged between 2.4 and 3.6 (average of 2.9). This value of “n” is applicable if a specimen from a given mixture and subject to a certain condition is allowed to dry. This “n” value over-predicts the impact of DOS on measured BR when comparing air-entrained concrete mixtures to equivalent non-air-entrained concrete mixtures.
7. For the different mixtures evaluated, specimens subjected to the same curing condition had different values of DOS at the end of conditioning period. Concrete specimens with lower chloride penetrability (0.40SL), however, had a higher BR than concrete specimens with higher chloride penetrability (0.50SL). Consequently, the resistivity measurement accurately classified the mixtures. Normalizing the BR to the same DOS level using Eqn. 2 resulted in an incorrect classification of mixtures for the expected chloride penetrability. For many of the conditions the 0.50SL mixture had a higher normalized BR than the 0.40SL mixture. This research indicates that measured BR should not be normalized to a BR of a saturated condition. For specimens measured in controlled laboratory environment, the correction for specimen temperature is small and can be ignored.

8. The single-operator precision of the BR test is considerably better than ASTM C1202 (RCPT) and marginally better than the SR test. BR measured on the 4 by 8 in. cylinder is less variable than that measured on the top 2 in. thick disk. Conditioning specimens by SCB resulted in a higher variability of measured bulk resistivity. Vacuum saturation of test specimens after the curing/conditioning process did not change the variability of the resistivity test results.
9. BR measurements made on specimens immersed in simulated pore solution (Conditions SCB, PS, ACPS) do not stabilize and continue to increase with time. Since this can be a source of testing error, this needs to be resolved before using this condition for acceptance purposes.
10. There are several problems associated with subjecting specimens to sealed curing (Condition SC and SCB). If the specimens are sealed very well, it is surmised that consumption of water from the hydration reaction causes self-desiccation, which prevents the effective DOH/DOR of SCMs and can inaccurately classify mixtures for lower chloride penetrability. Specimens subjected to condition SC and SCB were at a lower DOS compared to specimens subjected to other conditions. Mixture classification based on BR measured on specimens subjected to condition SCB and LW was similar; specimens subjected to condition SC indicated an improved level of chloride penetrability. The specimen sealing process is likely to be inconsistent and is a source of testing error.
11. Specimens subjected to condition PS and SCB had measured resistivity within 10% of that of specimens subjected to condition LW. Lime water immersion is easier and more practical for technicians and testing agencies. For specimens from condition LW, the resistance readings stabilized quickly and were less sensitive to elapsed time. Therefore, they are less prone to recording error. It is recommended that resistivity should be measured on full 4 by 8 in. specimens. There was no benefit observed from vacuum saturating specimens.
12. There does not appear to be any advantage in measuring bulk resistivity on 2 in. disk specimens. If disk specimens are prepared for the RCPT 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 should be immersed in lime water and not in simulated pore solution. There was no difference in measured BR of the top and middle disk specimens cut from cylinders.
13. The DOS of specimens stored to simulate service conditions varied between concrete mixtures. Measurements made after 12 months shows that external exposure did not adversely impact the development of improved transport properties for the SCM mixtures. Companion specimens from the SCM mixtures stored at a constant 50% relative humidity and 73°F environment did not have a similar level of improvement in transport properties. Bulk resistivity measured on 2 in. disks of bottom cast surface (last 2 in. of a 4 by 8 in. cylinder) was about 20% higher than that measured on the top finished surface of the specimens. This difference was observed even after one year of exposure.

SUGGESTIONS FOR FUTURE RESEARCH

BR measurements made on specimens immersed in simulated pore solution (Conditions SCB, PS, ACPS) did not stabilize and increased by 10% or more over a two-minute period when the specimens were maintained between the plates. The reason for this needs to be better understood. Since this can be a source of testing error, this needs to be resolved before using this condition for acceptance purposes.

Surface resistivity results were about 10-20% lower than the measured bulk resistivity on the same test specimens in this study. Conceptually, these should be the same when specimen geometry and other corrections are applied. This difference resulted in several cases where the chloride penetrability classification based on SR diminished one level from the classification based on measured BR. Reasons for this difference should be determined. If this is consistently observed, a correction factor for the SR test results should be applied for an equivalent BR and to use the chloride penetrability criteria stated in Table 1 to classify mixtures with better confidence.

ASTM C1876 requires cores to have a length-to-diameter ratio of at least 1. Factors such as core length, core conditioning, and the difference between the BR measured on cores and BR measured on 4 by 8 in. cylinders conditioned in accordance with the standards should be studied. This is in addition to construction parameters such as location of the concrete in the structural element from where the core is taken, core orientation, etc. This will help determine correction factors based on core length (if any), optimal conditioning of cores, and criteria for referee bulk resistivity tests on cores.

Multi-batch variation should be evaluated based on field batches. This will help determine expected variability and to help develop mixtures to achieve the required level of bulk resistivity that will minimize the potential for failing test results.

The DOS in service varied between concrete mixtures. Varying DOS can impact chloride ingress and freeze-thaw resistance. A mixture that has a lower rate of drying and rewetting tends to be at a higher level of saturation in service. Such a concrete mixture is likely to have a better degree of hydration/reaction. Chloride ingress may be impacted as the impact of sorption of the chloride laden water will be less. Sorption is generally a faster mechanism of chloride ingress when compared to diffusion, however, once the outside surface of concrete is saturated, chloride ingress reverts to diffusion. Service life models for corrosion of steel reinforcement due to chloride ingress are based on the chloride diffusion coefficient. By measuring DOS in service and periodic application of chlorides to simulate service conditions, it is possible to estimate the impact that sorptivity has on chloride ingress. Service life models for freeze-thaw durability are based on an increase in DOS due to sorptivity and freeze-thaw failure once the DOS reaches a critical value. The DOS in service measurement combines the effect of sorptivity, desorption, and local environmental conditions and makes it easier to develop more robust models for freeze-thaw durability.

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Table 1 Chloride Ion Penetrability based on RCPT and Resistivity Test Results (reproduced from ASTM C1202 and AASHTO PP84 Guidance Document)

Chloride Ion Penetrability	RCPT, ASTM C1202 (coulombs)	Electrical Resistivity (Ω-m)
High	> 4000	< 50
Moderate	2000 - 4000	50 - 100
Low	1000 - 2000	100 – 200
Very Low	100 - 1000	200 - 2000
Negligible	< 100	> 2000

Applicable for saturated specimens

Table 2 Differences in Curing and Conditioning Requirements for the Electrical Test Methods

	ASTM			AASHTO	
	C1760	**C1202**	**C1876**	**T 358**	**TP119**
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	2 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-inch cylindrical disk	2-inch cylindrical disk	Cylinders	Cylinders	Cylinders

Table 3 Chemical Characteristics of Cementitious Materials

Material	Type II portland cement	Slag Cement	Class F Fly Ash
Silicon oxide (SiO_2), %	20.9	-	43.8
Aluminum oxide (Al_2O_3), %	4.7	11.4	21.9
Iron oxide (Fe_2O_3), %	2.8	-	22.8
Calcium oxide (CaO), %	64.4	-	4
Magnesium oxide (MgO), %	1.9	-	0.8
Sulfur trioxide (SO_3), %	2.8	0	0.62
Loss of Ignition, %	2.5	-	1.7
Relative Density		2.93	2.5
Alkali, Na_2O, %	0.1	-	0.58
Alkali, K_2O, %	0.67	-	1.6
Total Alkali (as Na_2O eq), %	0.54	0.6	1.64
Tricalcium Silicate (C_3S), %	57.3	-	-
Dicalcium silicate (C_2S), %	15.9	-	-
Tricalcium Aluminate (C_3A), %	7.4	-	-
Tetracalcium Aluminoferrite (C_4AF), %	8.4	-	-

Table 4 Planned Concrete Mixtures

Mixture Designation	Mixture Details	Air, %	Expected 56-day C1202, coulombs
0.55PC	0.55 PC	2	>3000
0.45FA	0.45 25% fly ash	2	1000-2000
0.40SL	0.40 50% slag cement	2	<1000
0.50SL	0.50 50% slag cement	2	<1000
0.55PC-A	0.55 PC	5	>3000
0.45FA-A	0.45 25% fly ash	5	1000-2000
0.40SL-A	0.40 50% slag cement	5	<1000
0.50SL-A	0.50 50% slag cement	5	<1000
0.40SL-HA	0.40 50% slag cement	8	<1000

Table 5a Mixture Proportions and Test Results for Non-air-entrained Concrete Mixtures

Mixture Designation	0.55PC	0.45FA	0.40SL	0.40SLR[1]	0.50SL
Yield Adjusted Mixture Proportions					
Total Cementitious, lb/yd^3	527	583	627	630	554
Portland cement, lb/yd^3	527	438	313	315	277
Fly ash, lb/yd^3	0	146	0	0	0
Slag cement, lb/yd^3	0	0	313	315	277
Coarse Aggregate (No.57), lb/yd^3	1995	2000	1993	2004	2001
Fine Aggregate, lb/yd^3	1179	1178	1177	1184	1181
Mixing Water, lb/yd^3	290	262	247	249	277
WR, oz/cwt	4.00	4.00	4.00	4.00	4.00
HRWR, oz/cwt	0.00	3.50	4.50	4.50	1.58
w/cm	0.550	0.450	0.395	0.395	0.500
% Paste Volume	27.1	27.3	26.9	27.1	27.2
Fresh Concrete Properties					
ASTM C1064, Temperature, °F	73	73	74	75	73
ASTM C143, Slump, in.	7 ½	8	6 ¾	6	7 ¾
ASTM C138, Density, lb/ft^3	147.8	149.0	149.8	150.6	148.6
ASTM C138, Gravimetric Air Content, %	1.6	1.4	1.7	1.2	1.3
ASTM C231, Pressure Air Content, %	1.7	1.8	1.8	1.9	1.9
Strength, psi (ASTM C39)					
28-day	5,715	5,860	8,020	8,450	5,790
56-day	6,160	6,795	8,690	NA	6,885

[1] Replicate mixture

Table 5b 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 Mixture Proportions					
Total Cementitious, lb/yd^3	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 cement, lb/yd^3	0	0	311	312	272
Coarse Aggregate (No.57), 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 Entraining Admixture, oz/cwt	0.70	1.00	2.10	1.73	0.85
WR, oz/cwt	0.00	4.00	4.00	4.00	4.00
HRWR, 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 ¾	5	7 ¾	5 ¾
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	4,125	4,610	6,480	6,440	5,465

Table 5c Mixture Proportions and Test Results for Repeated Air-Entrained Concrete Mixtures

Mixture Designation	0.55PCR-A	0.45FAR-A	0.40SLR-A	0.40SLR-HA	0.50SLR-A
Yield Adjusted Mixture Proportions					
Total Cementitious, lb/yd^3	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 cement, lb/yd^3	0	0	311	311	272
Coarse Aggregate (No.57), 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 Entraining Admixture, oz/cwt	0.70	1.24	2.20	1.72	0.50
WR, oz/cwt	0.00	5.19	4.00	4.00	4.00
HRWR, 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 ¾	6 ½
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
Strength, psi (ASTM C39)					
56-day	NA	NA	NA	NA	NA

Table 6a Resistivity, RCPT, and Bulk Conductivity Test Results for Non-Air-Entrained (NAE) Mixtures

SC[1]	0.55PC				0.45FA				0.40SL				0.50SL				0.40SLR			
	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]
MRVS	#N/A	52.9	4499	16.45	#N/A	175.2	1230	5.11	189.3	237.6	925	3.92	169.2	212.7	1301	4.44	211.6	271.3	739	3.29
LW	37.0	41.9	4486	18.84	118.0	142.9	1313	5.67	148.2	179.8	1047	4.62	145.7	174.6	1000	4.63	169.0	212.3	771	3.52
MR	41.8	50.6	3521	18.08	133.0	163.2	1205	5.18	174.2	224.1	924	3.83	168.4	213.1	1027	4.67				
SC	38.8	44.4	7487	26.93	155.8	190.2	1859	8.57	204.9	253.9	1308	6.25	177.7	229.8	1623	7.49	222.6	284.2	1097	5.35
SCB	30.2	32.6	6289	32.16	117.2	132.3	1187	6.03	149.7	179.4	1025	5.27	121.8	144.3	1359	5.95				
PS	33.5	38.0	5408	20.51	116.2	141.8	1230	5.65	160.0	184.5	1031	4.83	148.5	181.4	1201	4.72				
AC	40.1	47.6	4164	17.82	234.1	268.9	680	3.12	221.8	268.0	789	3.55	201.0	242.5	852	4.15				

[1] SC – Specimen Condition; SR = Surface Resistivity, Ω-m, BR = Bulk Resistivity, Ω-m; RCP = Rapid Chloride Permeability, Coulombs; BC = Bulk Conductivity, mS/m

▭ Specimens were not vacuum saturated

Table 6b Resistivity, RCPT, and Bulk Conductivity Test Results for Air-Entrained (AE) Mixtures

SC[1]	0.55PC-A				0.45FA-A				0.40SL-A				0.40SL-HA				0.50SL-HA			
	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]	SR[1]	BR[1]	RCP[1]	BC[1]
LW	45.2	55.1	3522	14.98	136.3	149.9	1375	5.97	206.1	248.9	807	3.46	222.4	258.5	888	3.96	197.2	232.7	921	3.81
LWR[2]	44.4	52.3	4023	17.0	146.8	167.0	1048	4.53	271.4	305.5	603	2.74	260.3	299.8	685	2.95	214.4	256.8	846	3.65
SC	44.5	50.9	5017	18.98	164.1	195.3	1349	5.99	272.3	323.3	839	3.63	260.0	321.5	1114	4.68	237.1	296.2	854	3.82
SCB	36.5	42.4	4995	20.98	143.0	166.5	1070	4.70	199.4	230.8	749	3.44	211.7	221.5	896	4.59	162.6	208.5	956	4.95
PS[2]	40.3	47.8			145.5	168.4			239.0	281.2			244.1	266.8			197.1	225.8		
AC	56.1	62.0	3650	13.64	191.8	219.9	810	3.52	259.2	331.1	662	2.90	282.9	377.7	683	2.93	263.6	311.2	626	2.85
ACPS[2]	38.3	46.4			226.5	267.3			297.6	353.7			288.6	324.0			217.5	250.2		
PS2	41.3	50.0			130.1	152.7			193.8	240.6			204.4	243.5			182.4	200.4		
PS1	42.7	51.5	4622	16.89	139.5	161.0			206.2	244.3			210.7	245.1			195.8	225.1		
ACPS1	39.9	49.0	4025	17.51	219.3	241.0	816	3.93	211.8	275.3	587	2.54	223.3	285.0	656	2.67	206.5	251.1	636	3.06

[1] SC – Specimen Condition; SR = Surface Resistivity, Ω-m, BR = Bulk Resistivity, Ω-m; RCP = Rapid Chloride Permeability, Coulombs; BC = Bulk Conductivity, mS/m

[2] Conditions LWR, PS, ACPS were done on repeat mixtures

▭ Specimens were not vacuum saturated

Table 7a Chloride Penetrability Level for Mixtures and Specimen Conditions for Bulk Resistivity

Specimen Condition	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	0.55PC	0.45FA	0.40SL	0.50SL
LW	M	L	VL	VL	VL	H	L	L	L
LW(r)	M	L	VL	VL	VL	-	-	-	-
SC	M	L	VL	VL	VL	H	L	VL	VL
SCB	H	L	VL	VL	VL	H	L	L	L
PS	H	L	VL	VL	VL	H	L	L	L
AC	M	VL	VL	VL	VL	H	VL	VL	VL
ACPS	H	VL	VL	VL	VL	-	-	-	-
PS2	H	L	VL	VL	VL	-	-	-	-
PS1	H	L	VL	VL	VL	-	-	-	-
ACPS1	M	VL	VL	VL	VL	-	-	-	-
MR	-	-	-	-	-	M	L	VL	VL
MRVS	-	-	-	-	-	M	L	VL	VL

H="High", M="Moderate", L="Low", VL="Very low" based on criteria in Table 1

Table 7b Chloride Penetrability Level for Charge Passed (ASTM C1202)

Specimen Condition	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	0.55PC	0.45FA	0.40SL	0.50SL
LW	M	L	VL	VL	VL	H	L	L	L
LW(r)	***H***	L	VL	VL	VL	-	-	-	-
SC	***H***	L	VL	***L***	VL	H	L	***L***	***L***
SCB	H	L	VL	VL	VL	H	L	L	L
PS	-	-	VL	VL	VL	H	L	L	L
AC	M	VL	VL	VL	VL	H	VL	VL	VL
ACPS	-	-	VL	VL	VL	-	-	-	-
PS2	-	-	VL	VL	VL	-	-	-	-
PS1	H	-	VL	VL	VL	-	-	-	-
ACPS1	***H***	VL	VL	VL	VL	-	-	-	-
MR	-	-	-	-	-	M	L	VL	***L***
MRVS	-	-	-	-	-	***H***	L	VL	***L***

H="High", M="Moderate", L="Low", VL="Very low" based on criteria in Table 1

Table 7c Chloride Penetrability Level based for Surface Resistivity

Specimen Condition	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***	L	VL	VL	***L***	H	L	L	L
LW(r)	***H***	L	VL	VL	VL	-	-	-	-
SC	***H***	L	VL	VL	VL	H	L	VL	***L***
SCB	H	L	VL	VL	***L***	H	L	L	L
PS	H	L	VL	VL	***L***	H	L	L	L
AC	M	***L***	VL	VL	VL	H	VL	VL	VL
ACPS	H	VL	VL	VL	VL	-	-	-	-
PS2	H	L	***L***	VL	***L***	-	-	-	-
PS1	H	L	VL	VL	***L***	-	-	-	-
ACPS1	***H***	VL	VL	VL	VL	-	-	-	-
MR	-	-	-	-	-	***H***	L	***L***	***L***
MRVS	-	-	-	-	-	***H***	L	***L***	***L***

H=”High”, M=”Moderate”, L=”Low”, VL=”Very low” based on criteria in Table 1

Table 8a Effect of Curing/Conditioning on Bulk Resistivity Normalized to Condition LW (NAE mixtures)

Specimen Condition	0.55PC	0.45FA	0.40SL	0.50SL	Average (SCM mixtures)
SCB	0.78	0.93	1.00	0.83	**0.92**
LW	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
PS	0.91	0.99	1.03	1.04	**1.02**
MRVS	1.26	1.23	1.32	1.22	**1.25**
MR	1.21	1.14	1.25	1.22	**1.20**
SC	1.06	1.33	1.41	1.32	**1.35**
AC	1.14	1.88	1.49	1.39	**1.59**

Table 8b Effect of Curing/Conditioning on Bulk Resistivity Normalized to Condition LW (AE mixtures)

Specimen Condition	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	Average (SCM mixtures)
PS	0.91	1.01	0.92	0.89	0.88	**0.92**
PS2	0.91	1.02	0.97	0.94	0.86	**0.95**
SCB	0.77	1.11	0.93	0.86	0.90	**0.95**
PS1	0.93	1.07	0.98	0.95	0.97	**0.99**
LW	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
ACPS	0.89	1.60	1.16	1.08	0.97	**1.20**
ACPS1	0.89	1.61	1.11	1.10	1.08	**1.22**
SC	0.92	1.30	1.30	1.24	1.27	**1.28**
AC	1.12	1.47	1.33	1.46	1.34	**1.40**

Table 9a Effect of Curing/Conditioning on the Estimated Degree of Saturation (NAE mixtures)

Specimen Condition	0.55PC	0.45FA	0.40SL	0.50SL	Average (SCM mixtures)
LW	100%	100%	98%	97%	99%
AC	100%	100%	92%	100%	97%
PS	100%	100%	96%	94%	97%
MR	99%	98%	97%	94%	96%
SCB	N/A	90%	N/A	N/A	90%
SC	81%	81%	75%	80%	78%

Table 9b Impact of Curing/Conditioning on the Estimated Degree of Saturation (AE mixtures)

Specimen Condition	0.55PC-A	0.45FA-A	0.40SL-A	0.40SL-HA	0.50SL-A	Average (SCM mixtures)
LW	89%	82%	76%	85%	81%	81%
LW(r)	86%	84%	79%	66%	87%	79%
ACPS	84%	78%	85%	68%	84%	79%
ACPS1	84%	79%	73%	74%	81%	77%
AC	92%	78%	72%	70%	83%	76%
PS2	81%	75%	74%	75%	81%	76%
PS1	79%	75%	70%	78%	80%	76%
SCB	82%	69%	77%	75%	76%	74%
PS	82%	75%	73%	62%	84%	73%
SC	72%	65%	63%	62%	71%	65%

Table 10 Corrected Bulk Resistivity and Chloride Penetrability Level

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***	L	***L***	***L***	***L***	H	L	L	L
LW(r)	***H***	L	***L***	***L***	***L***	-	-	-	-
SC	***H***	L	***L***	***L***	***L***	H	***M***	***L***	***L***
SCB	H	***M***	***L***	***L***	***L***	H	***M***	L	***M***
PS	H	L	***L***	***L***	***L***	H	L	L	L
AC	***H***	***M***	***L***	***L***	***L***	H	VL	VL	VL
ACPS	H	**L**	***L***	***L***	***L***	-	-	-	-
PS2	H	L	***L***	***L***	***L***	-	-	-	-
PS1	H	L	***L***	VL	***L***	-	-	-	-
ACPS1	***H***	***M***	***L***	***L***	***M***	-	-	-	-
MR	-	-	-	-	-	***H***	L	VL	VL
MRVS	-	-	-	-	-	***H***	L	***L***	VL

H=”High”, M=”Moderate”, L=”Low”, VL=”Very low” based on criteria in Table 1

Table 11a Bulk Resistivity of 2 in. disk specimen Vacuum Saturated After Conditioning (NAE mixtures)

Specimen Condition	Measured BR, Ω-m (relative BR*)				Avg. relative BR (SCM 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

* BR of specimen divided by BR of specimen in LW

Table 11b Bulk Resistivity of 2 in. Disk Specimen Vacuum Saturated After Conditioning (AE mixtures)

Specimen Condition	Measured BR, Ω-m (relative BR*)					Avg. relative BR (SCM mixtures)
	0.55PC-A	**0.45FA-A**	**0.40SL-A**	**0.40SL-HA**	**0.50SL-A**	
AC	61.7 (1.09)	209.9 (1.60)	NA	303.5 (1.38)	279.4 (1.42)	1.47
LW	**56.6 (1.00)**	**131.5 (1.00)**	**235.5 (1.00)**	**220.6 (1.00)**	**216.6 (1.00)**	**1.00**
SC	45.9 (0.81)	135.2 (1.03)	219.5 (0.93)	187.2 (0.85)	211.2 (0.98)	0.95

* BR of specimen divided by BR of specimen in LW

Table 12 Mass gain of Specimens After 56 days of Sealed Curing (Condition SC)

Mixture	Mass Gain, g
0.55 PC	0.3
0.55PC-A	14
0.45FA	0.1
0.45FA-A	14
0.40SL	0.6
0.40SL-A	12
0.40SL-HA	14
0.50SL	0.3
0.50SL-A	17

Table 13 Percent Mass gain of Disk Specimens with Vacuum Saturation

Mixture	Mass Gain, percent of mass at end of conditioning			
	Condition LW		Condition SC	
	Not dried	Dried [1]	Not dried	Dried [1]
0.55 PC	0.0	0.0	0.7	0.9
0.55PC-A	0.1	0.5	0.3	1.7
0.45FA	0.1	0.0	0.8	0.7
0.45FA-A	0.0	1.0	0.5	1.9
0.40SL	0.0	0.1	0.6	0.8
0.40SL-A	0.1	0.8	0.2	1.5
0.40SL-HA	0.1	0.5	0.6	1.9
0.50SL	0.1	0.1	0.9	0.7
0.50SL-A	0.0	0.9	0.1	1.4

[1] represents specimens for DOS determination

Table 14a Single-operator precision of Results of Electrical Tests (NAE mixtures)

Specimen Condition	Single-operator precision, Coefficient of Variation, for different test methods				
	SR	**BR**	**BR (S1)**	**RCPT**	**BC**
MRVS	2.4%	3.1%	3.9%	9.0%	10.5%
LW	3.5%	2.3%	3.0%	8.6%	4.1%
MR	3.1%	2.0%	4.7%	13.4%	3.9%
SC	4.1%	1.8%	4.3%	7.7%	6.9%
SCB	5.8%	2.5%	10.4%	13.3%	9.8%
PS	2.2%	2.5%	4.6%	9.0%	12.9%
AC	4.9%	3.0%	5.5%	9.6%	5.8%
Average	**3.7%**	**2.4%**	**5.2%**	**10.3%**	**7.7%**

Each value is the average of measurements from four mixtures

Table 14b Single-operator precision of Results of Electrical Tests (AE mixtures)

Specimen Condition	Single-operator precision, Coefficient of Variation, for different test methods				
	SR	**BR**	**BR (S1)**	**RCPT**	**BC**
LW	3.8%	2.7%	3.9%	5.0%	7.5%
LW(r)	3.5%	2.0%	3.6%	7.1%	7.3%
SC	3.4%	3.3%	5.9%	17.2%	12.7%
SCB	9.0%	9.5%	9.2%	7.6%	9.3%
PS	3.2%	1.8%			
AC	5.3%	2.4%	2.9%	7.3%	7.2%
ACPS	4.4%	4.0%			
PS2 (NIST)	2.8%	2.6%			
PS1	3.0%	4.0%		24.3%	
ACPS1	3.8%	4.9%	9.1%	12.5%	12.1%
Average	**4.2%**	**3.7%**	**5.8%**	**11.6%**	**9.3%**

Each value is the average of measurements from five mixtures

Table 15a Effect of Vacuum Saturation on the Precision of Bulk Resistivity Measurements (NAE Mixtures)

Specimen Condition	Single-operator precision (COV)	
	BR (before VS) [1]	BR (after VS) [1]
LW	3.8%	4.2%
MR	3.2%	2.7%
SC	3.2%	4.7%
AC	5.6%	3.8%
Average	**4.0%**	**3.9%**

[1] BR measured on disk S2 (2-4 in. from the top)

Table 15b Effect of Vacuum Saturation on the Precision of Bulk Resistivity Measurements (AE Mixtures)

Specimen Condition	Single-operator precision (COV)	
	BR (before VS)	BR (after VS)
LW	3.9%	4.3%
LW (r)	3.6%	1.4%
SC	5.9%	11.9%
AC	2.9%	3.4%
Average	**4.1%**	**5.3%**

Table 16 Ratio of Measured BR of Disk S2 (2-4 in. from the Top) to Disk S1 (top 2 in.)

Specimen Condition	0.55PC	0.45FA	0.40SL	0.50SL	Average (SCM mixtures)
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

Table 17a. Impact of Long-Term Exposure on Bulk Resistivity of 2 in. Disk Specimen of NAE Concrete Mixtures

Mixture	Bulk Resistivity at 56-day, Ω-m				Bulk Resistivity at 1-year, Ω-m				Avg. Change @ 1 y	
	Exterior Exposure		Interior Exposure		Exterior Exposure		Interior Exposure		Exterior	Interior
	Top[1]	Bottom[2]	Top[3]	Bottom[4]	Top[1]	Bottom[2]	Top[3]	Bottom[4]		
0.55PC	58.4	55.4	59.5	54.4	186.4	178.4	167.6	204.2	321%	326%
0.45FA	165.9	206.6	147.8	203.5	463.5	561.6	240.8	360.4	275%	171%
0.40SL	215.0	224.0	209.6	231.1	421.5	454.5	427.6	508.5	200%	212%
0.50SL	193.8	245.5	196.5	238.8	425.2	499.1	299.9	393.0	210%	159%

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

[1]E (T); [2]E (B); [3]I (T); [4]I (B)

Table 17b. Impact of Long-Term Exposure on Bulk Resistivity of 2 in. Disk Specimen of AE Concrete Mixtures

Mixture	Bulk Resistivity at 56-day, Ω-m				Bulk Resistivity at 1-year, Ω-m				Avg. Change @ 1 y	
	Exterior Exposure		Interior Exposure		Exterior Exposure		Interior Exposure		Exterior	Interior
	Top[1]	Bottom[2]	Top[3]	Bottom[4]	Top[1]	Bottom[2]	Top[3]	Bottom[4]		
0.55PC-A	72.6	108.8	71.9	104.8	223.7	285.5	194.1	270.7	281%	263%
0.45FA-A	188.1	260.6	181.4	268.0	474.9	634.8	301.0	372.2	247%	150%
0.40SL-A	313.0	334.5	297.6	414.5	621.4	692.6	457.5	597.9	203%	148%
0.40SL-HA	358.7	401.7	336.6	456.1	738.3	797.4	430.6	546.8	202%	123%
0.50SL	294.2	296.9	268.7	318.4	584.4	657.7	305.7	341.3	210%	110%

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

[1]E (T); [2]E (B); [3]I (T); [4]I (B)

Table 17c. Impact of Long-Term Exposure on Bulk Resistivity of 2 in. Disk Specimen of Replicate AE Concrete Mixtures

Mixture	BR at 7-day, Ω-m		BR at 1-year, Ω-m		Avg. Change @ 1 y
	Exterior Exposure		Exterior Exposure		
	Top[1]	Bottom[2]	Top[1]	Bottom[2]	
0.55PC-A	47.7	56.4	261.3	281.5	521%
0.45FA-A	43.7	68.5	469.6	696.0	1039%
0.40SL-A	129.0	149.8	720.8	842.4	561%
0.40SL-HA	88.7	161.2	654.3	833.0	595%
0.50SL	100.8	121.6	533.4	637.5	526%

Cylinders were cured in lime water for 7 days after which disk specimens were cut.

[1]E (T); [2]E (B)

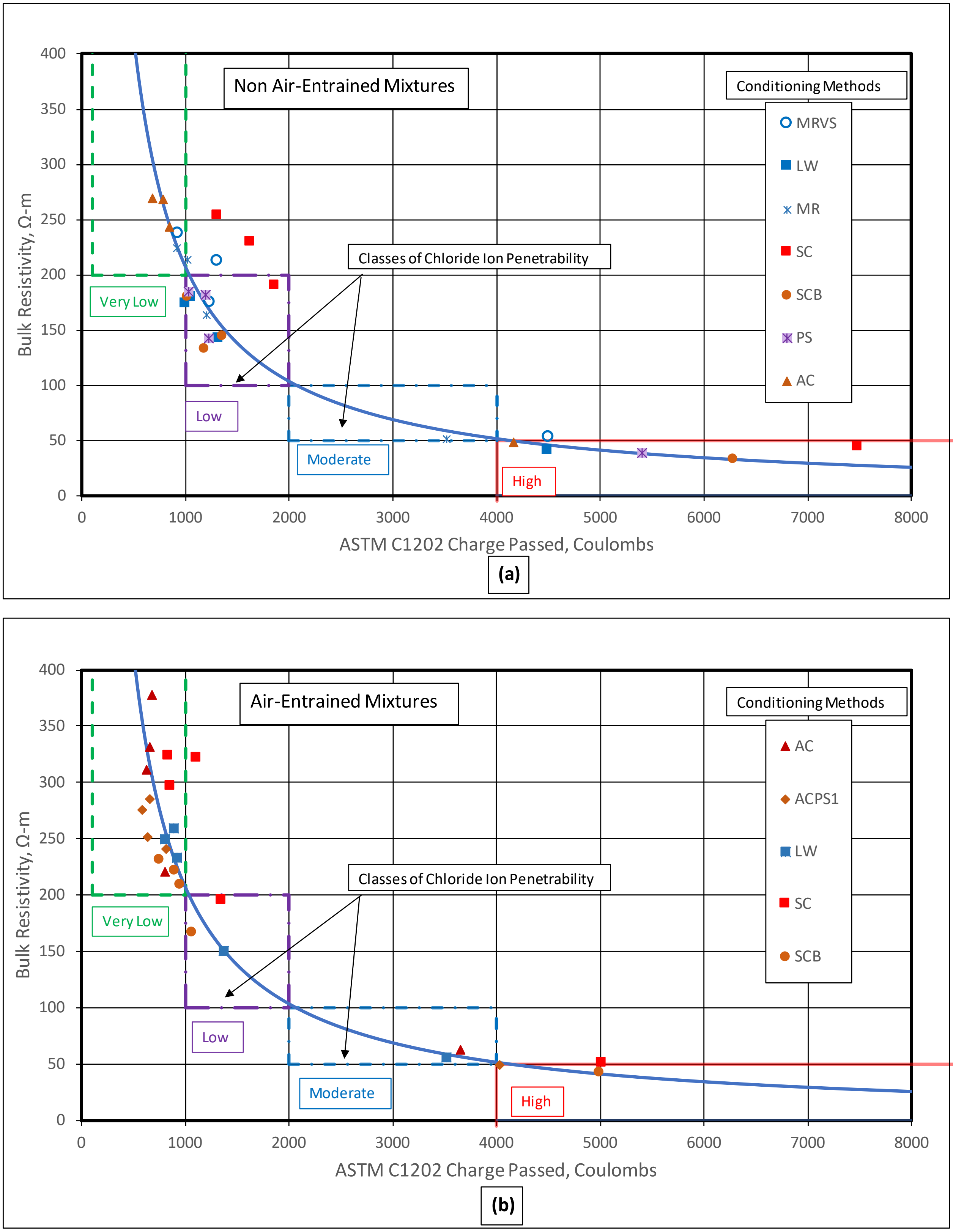
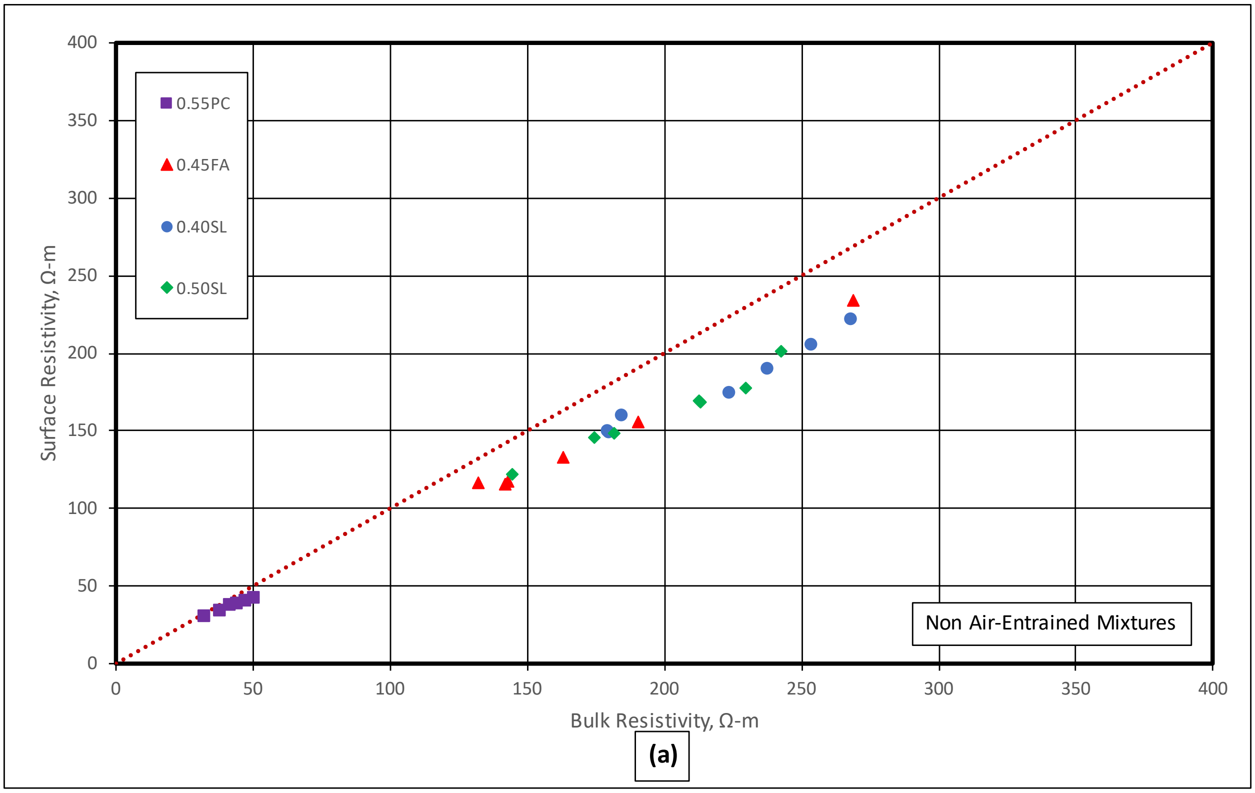


Fig. 1. RCPT vs Bulk Resistivity for All Conditions and Concrete Mixtures (a) Non-air-entrained (b) Air-entrained. The zones for Chloride Ion Penetrability classification are based on Table 1



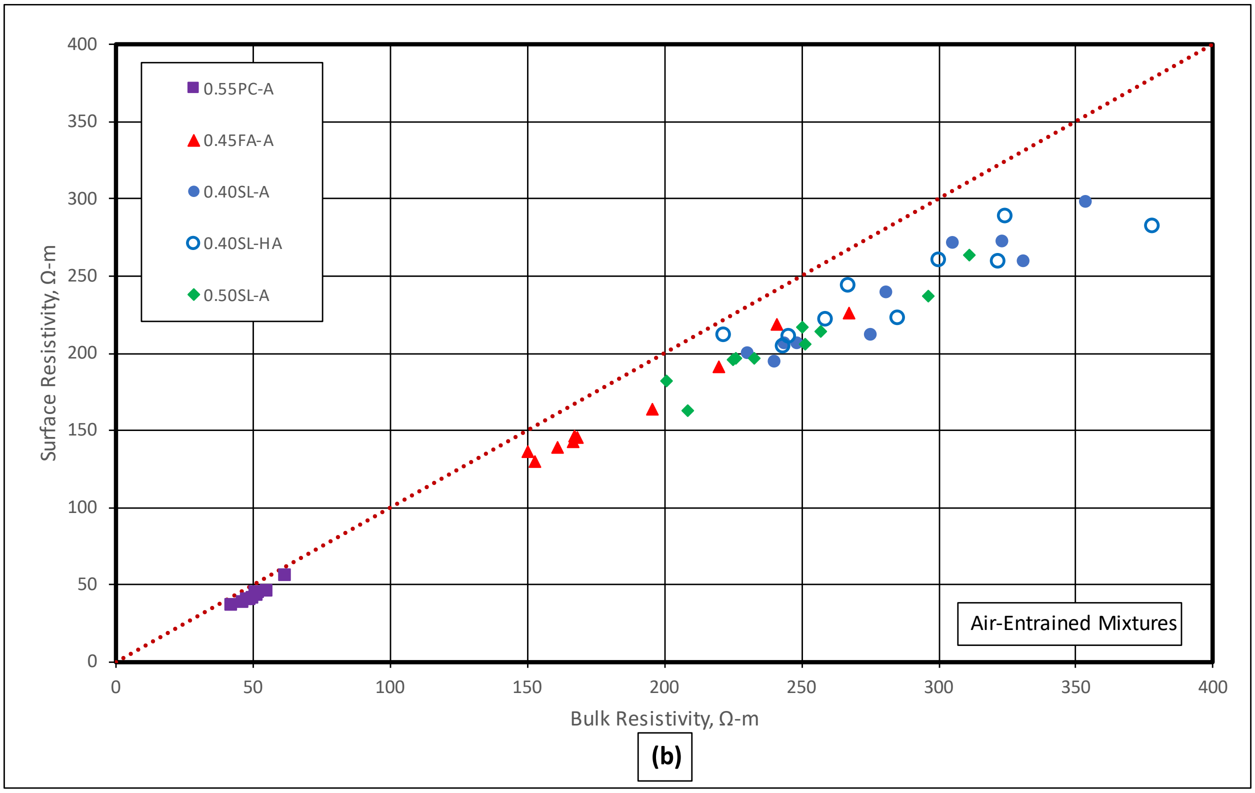


Fig. 2. Bulk Resistivity vs Surface Resistivity for all Conditions and Concrete Mixtures (a) Non-air-entrained (b) Air-entrained

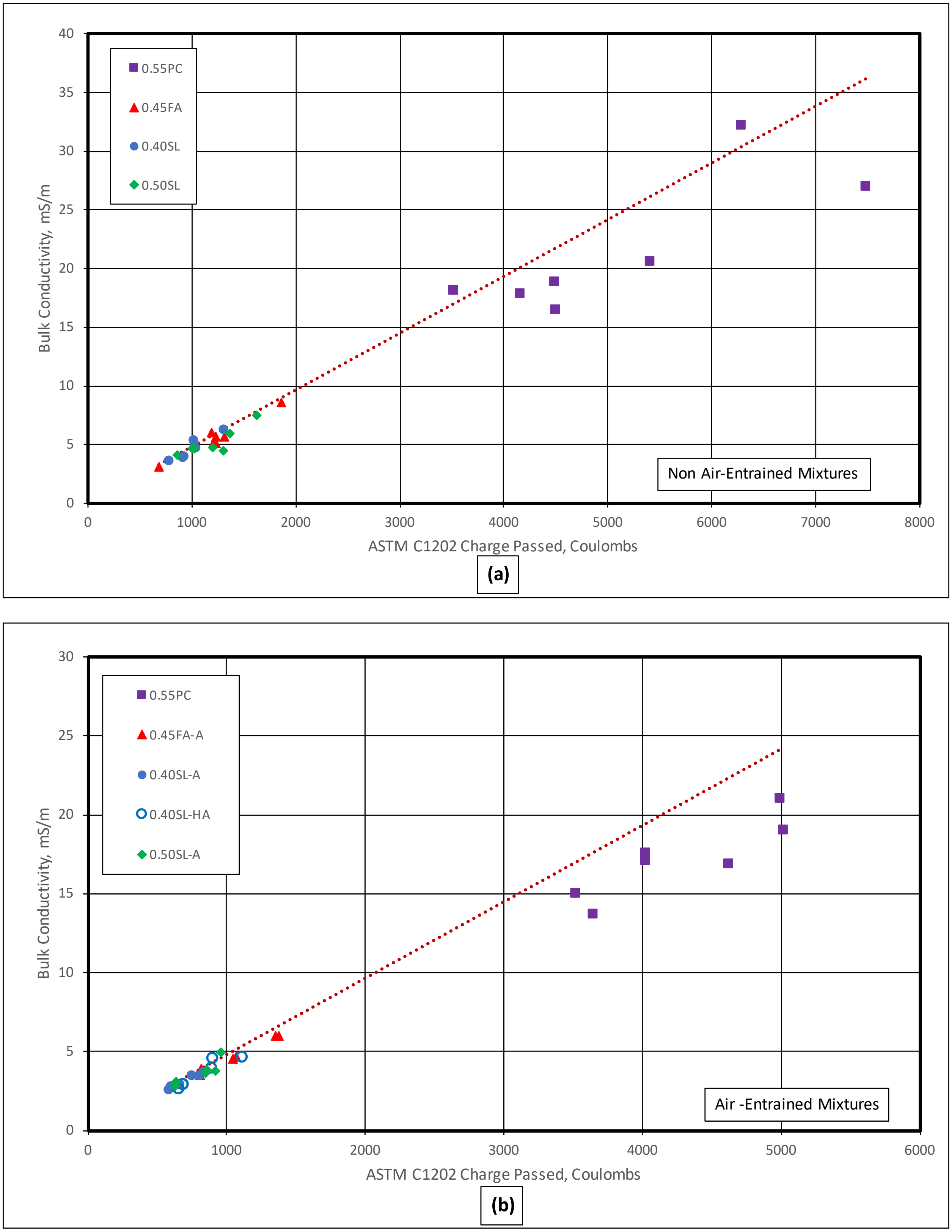


Fig. 3. RCPT vs Bulk Conductivity for all conditions and Concrete Mixtures (a) Non-air-entrained (b) Air-entrained

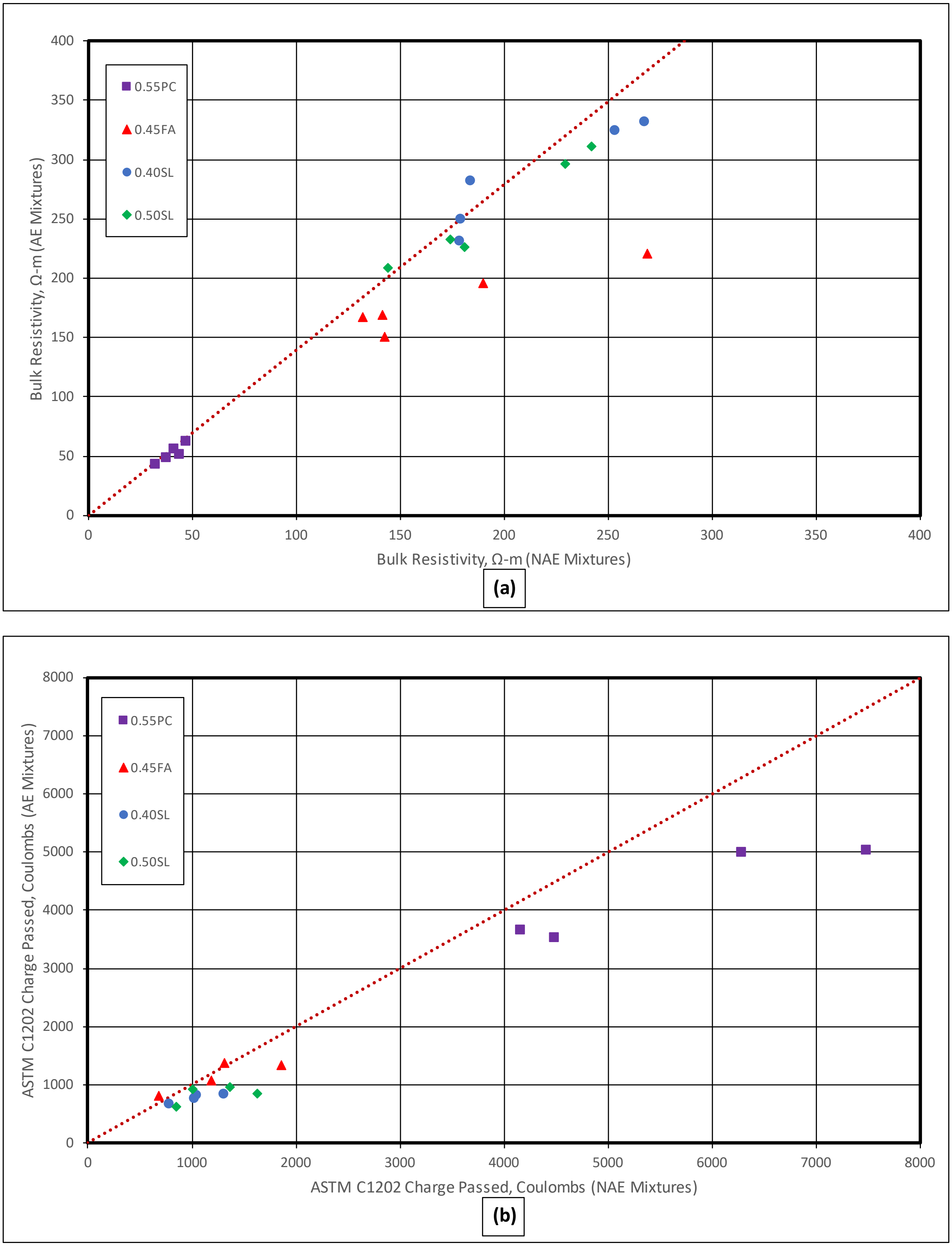
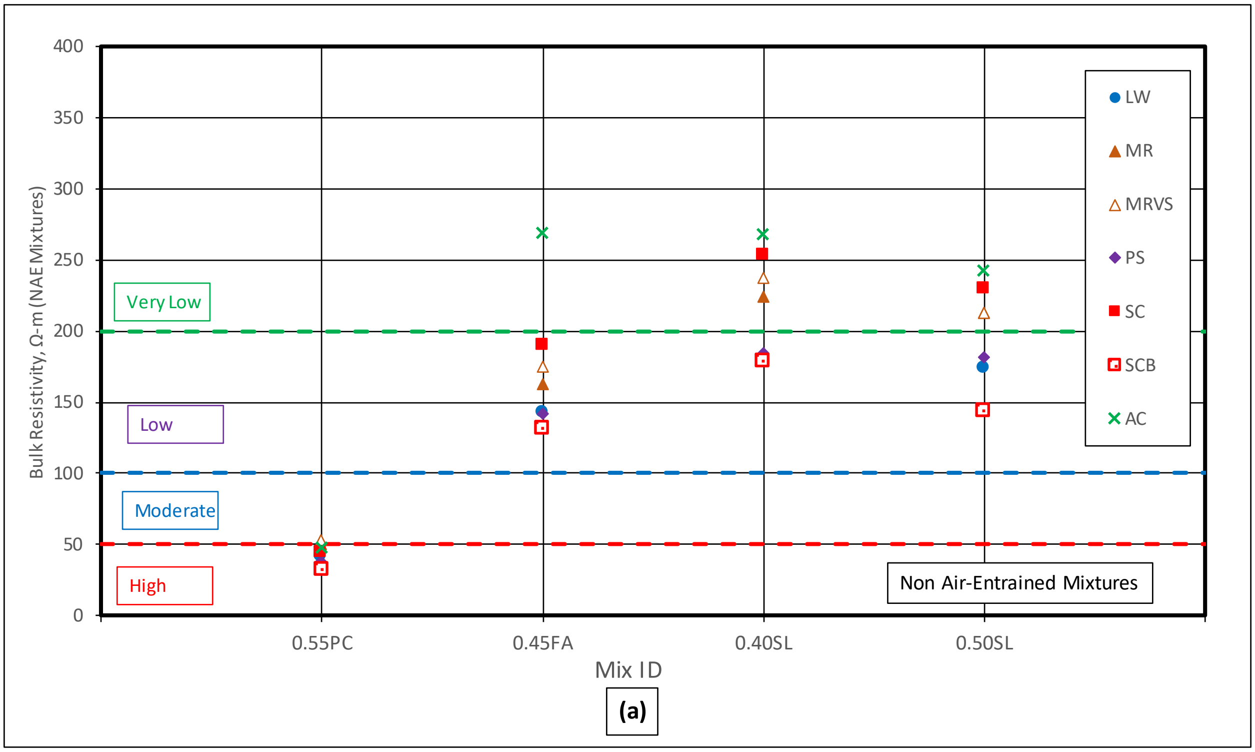


Fig. 4. Impact of Entrained Air- on Concrete (a) Bulk Resistivity (b) RCPT



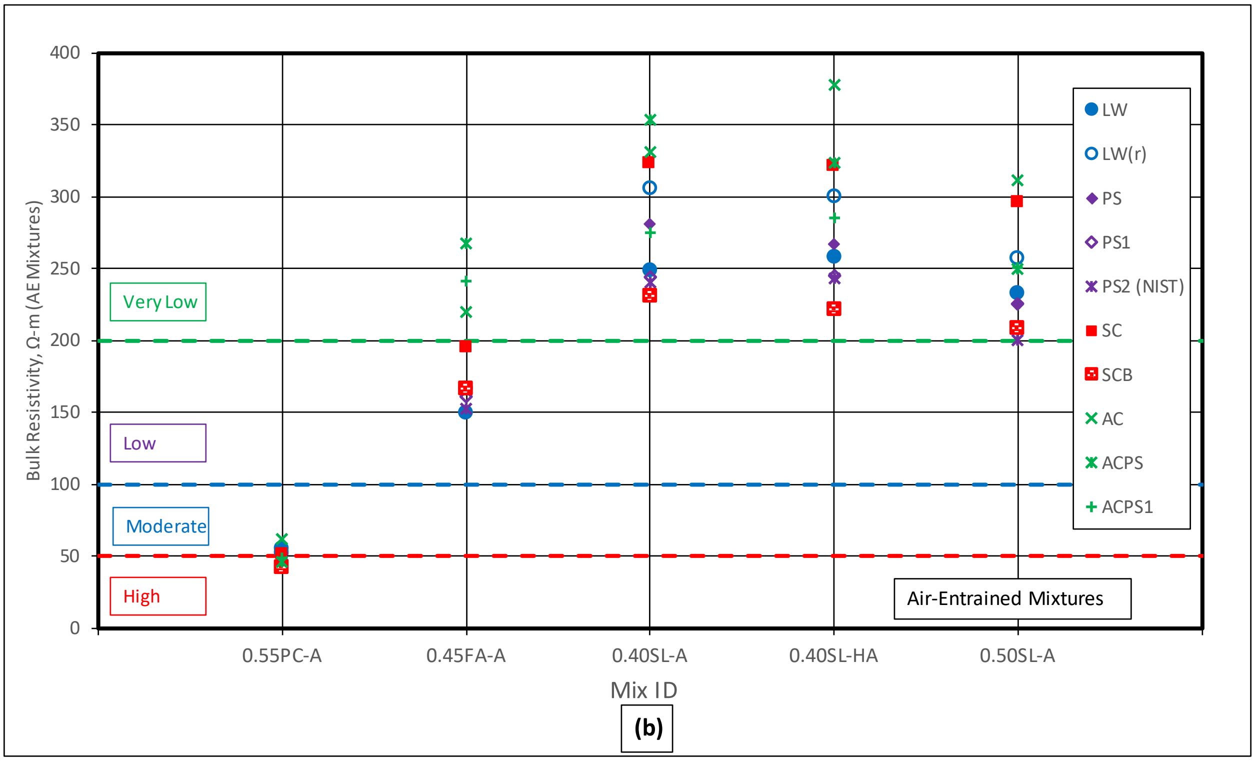


Fig. 5. Bulk Resistivity of Various Conditions and Mixtures (a) Non-air-entrained (b) Air-entrained

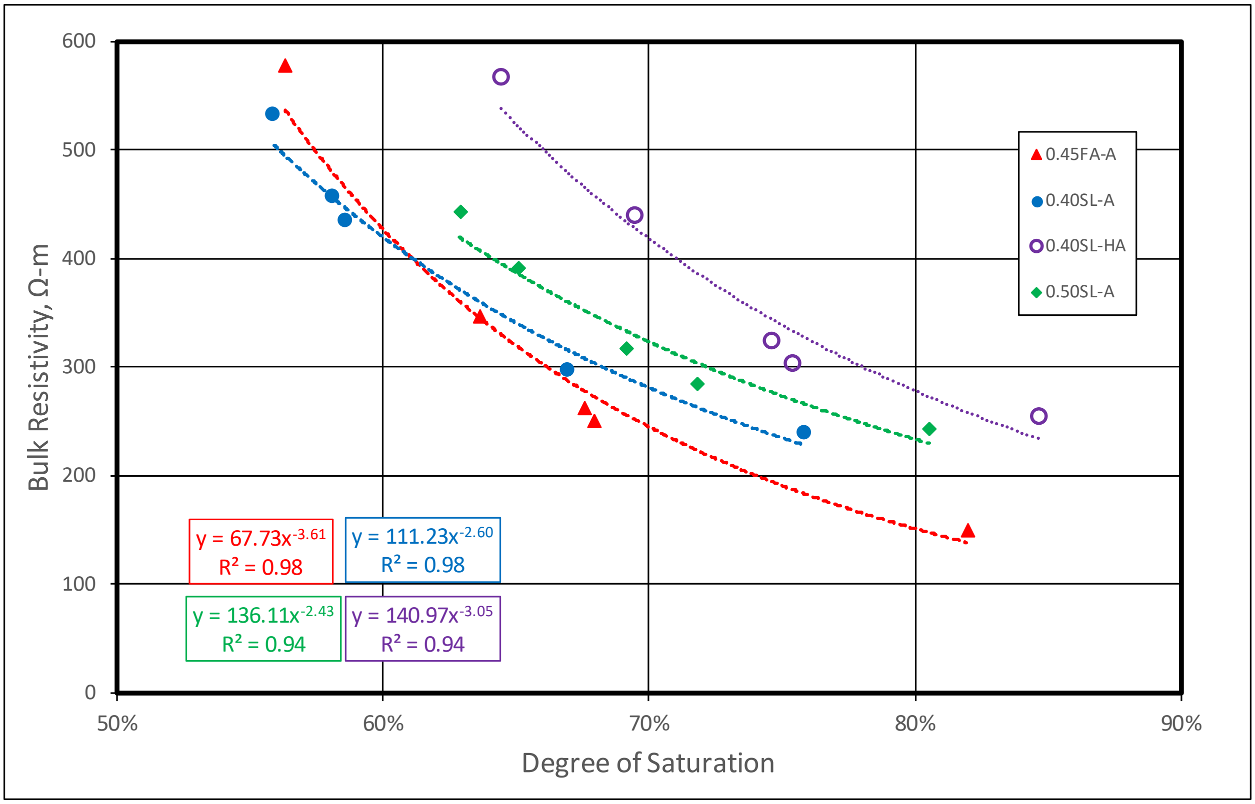


Fig. 6. Impact of Drying on Measured DOS and Bulk Resistivity. *Specimens dried after 56 days of lime water curing*

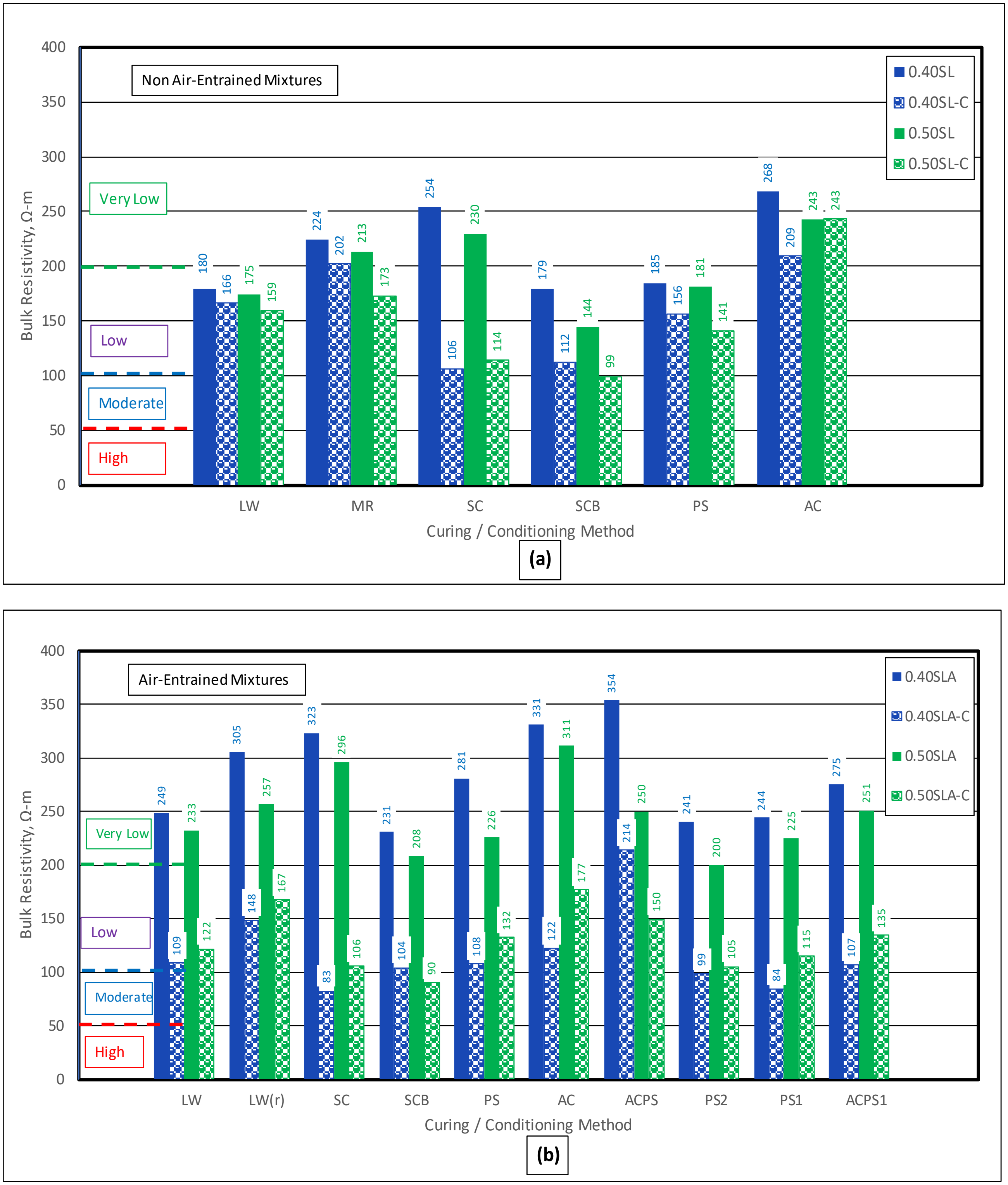


Fig. 7. Measured and Corrected (C) Bulk Resistivity for mixtures with slag cement with w/cm 0.40 and 0.50 (a) Non-air-entrained (b) Air-entrained

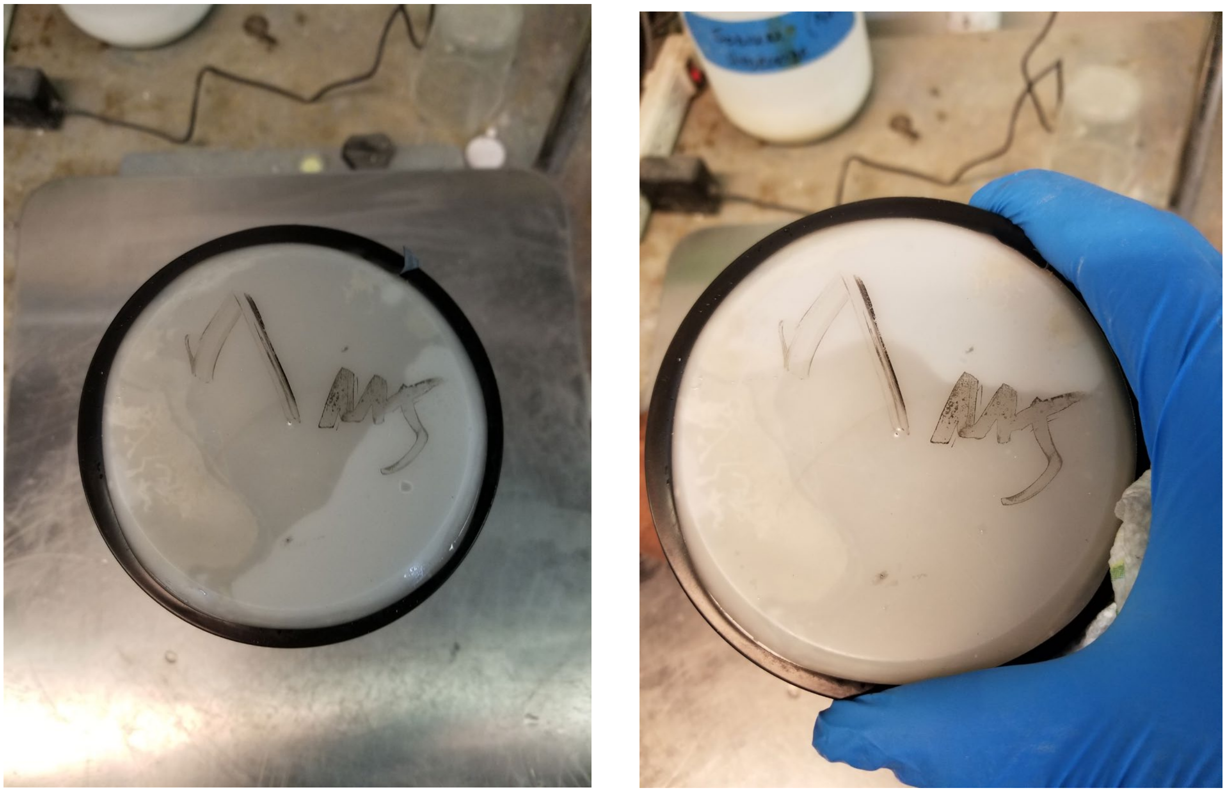


Fig. 8 Specimens subject to Condition SC (AE mixtures) after 56 days in moist room showing water under the seals

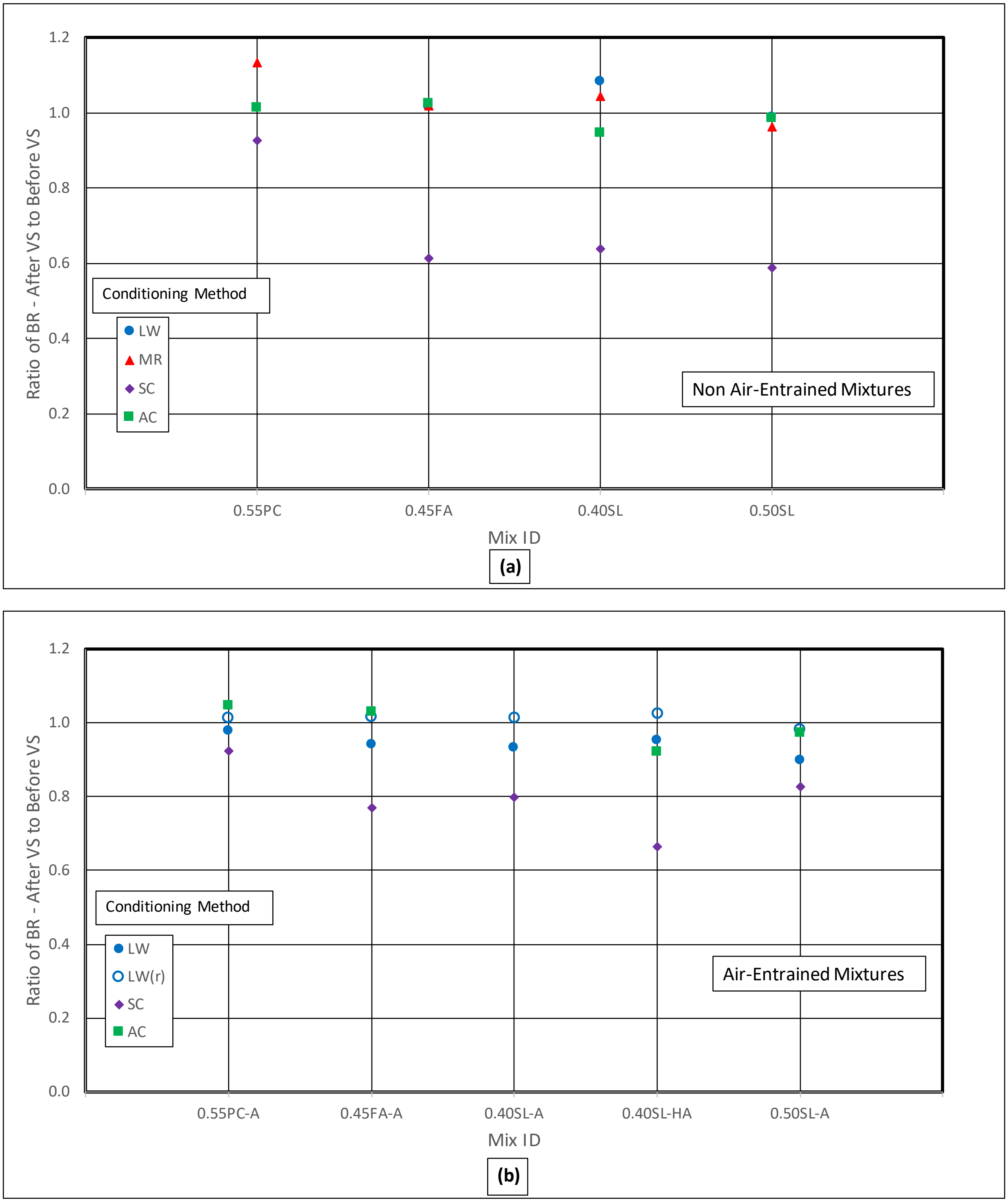


Fig. 9. Ratio of Bulk Resistivity of 2-in. Disk - After Vacuum Saturation (VS) to Before of Various Conditions and Concrete Mixtures (a) Non-air-entrained (b) Air-entrained

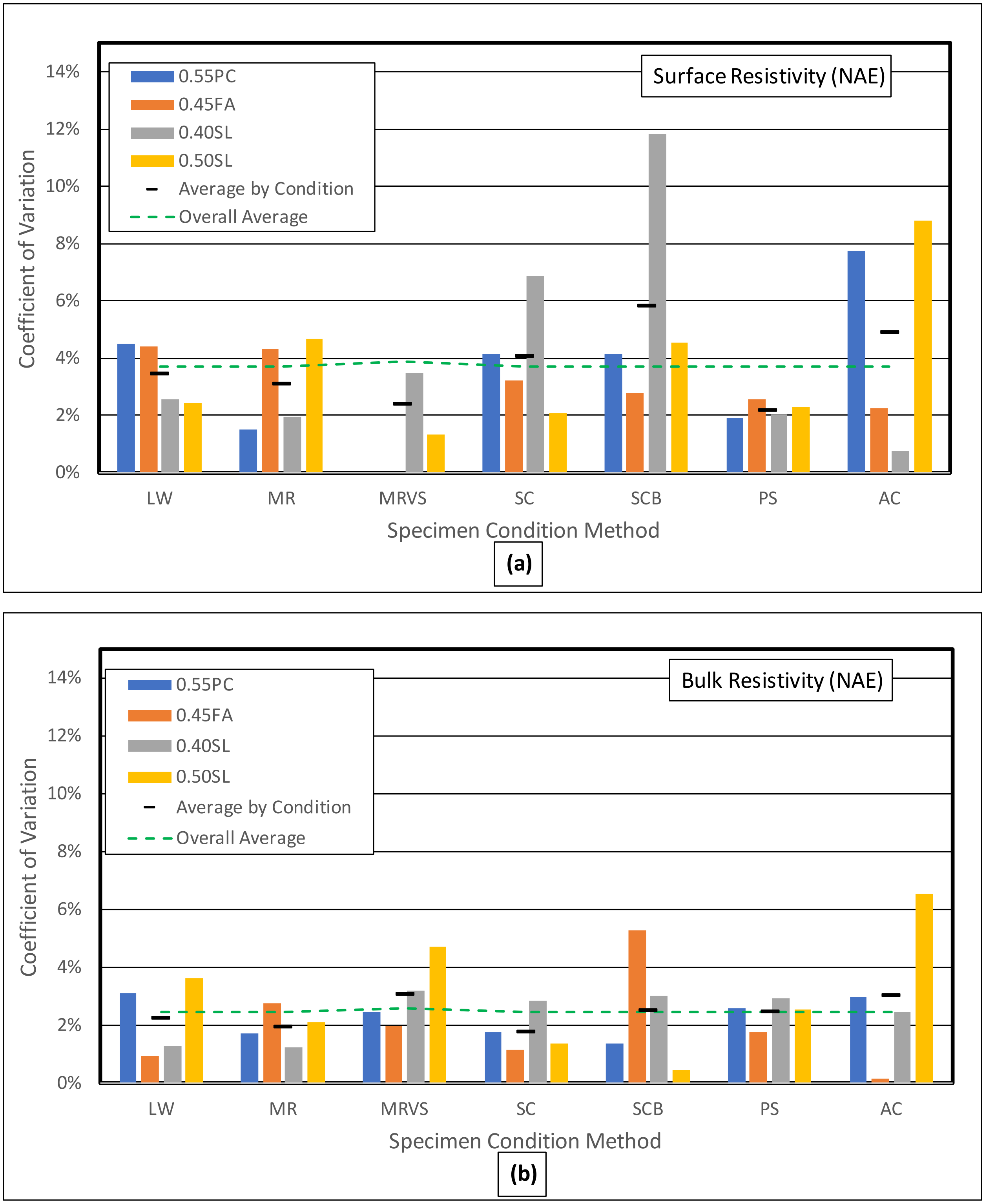
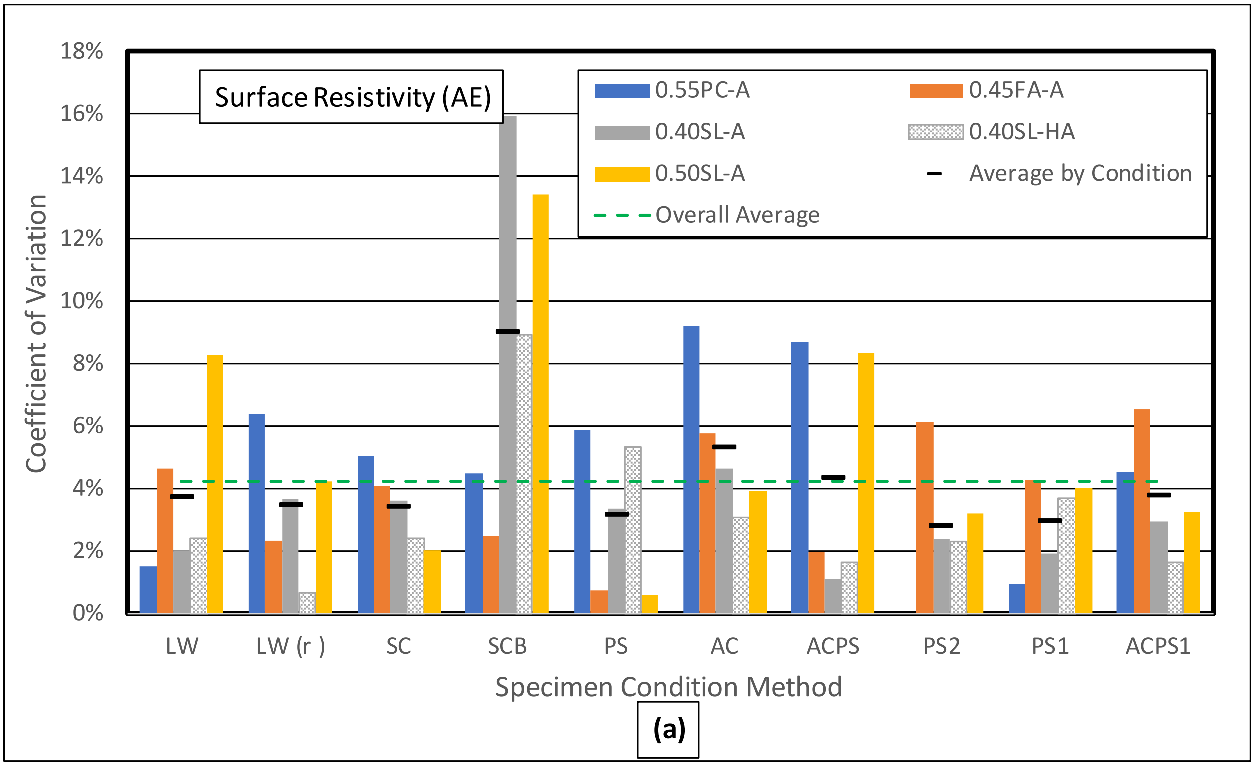


Fig. 10. Coefficient of Variation of (a) Surface Resistivity (b) Bulk Resistivity Test Specimens subjected to different Conditions for NAE Mixtures



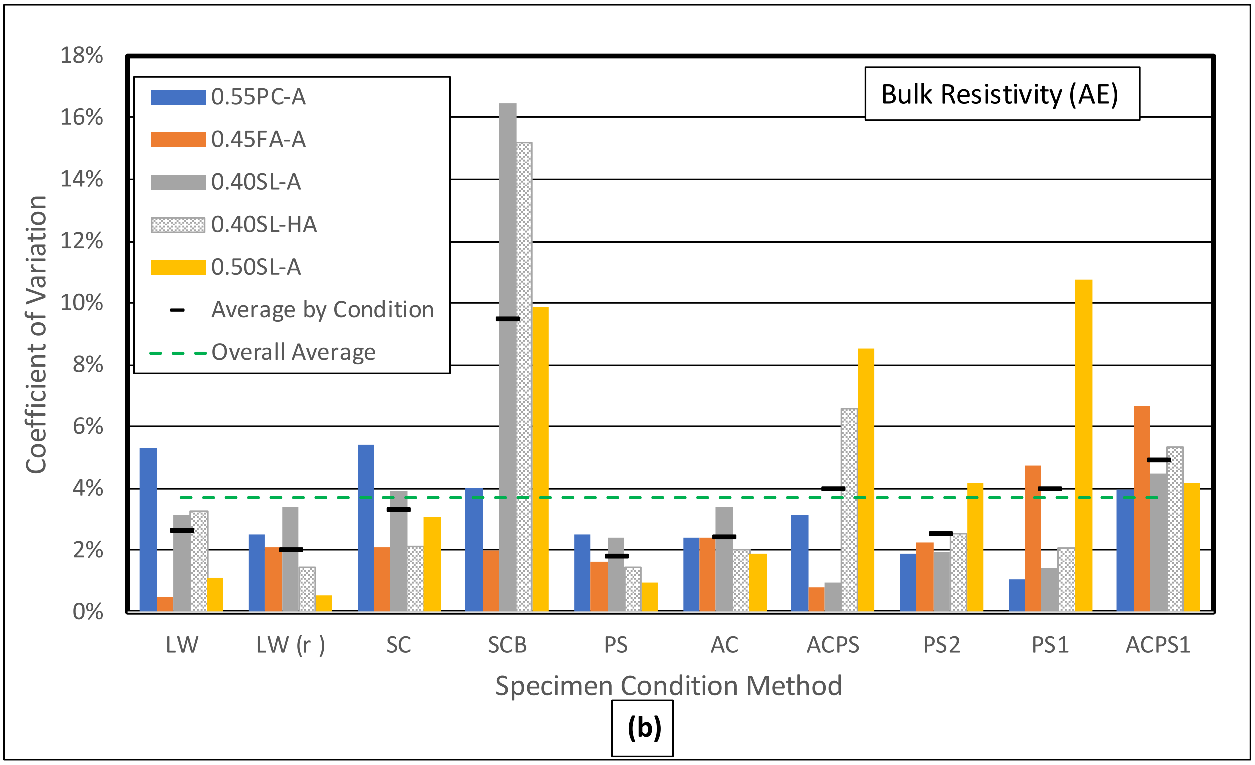


Fig. 11. Coefficient of Variation of (a) Surface Resistivity (b) Bulk Resistivity Test Specimens subjected to different Conditions for AE Mixtures

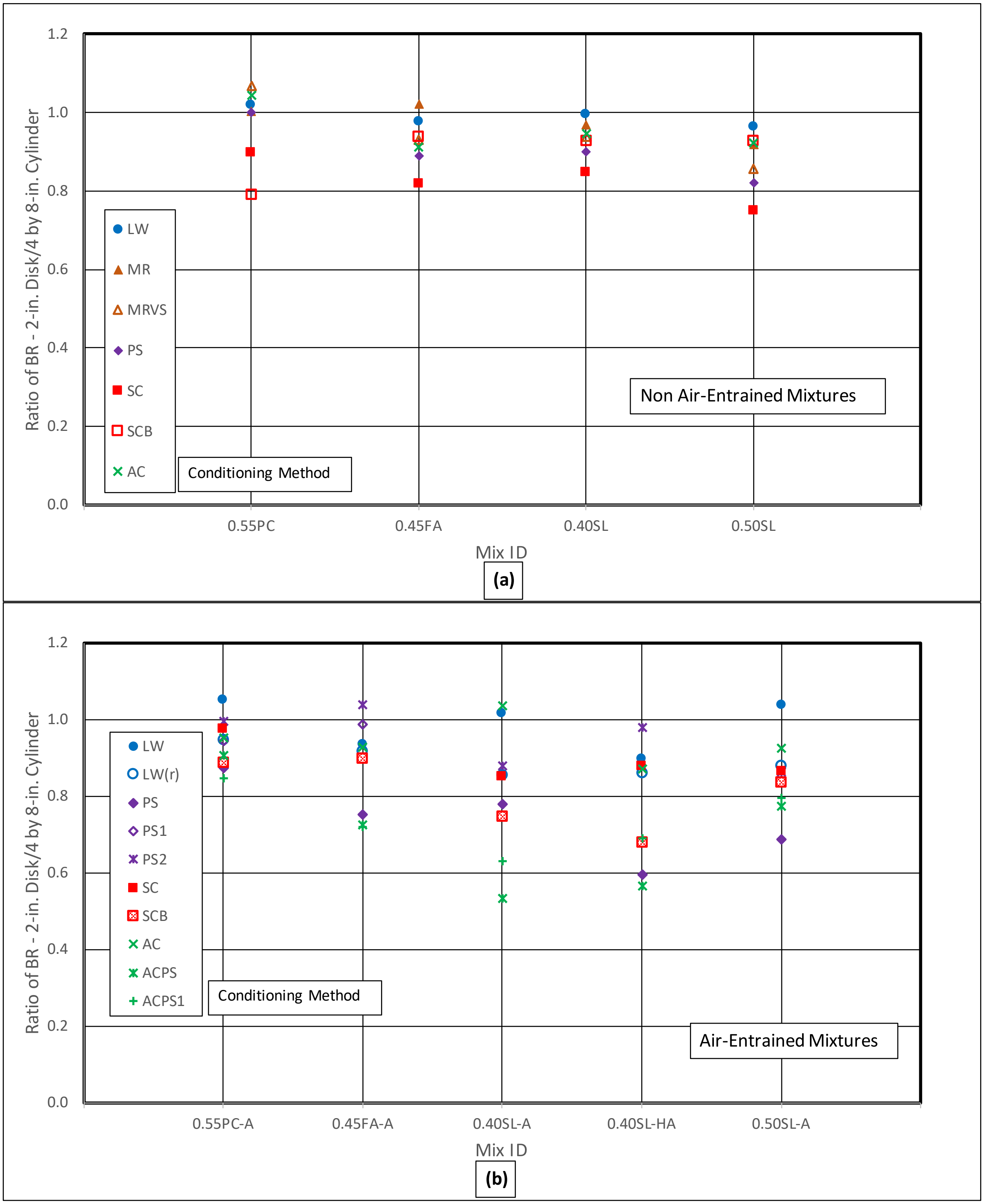


Fig. 12. Ratio of Bulk Resistivity of Top 2 in. Disk to the Whole Specimen of Various Conditions and Concrete Mixtures (a) Non-air-entrained (b) Air-entrained

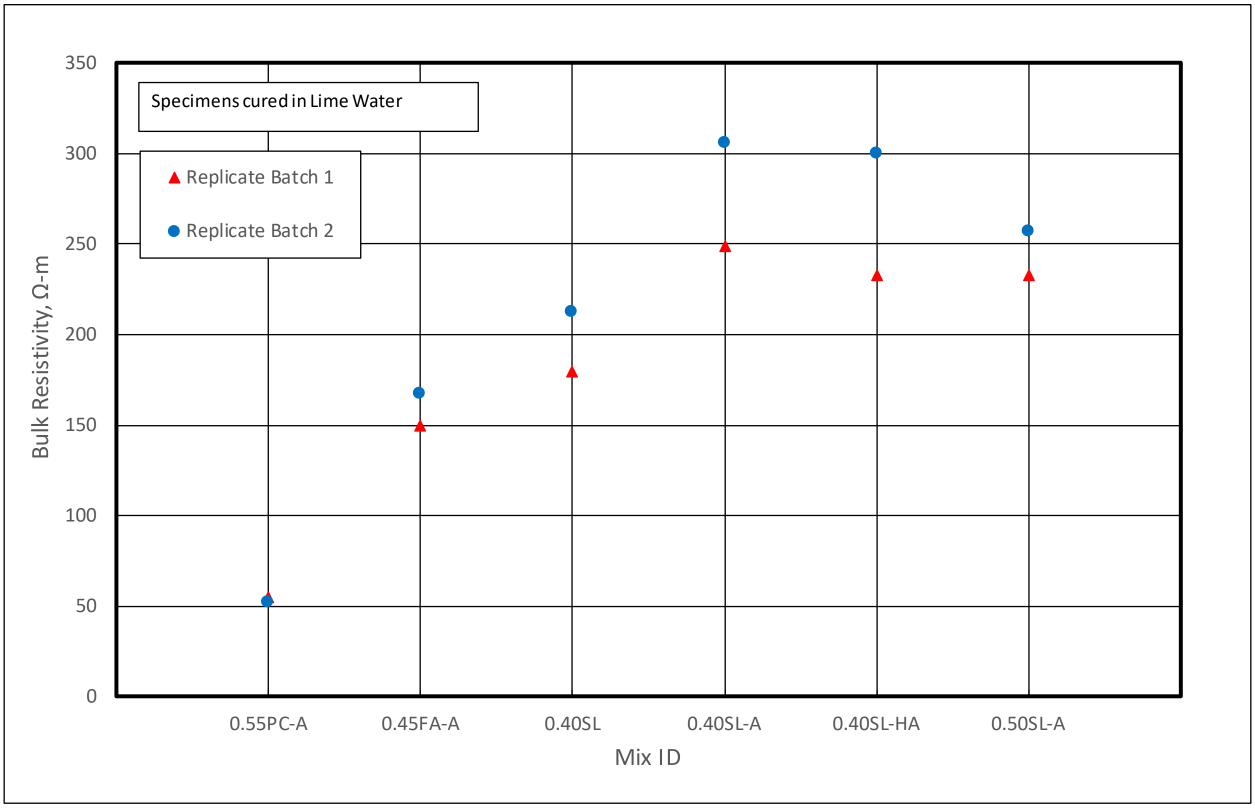


Fig. 13. Batch to batch Variation of Bulk Resistivity test Results

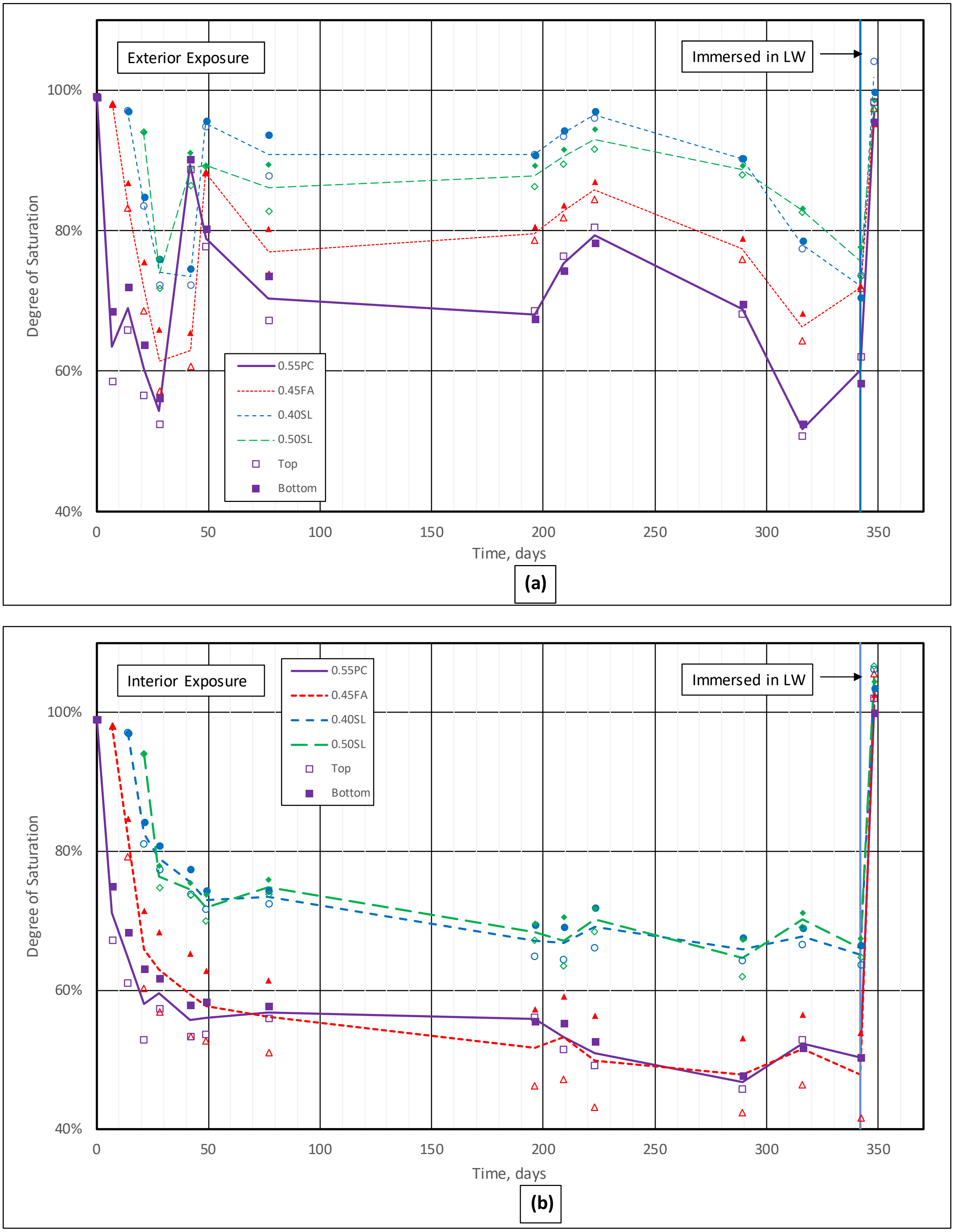


Fig. 14a-b. Change in DOS of Disk Specimens Subject to Exposure (a) Outdoor (b) Indoor

Addendum: Optimal Curing/Conditioning for Resistivity Specimens

There were several curing/conditioning methods used in this research program. Of these, the following are more commonly under consideration:

- Immersion in simulated pore solution
- Immersion in saturated lime water.
- Sealed curing or Sealed Cured followed by immersion in simulated pore solution

Conditioning specimens in simulated pore solution is the preferred option in AASHTO T 359, TP 119, and ASTM C1876. The intent is to reduce leaching of alkalis and progress towards attaining a steady-state between the simulated pore solution and the internal pore solution within the concrete specimen. ASTM C1876 requires that measurements should be recorded after allowing the readings to stabilize for 2 to 5 s. It is not possible to adhere to this requirement since the bulk resistivity measurements for specimens conditioned in pore solution do not stabilize and continue to increase with time. Recent work (Table A1) verified that bulk resistivity of three different mixtures (three specimens/mixture) increased between 8% and 20% (average 14%) when measured at 2 min. when compared to the measurement at 5 s. The specimens had been blotted off after removing from the pore solution as required in ASTM C1876 and were maintained between the plates over the 2-min duration.

As part of the evaluation, specimens conditioned in pore solution were washed under tap water for 45 s before the measurement. After this treatment, the bulk resistivity measurements were stable and did not show the drifting trend over a 2-min. duration. Testing variation based on the range of three specimens reduced from 13% before washing to 4% after washing. This additional evaluation suggests that washing the specimens conditioned in pore solution under tap water for 45 s will stabilize the measurements without causing an increasing drift with time and results in a lower testing variation. After washing, the bulk resistivity of specimens conditioned in pore solution increased between 20% and 44% (average 28%) for the three mixtures. However, the measured resistivity was still lower than the measured bulk resistivity of specimens conditioned in lime water. After washing, the measured surface resistivity of specimens conditioned in pore solution increased between 4% and 14% (average 9%) for the three mixtures, a much lower increase than the measured bulk resistivity. It is postulated the presence of the pore solution on the surface impacted the bulk resistivity measurements considerably. This is an artifact of the test method and not the concrete mixture and is therefore of concern. Further, in pore solution conditioning there is a potential for error in preparing the pore solution and its unknown impact on the resistivity results.

Specimens conditioned in lime water provided reliable measurements that did not drift with time and had a low level of testing variation. Mixtures were predictably classified for transport properties and consistent with classification with ASTM C1202 (RCPT). Based on all the curing conditions evaluated in this research project it is recommended that test specimens be immersed in lime water 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 lime water at 73°F for seven days followed by 21 days at 100°F in accordance with the accelerated curing methods of ASTM C1202, Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration (RCPT). This would be important for mixtures containing slower reacting pozzolans like fly ash.

There are several problems associated with subjecting specimens to sealed curing (Condition SC and SCB) and therefore they are not recommended for conditioning specimens for resistivity testing. If the specimens are sealed very well, it is surmised that consumption of water from the hydration reaction causes self-desiccation, which prevents an effective degree of hydration/degree of reaction of supplementary cementitious materials, especially with fly ash, and can inaccurately classify mixtures for lower chloride penetrability. Specimens subjected to condition SC and SCB were at a lower degree of saturation compared to specimens subjected to other conditions and this can result in higher measured resistivity. It is also suggested that because of the potential curtailment of reactivity of SCMs, the comparability of mixtures for transport properties will be uncertain. The specimen sealing process is likely to be inconsistent and is also a source of testing error.

There does not appear to be any advantage in measuring bulk resistivity on 2 in. disk specimens. If disk specimens are prepared for the RCPT or if disks are obtained as cores, bulk resistivity 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 lime water and not in simulated pore solution.

Based on these findings, it is recommended that ASTM C1876 be modified to:

1. Incorporate lime water conditioning as an option

2. For the pore solution conditioning option, require that specimens be washed for 45 s in tap wash before the measurements

Table A1. Stability of Measured Resistivities

Spec ID[1]	**BR LW**		**BR PS**		**BR LW (AW)**		**BR PS (AW)**		**SR LW**	**SR PS**	**SR LW (AW)**	**SR PS (AW)**
	5 sec.	**2 min.**	**5 sec.**	**2 min.**	**5 sec.**	**2 min.**	**5 sec.**	**2 min.**	**5 sec.**	**5 sec.**	**5 sec.**	**5 sec.**
M1-1	139.5	140.2	100.4	111.5	137.2	137.2	114.3	114.0	106.5	103.0	100.8	103.1
M1-2	140.0	141.0	91.1	106.3	137.9	137.9	112.1	112.0	114.1	91.5	105.1	98.1
M1-3	146.9	148.1	91.1	105.6	144.6	144.6	115.3	115.3	115.3	90.1	111.1	95.6
M1-Avg.	142.2	143.1	94.2	107.8	139.9	139.9	113.9	113.7	111.9	94.9	105.7	98.9
M2-1	391.0	399.4	188.8	233.1	382.7	384.4	259.7	257.0	305.6	211.5	291.2	229.0
M2-2	347.6	355.9	160.6	194.0	344.2	344.2	242.8	238.8	285.5	188.8	268.6	216.1
M2-3	381.0	389.4	170.3	198.0	371.0	369.3	245.7	236.8	286.3	180.4		217.9
M2-Avg	373.2	381.6	173.2	208.4	366.0	366.0	249.4	244.2	292.5	193.6	279.9	221.0
M3-1	94.6	95.1	69.0	73.4	92.2	92.4	77.2	76.2	79.3	62.1	75.5	67.1
M3-2	101.6	102.3	60.0	66.2	99.8	100.1	75.9	75.2	79.9	59.9	74.2	64.0
M3-3	110.3	111.1	61.7	65.5	110.5	109.8	74.9	74.9	80.0	57.9		62.8
M3-Avg	102.2	102.8	63.6	68.3	100.8	100.8	76.0	75.4	79.7	60.0	74.9	64.6

[1] Specimen ID = M1, M2, M3 are 3 different mixtures. Specimens 1, 2, 3 correspond to 3 different specimens each conditioned either in lime water or pore solution.

BR=bulk resistivity; SR=Surface resistivity; PS=pore solution, LW=lime water; AW=After washing under tap water for 45 s. SR PS (AW) = Surface resistivity of specimen conditioned in pore solution measured after washing under tap water for 45 s.

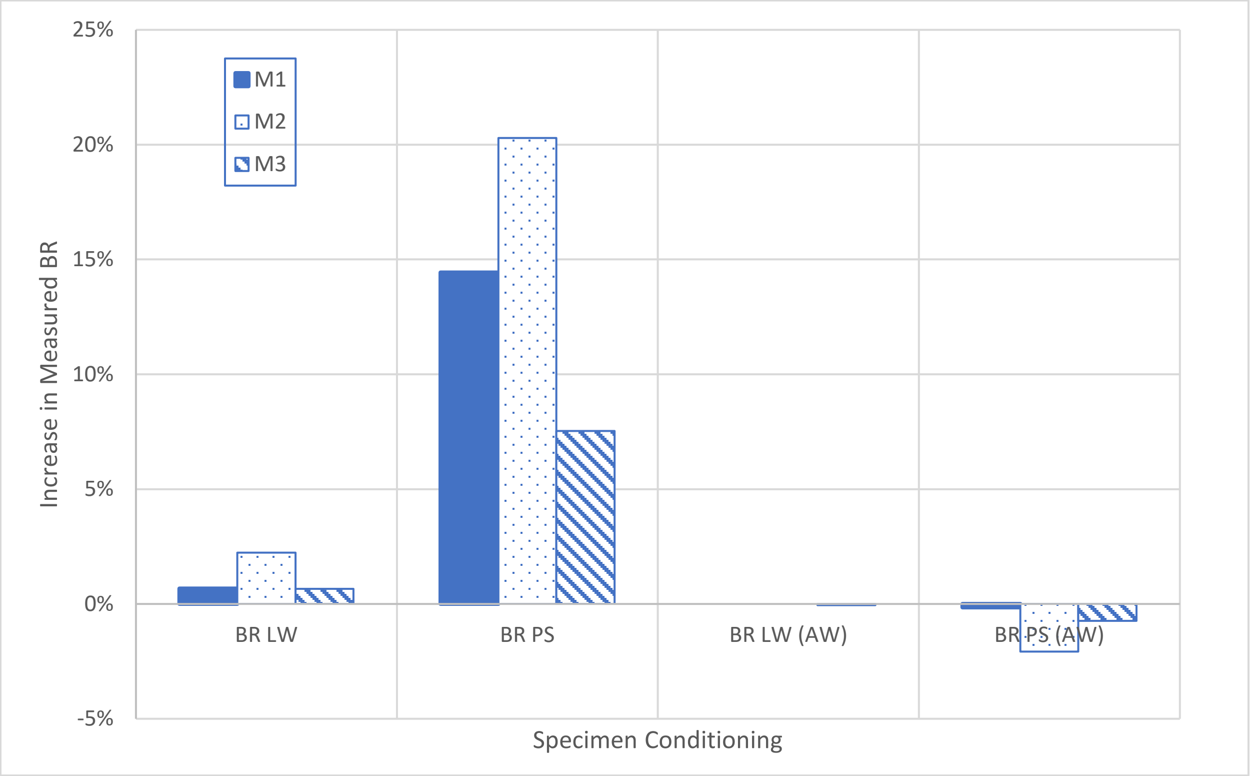


Fig. A1. Increase in Bulk Resistivity Measured at 2 min. when Compared to the Measurement at 5 s for the three Different Mixtures.