Improving the Reliability of Resistivity Tests of Concrete

PHASE A REPORT

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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 318-14, 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 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 NRMCA research (Obla et al. 2016) has shown a good correlation between apparent chloride diffusion coefficient, determined in accordance with ASTM C1556 and the rapid chloride permeability test (RCPT), in accordance with ASTM C1202, for vacuum saturated specimens. 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, and combination of dilution 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 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 practice where a minimum specified compressive strength is specified with a maximum *w/cm*.

More recent work (Archie 1942; Weiss et al. 2017) has recommended the concept of the formation factor (FF) as a scientifically sound principle as an indicator of the transport properties of concrete. The use of FF addresses the impact of the pore solution conductivity with electrical measurements. This evolution permitted 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 accepted). FF has also been correlated with concrete sorptivity (Moradllo 2018) and therefore can also be used to specify requirements for concrete mixtures that will be resistant to cycles of freezing and thawing (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 the test is relatively expensive. RCPT primarily measures the conductivity of concrete. Another electrical measurement that has evolved is to measure the resistivity of concrete. Resistivity is the inverse of conductivity. A higher resistivity measured on a concrete specimen is an indication of a lower permeability. Specification criteria based on resistivity can thereby be used for selecting concrete mixtures with a low chloride penetrability. State highway agencies have more recently been moving towards using the resistivity test, AASHTO T 358 or TP 119. This test is one of the important test methods proposed in the FHWA-supported AASHTO PP 84, *Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures*. It also supports NRMCA's P2P Initiative to replace prescriptive *w/cm* requirements for concrete. The measurement in this test method is relatively easy and has a considerably lower variability. There are, however, several factors that impact the test result. One of the more significant factors is the degree of saturation (DOS) of the test specimen. A lower DOS, i.e. testing the specimens in a drier than the saturated condition will result in a higher measured resistivity.

Background on Resistivity Test Standards

There is increasing interest within state highway agencies to use resistivity tests to specify low permeability concrete. Two different methods are available: AASHTO T 358, *Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*, and AASHTO provisional standard TP 119, *Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test*, also referred to as bulk resistivity. A higher measured resistivity is indicative of lower permeability concrete. Specification criteria would specify a minimum resistivity value (RCPT specifies maximum charge passed).

There is considerable difference in how concrete test specimens are conditioned for these tests. The RCPT 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 for specimens to be maintained sealed in molds until tested, vacuum saturated after a curing period, and cured/conditioned in lime-saturated simulated pore solution. The surface resistivity, (AASHTO T 358) and the bulk conductivity (ASTM C1760) test method require moist curing which could be either moist room curing or immersion in a lime water bath. The bulk resistivity test method being standardized by ASTM requires curing/conditioning in lime-saturated simulated pore solution. As currently written, resistivity and conductivity test methods permit alternatives for specimen conditioning without any specificity. The surface resistivity test method being standardized by ASTM permits moist curing, vacuum saturation, or sealed conditioning. Moist curing in accordance with ASTM C511 can be by moist room curing or by immersion in lime-saturated water. The specifying agencies using the resistivity test methods invoke a wide range of specimen conditioning procedures. The conditioning procedures impact the DOS, the degree of reaction/hydration of the cementitious materials (DOH), and the leaching of alkalis from the specimen. These factors impact the measured resistivity (Spragg et al. 2013). If the project specification is not clear on the curing/conditioning method before the measurement, it will be difficult for the concrete supplier to ensure that the mixtures comply with the requirements when developing the concrete mixture proportions.

The following relationship is used to correct the measured resistivity of a test specimen based on its saturation level. This indicates that a lower DOS results in a higher resistivity (Spragg et al. 2016; Weiss et al. 2013).

$$\frac{\rho_c^o}{\rho_c} = f(S) = S^n$$

(1)

Where:

ρ_c^o is the resistivity of the concrete at 100% saturation,

S = DOS (the percentage of the total pore volume that is filled with fluid),

ρ_c is the resistivity of the concrete at any DOS, and

n = varies between 3 and 5.

From this equation, for a given mixture, if the specimen DOS increases from 60% to 75% the resistivity can decrease by a factor of 2 to 3, depending on the value of *n* used. If the DOS of the specimen is higher by just 5% at the end of the conditioning period the measured resistivity can be lower by 25 to 50%. This can result in a different interpretation on the quality of the mixture for specification compliance. A change in the specimen DOS can occur due to the following:

1. Potential variation in specimen conditioning procedures between two batches of the same mixture
2. A 1% change in air content between two batches of the same mixture
3. Between two mixtures that differ in their paste pore structure due to varying *w/cm* and/or SCM contents

The first two conditions will result in a higher variability of test results thereby making specification compliance more difficult. The last condition can impact the proper assessment of mixtures for their potential for low chloride permeability. This is especially a problem if a lower permeability concrete had higher DOS than that of a concrete with a higher permeability. In addition, indications of concrete mixture characteristics for transport properties will be inconsistent with that based on RCPT. As stated earlier, RCPT test results have been correlated with chloride diffusion coefficient and RCPT is measured on vacuum saturated specimens.

Due to the varying conditioning procedures adopted by states or districts within a state for the same test, the same concrete mixture will produce different test results. This makes mixture development for specification compliance difficult.

Objective

This study evaluates current and proposed AASHTO and ASTM electrical-based test methods used as indicators of transport characteristics, using various specimen conditioning procedures. It provides comparisons between the various electrical measures as indicators of permeability and is intended to recommend standardized specimen conditioning procedures for the resistivity tests for reliable specification criteria.

The goal of this work is to establish a moisture conditioning procedure that results in:

1. A low single operator test variation

2. A statistically significant difference between resistivity results to differentiate between the permeability characteristics of different concrete mixtures and sensitive enough to determine this for similar mixtures with a small difference in *w/cm*
3. Classify concrete mixtures for permeability characteristics consistent with that based on RCPT
4. Variation in results that are not significantly impacted by air content ranges within typically used tolerance.
5. Identifying concrete mixtures that will provide good performance in service

This research project will help establish a simple specimen conditioning procedure for the resistivity test methods, relevant to estimation of FF, used to determine concrete's potential durability; it also supports the evolution to performance-based specifications that allow the producer to better optimize concrete mixtures for required performance. The study includes different concrete mixtures by varying mixture parameters such as *w/cm*, SCM type and content, and the effect of air entrainment.

This study will evaluate the impact of DOS, DOH, and leaching on the measured resistivity for a given mixture and how their impact varies with different mixture parameters. The study helps compare the DOS and resistivity of concrete test specimens using different moisture conditioning methods with DOS and resistivity of concrete specimens kept in simulated service conditions. This will help compare the resistivity measurements of mixtures with standardized conditioning methods in a laboratory with that in a structure.

EXPERIMENTAL PROGRAM

MATERIALS AND MIXTURES

Table 1 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 (II), Lot # 9116
- ASTM C989 slag cement (SL), Lot # 9270
- ASTM C618 Class F fly ash (FF), Lot # 9152
- ASTM C33 No. 57 crushed limestone coarse aggregate, Lot # 9100
- ASTM C33 natural sand with an FM=2.67, Lot # 9101
- ASTM C494 Type A water-reducing admixture, Lot # 9102
- ASTM C494 Type F high-range water-reducing admixture, Lot # 9103

Table 2 lists the concrete mixtures evaluated in this study. The first four mixtures are non-air-entrained concrete mixtures evaluated in Phase A. Phase A mixtures cover the range of expected permeability (as indicated by ASTM C1202) and include typical types and quantities of SCMs used in concrete. Paste quality as it impacts transport properties is varied by varying the *w/cm* and SCM type and content. These mixtures were selected to better understand the effect of paste pore structure (volume and tortuosity) on the DOS and resistivity, as well as the impact on these characteristics by the different conditioning procedures.

In Phase B, air entrained mixtures are in the process of being evaluated. These include 5 air-entrained concrete mixtures. Four of the mixtures, the same as the Phase A mixtures, are targeted for a moderate air content of 5%. One mixture with 50% slag cement at a *w/cm* of 0.40 is targeted at a higher air content of 8%. It is anticipated that air entrainment will result in a lower DOS at the end of conditioning and its impact on measured resistivity will be evaluated. This report discussed only results from Phase A.

Mixture designations were assigned by the *w/cm* followed by the SCM type used in the mixture (FA for fly ash, SL for slag cement). Mixtures without SCM use the designation "PC". Air-entrained concrete mixtures with moderate and high air contents have the suffix MA and HA, respectively. The fly ash mixture contained 25% fly ash by mass of cementitious materials; whereas the slag cement mixtures contained 50% slag cement. 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 with a dosage of 4 oz/cwt. of cementitious materials was used for all the mixtures. An ASTM C494 Type F admixture was used at a dosage level required by the slump.

EXPERIMENTAL PROCEDURES

Concrete mixtures were mixed in a revolving drum mixture in accordance with ASTM C192. A 3.8 ft^3 batch of concrete was prepared. Fresh concrete was tested for slump (C143), temperature (C1064), air content by the pressure method (C231), and density (C138). The gravimetric air content was calculated in accordance with ASTM C138. This was followed by casting 4x8 in. cylindrical specimens which were consolidated using external vibration on a vibration table and finished by 2 different operators. A total of 54 4x8 in. cylindrical specimens were cast as follows:

Four for measuring compressive strength at 28 and 56 days, with two specimens at each age.

21 for electrical tests with 7 conditions and 3 specimens per condition

10 for the DOS measurements (for 5 conditions)

Four for the "in service" measurements, and

Fifteen for supplementary testing by the Federal Highway Administration (FHWA).

Supplementary tests by FHWA included independent resistivity measurements, total 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 and DOH for the various 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 and to compare to the composition of extracted pore solution of these specimens. In addition, portions of the specimens tested by NRMCA were provided to FHWA for extraction of pore solution to measure composition and conductivity (resistivity).

The electrical tests evaluated included surface resistivity (SR), bulk resistivity (BR), RCPT, and bulk conductivity (BC). The SR and BR test methods were conducted in accordance with the draft ASTM standards. Typically, RCPT is measured as the charge passed over a 6h period. In the bulk conductivity test the current passing in the RCPT at 5-min is measured from which the conductivity is calculated. It is thereby a modified ASTM C1760 test using the ASTM C1202 equipment. Measurements were made on three 4x8 in. concrete cylinders, or slices of cylinders, for each condition and averaged for the results. Unless otherwise stated the cylindrical specimens were demolded 1 day after casting and tested at the stated age.

CONDITIONING PROCEDURES FOR THE ELECTRICAL TESTS

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

1. MRVS - 56-day curing in the moist room followed by vacuum saturation of the whole cylinder in accordance with ASTM C1202. This conditioning is expected 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 using a solution to specimen ratio by volume of 2:1 (3 4x8 s in a 5-gal bucket to reduce leaching as per the ASTM draft SR test method and Spragg et al. 2013). The DOS will depend on the type of mixture and alkali leaching into the curing solution is expected.
3. MR - 56-day curing in the moist room that conforms to ASTM C511.
4. SC – specimens were sealed and retained in the molds for 56-days. Specimens in the molds were capped with lids that were taped and the molds were double-wrapped in plastic bags. 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. This conditioning process is recommended as the preferred method to estimate the FF of concrete because it preserves the composition of the pore solution. 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. It is expected that this condition will have the lowest DOH compared to the other methods.
5. SCB – specimens were sealed in molds for 56-day following which they were demolded and immersed in lime-saturated simulated pore solution. The immersion solution is described in condition 6. The solution to specimen volume ratio was maintained at 4:1. It is expected that DOS and DOH will be higher than that for specimens subjected to the SC condition. It is expected that leaching would be negligible but may be evident if the pore solution composition is not similar to that of the immersion solution. For the SCB condition, SR and BR was measured once before immersing in the lime-saturated simulated pore 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 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 was based on that recommended to be adopted in the PEM standard. The

solution is intended to simulate an average pore solution composition to minimize alkali leaching. It is expected that leaching would be negligible but may be evident if the pore solution composition is not similar to that of the immersion solution. The level of DOS and DOH 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. It is expected that DOS and DOH 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.

To minimize the effects of surface drying on resistivity readings, specimens were removed in sets of 3 (for each conditioning environment). Each specimen was rolled on a wet towel first. SR was measured followed by BR of the whole cylinder. A 2 in. thick disk, referred to as S1, was cut from the top of the specimen. BR, RCPT and BC were measured on the disk specimen. Another 2 in. thick disk, referred to as S2, 2-4 in. from the top of the specimen was cut for conditions LW, MR, SC, and AC. Mass, BR, RCPT and BC were measured on the disk specimen. These specimens were subject to vacuum saturation and once again mass, BR, RCPT and BC were measured.

In addition to the 7 conditions, four specimens from each mixture were prepared to evaluate the resistivity and DOS in service conditions. Four cylindrical specimens from each mixture were cured in the moist room for 56 days. Disks of height 2-in. disks were cut from top and from bottom of the cylinders. These were placed in an undisturbed outdoor location on a raised platform exposed to the sun at the NRMCA laboratory in College Park, MD. Four disks from 2 cylinders with the top and bottom surface facing upwards were exposed to the environment. Four disks from the other 2 cylinders were similarly 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. The mass and BR of the specimens were measured periodically to estimate the change in DOS and transport properties of the different mixtures. Before taking the reading the surfaces were lightly cleaned while ensuring no loss of mass. The specimens were wiped with a wet cloth before taking the readings. Mixtures with a lower permeability are expected absorb less water in service conditions. This may be offset by a lower drying rate and the net effect may result in the average DOS of all the mixtures during service to be similar.

Estimating Degree of Saturation (DOS)

The DOS at the end of the conditioning period was measured for conditions LW, MR, SC, PS, and AC. At the end of the conditioning period the top 2-in. was cut from two 4x8-in. cylinders. The surface of the specimen was wiped with a wet cloth and the mass (W_C) was measured. The specimens were placed in an oven at 140°F and dried for 7 days. The dry mass (W_D) was measured. The specimens were vacuum saturated in accordance with ASTM C1202 to represent the 100% saturation level. The mass of the saturated specimen was measured (W_S). The DOS of the test specimens at the end of the conditioning period was calculated from the following equation:

$$\%DOS = \frac{(W_C - W_D)}{(W_S - W_D)} X100$$

For specimens subjected to the MRVS, the mass of the specimens was obtained after 56-days in the moist room and again after vacuum saturation. The DOS after vacuum saturation was estimated from the anticipated mass change for 100% saturation obtained from the other specimens. For the specimens subjected to SCB condition, the mass of the specimens was measured after the cylinders were removed from the molds at 56 days and after the immersion in the pore solution 7 days later. The DOS after the immersion was estimated based on the anticipated mass change for 100% saturation.

EXPERIMENTAL RESULTS AND DISCUSSIONS

For Phase A, the concrete mixture proportions and results of fresh concrete test and compressive strength are shown in Table 3. The 0.40SL mixture was repeated to measure the batch to batch variation of the test results. The air contents of all the Phase A non-air-entrained mixtures were determined to be between 1 and 2%. A portion of the results of the electrical tests on the four mixtures with the different conditioning procedures are reported in Table 4. The SR and BR are measurements on the 4 x 8-in specimens; the RCPT and BC are measured on 2-inch slices that were vacuum saturated after the end of the conditioning process except for Conditions SCB, and PS which were not vacuum saturated. The results are at an age of 56 days with 2 additional days for processing the RCPT and BC specimens. The age of the specimens subjected to AC condition was 28 days. The age of the SCB specimens was 56 + 7 days immersion in the simulated pore solution.

1. Fig. 1 shows the bulk resistivity averaged over for all conditions (except AC, and SC) plotted for the 4 mixtures. As expected the 0.55PC mixture had the lowest resistivity and the 0.40SL mixture had the highest resistivity. The 0.50SL mixture had slightly lower resistivity than the 0.40SL mixture but had higher resistivity than the 0.45FA mixture. The difference in the resistivity results between the two mixtures containing slag cement at 0.40 and 0.50 is not significant. The difference in compressive strength is relatively larger and can more easily discern the difference in *w/cm*. The 0.40 mixture has a higher cement content and a lower mixing water content thus resulting in a lower pore solution resistivity which will lower the resistivity of concrete. It is expected that the change in *w/cm* can be better discerned when comparing the formation factor – the resistivity divided by the pore solution resistivity. Further, if the increase in *w/cm* was only due to increased mixing water content, the newly proportioned 0.50 *w/cm* mixture would have had 3.9% higher paste volume (30.8% vs 26.9%). Past research (Obla et al. 2017; Obla et al. 2018) has shown that a higher paste volume will decrease resistivity. Therefore, from a quality control perspective, it should still be possible to distinguish a 0.50 from a 0.40 mixture if the difference was only due to an increase in mixing water content.
2. Fig. 2 shows the bulk resistivity of whole specimens and RCPT for specimens subjected to condition LW. There is a linear correlation between these results. The BR was measured on specimens that had not been subject to VS. Fig. 3 similarly plots the bulk conductivity and RCPT for all mixtures for the specimens subjected to condition LW. Since these are similar tests performed with the same equipment with the difference being the duration of measurement, as

expected there is a good linear correlation. Fig. 4 illustrates the ratio of SR to BR averaged for the 4 mixtures for each of 7 conditions. The ratio seems to range between 0.80 and 0.90. The SR should be the same as BR. The difference between these is being evaluated.

3. Fig. 5a-d plots the BR for each condition for all 4 mixtures. A relative comparison of the impact of the different conditioning procedures is provided in Table 5 for the BR results normalized to Condition LW. Additionally, this is averaged for the mixtures (2-4) containing SCMs). A general ranking of the results for the different conditions is: SCB < LW=PS < MR=MRVS < SC < AC. For a given mixture, DOS, leaching, and DOH that vary for each conditioning method affect the measured BR. Condition AC consistently gave the highest BR for the SCM mixtures and more significantly for the fly ash mixture. For specimens subjected to the AC condition, mixture 0.45FA mixture had a similar resistivity as the 0.40SL mixture whereas it was much lower for the specimens subjected to the other conditions. Fly ash typically reacts at a slower rate and reduces permeability with time. Condition AC represents a higher level of maturity of the cementitious system at 28 days than condition LW which is 56-days of lime water conditioning.
4. Table 6 reports the degree of saturation (DOS) level at the end of the conditioning period for all the mixtures and conditions. As expected, DOS is close to 100% for Condition AC and LW. In general, ranking of DOS based on the specimen conditioning was as follows: AC ~ LW > PS ~ MR > SCB > SC. As expected, Condition SC had the lowest DOS. For all conditions, slag cement mixtures had slightly lower DOS than the PC and FA mixtures. Since specimens at a lower DOS will have a higher measured BR at the same permeability the slag cement mixtures may have a slight advantage over the fly ash mixture. This can be ascertained when comparing the BR results before (Table 3) and after (Table 7) correcting for DOS. A DOS>100% is attributed to accuracy of measurements and testing, recognizing that a DOS difference of 1% represents a mass difference of about 0.35 g. Where a DOS>100% was measured, a DOS=100% was assumed, and used to correct the BR value in Table 7.
5. In Table 7 the measured BR for each condition is first corrected to a constant temperature of 77°F (Spragg et al. 2013) and a DOS of 100%. Equation 1 was used to correct the BR for DOS with an assumed value of n=3. For comparative purposes, the corrected BR for each condition is normalized to specimens subjected to condition LW. The normalized values are averaged for the 3 SCM mixtures in the last column. The differences in the corrected BR are primarily impacted by DOH and alkali leaching. Specimens subjected to condition AC had a measured BR on average 56% higher than those subjected to condition LW. This is likely due to the higher DOH of specimens subjected to condition AC. Specimens subjected to condition MR had a measured BR on average 13% higher than those subjected to condition LW. This is likely due to the higher leaching for condition MR which was confirmed by pore solution chemistry measurements carried out by FHWA. Specimens subjected to condition PS had a measured BR on average 7% lower than those subjected to condition LW, likely due to lesser leaching for condition PS which was also confirmed by pore solution chemistry measurements carried out by FHWA. Specimens subjected to conditions SC and SCB had a measured BR on average about 33% lower compared to those subjected to condition LW. There was a lower amount of leaching from these specimens (SC and SCB). but as observed for specimens subjected to condition PS the reduced leaching is unlikely to significantly reduce the measured BR. More likely the lower DOS during

the conditioning duration for SC and SCB contributed to a lower DOH which led to a poorer pore structure and hence a lower BR. The lower DOH of the SC and SCB specimens has also been experimentally confirmed by FHWA. It is understood that DOH of concrete starts decreasing below a DOS of 96% and ceases below 80%.

6. Table 8 reports the measured BR for specimens subjected to the various conditions after subsequently vacuum saturating a 2 in. thick disk specimen (2-4 in. from the top of the cylinder referred to as S2). The measured BR for specimens subjected to each condition is normalized to that of the specimens subjected to condition LW and the average value for the SCM mixtures is also indicated. Since after VS, the specimens are expected to be close at 100% saturation and the tests are performed at a constant temperature, relative values for the normalized BR can be compared to Table 7. The normalized BR for conditions MR, SC, AC are similar to those in Table 7. This validates the conclusions stated above about the impact of the conditioning methods on alkali leaching and DOH and the measured BR – when compared to Condition LW higher leaching for Condition MR results in higher resistivity; higher DOH for Condition AC results in higher resistivity; lower DOH for Condition SC results in lower resistivity.
7. Table 9 reports the measured coefficient of variation (COV) from replicate measurements on specimens of each mixture and conditioning method and then averaged for the four mixtures. BR (S1) is the COV results measured on a 2 in. thick disk specimen cut from the top of the cylinder. The BR was measured before VS for all conditions except MRVS. Variability of the various test methods were as follows: BR < SR < BR (S1) < BC < RCPT. The 2.4% average COV observed for BR is similar to the ASTM C39 strength test and is 1/4th the variability of the commonly used RCPT. BR has lower variation than SR. It is useful to perform BR on the whole specimen as opposed to the top 2 in. thick disk which tends to induce more variation. Among the conditions, conditioning specimens by SCB seems to have a higher COV in all test methods except BR. Other conditions are similar in variation.
8. Table 10 shows the impact of VS on the COV of BR of a 2 in. thick disk specimen (S2) for various conditions. This illustrates that VS did not reduce testing variability for BR for the mixtures evaluated.
9. Fig. 6 compares the measured BR of specimens subjected to the different conditioning methods for the four mixtures. For the PC mixtures the differences attributed to the conditioning methods are small. The differences are larger for the mixtures containing SCMs. Regardless of the conditioning method, there is a clear difference in measured BR between the 0.55PC and the 0.45FA25 mixture. The 0.40SL mixture had marginally higher resistivity than the 0.50SL mixture: between 2% and 12% higher (average 6%) for all conditions except the SCB which was 24% higher. From these results, resistivity cannot effectively distinguish mixtures with a *w/cm* of 0.40 or 0.50. In comparison the 28-day strength for the 0.40SL mixture was 39% higher than that of the 0.50SL mixture.
10. Table 11 reports the ratio of BR measured for the top 2 in. thick disk to that measured on the full 4x8-in. cylindrical specimen. Conditions MRVS, LW, MR, AC, and SCB had average ratios between 0.87 and 0.98. The BR can be measured on a 2 in. thick specimen (possibly if performing the RCPT test) or the full 4x8 in. cylindrical specimen and the results will be similar. The measured BR on the disk specimen was marginally lower. Condition SC had an average ratio

of 0.81. For this condition, the disk specimen probably had a higher DOS than the full cylindrical specimen due to the use of water during cutting the disk specimen.

11. Table 12 reports the ratio of the measured BR for a disk 2-4 in. from the top of the specimen to that measured on the top 2 in. specimen. Theoretically, it has been stated that due to effect of bleeding, concrete tends to be more porous near the top surface and so BR should be lower near the top. No noticeable difference is observed in the BR test results.
12. Table 13a-c reports the ratio of measured BR, RCPT, and BC after VS to that measured before VS. of a 2 in. thick disk specimen. VS is expected to increase DOS and hence should reduce BR and increase RCPT and BC. This is observed for Condition SC where the extent of the reduction in BR is similar to the increase in RCPT and BC. However, the ratios are very close to 1 for conditions LW, MR, and AC. As seen in Table 6 these conditions had a DOS close to 100% even before VS which is typical of non-air-entrained concrete mixtures. When concrete mixtures are air-entrained, the DOS is likely to be lower than 100% and therefore the effect of saturation resulting from VS on the electrical tests is expected to be more evident.
13. Table 14 reports the electrical test results of the replicate batches. Mixture 0.40SL was batched on two different weeks and conditions MRVS, LW, and SC were evaluated with both full cylinders and disk specimens tested. The disk specimens were also subject to VS. On average SR test results of the repeat batch were 11% higher while BR test results (whole cylinders) on average were 15% higher. After VS the BR, of the disk specimens of the repeat batches were 17% higher while the RCPT, and BC were 21%, and 17% lower. The compressive strength of the repeat batch was 5.4% higher. In summary, batch to batch variation seems to impact compressive strength the least, followed by resistivity, BC and RCPT results.
14. Table 15 shows the mass and resistivity change for Condition MR after VS for the whole cylinder and a 2 in. thick disk specimen. A 0.02% mass change corresponds to a mass change of 0.2g of a disk specimen and 0.8g of a whole cylinder. The mass change results show that the disk specimens had a slightly higher mass gain than the whole cylinder. As discussed earlier, since the DOS was close to 100% for all specimens even before VS the changes in resistivity are minor. If the DOS had been lower to begin with (such as in air-entrained mixtures) VS might have resulted in higher DOS of the disk specimens as compared to the whole cylinders as the disks offer a higher surface area to volume ratio and hence it should be easier for water to penetrate and saturate the specimen.
15. Figs. 7a-b show the results obtained thus far from long-term measurements of DOS of disk specimens subject to out-door external (referred to as E) exposure and the 70F room internal (referred to as I) exposure. In the plot, “T” refers to the top finished surface of the cylindrical specimen subject to exposure while “B” refers to the bottom cast surface of the cylinder subject to exposure. So, E (T) refers to the finished surface of a specimen exposed outdoors. As expected, DOS of “E” exposure for all mixtures tends to vary whereas DOS of “I” exposure shows a steady decrease as the specimens dried. For the “I” exposure, DOS of “T” specimens were slightly lower than the “B” specimens suggesting increased drying particularly for the 0.45FA25 mixture. For the “E” exposure there is no difference between the DOS of “T” and “B” specimens. Even though all mixtures started at a DOS between 94% and 99%, after about 9 months of external exposure the 0.55PC mixture has a DOS that was 40% lower while both the slag

mixtures had DOS that was lower by just 12%. The fly ash mixture had a DOS that was 27% lower. In absolute terms starting from an approximately 1000 g disk specimen the PC mixture had lost 18 g, the fly ash mix lost 9.6 g, while the SL mixtures had lost only 3.6 g. For the internally exposed specimens the results are similar. The PC and the FA mixture had a DOS that was 41% lower while the slag mixtures had a DOS that was on average 21% lower. Perhaps the slag cement mixture with its refined pore structure can retain moisture better and is therefore less prone to drying. As Fig. 8 shows when the climate changed, the slag cement mixtures appear to have a smaller change in DOS when compared to the PC and FA mixtures. 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 maybe 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. Concrete that is at a higher level of saturation tend to be prone to greater damage due to freezing and thawing such as scaling for example. While the differences in measured DOS in service between the mixtures are interesting, it deserves a more careful study. The specimens should be cast preferably on the same day and exposed at the same time after a given period of moist curing. In this study, the mixtures were cast one week apart and subject to exposure after 56 days of moist curing. The impact of different DOS levels on chloride ingress and freeze thaw resistance of concrete should also be measured.

For each mixture, the measured BR and DOS is plotted in Fig. 8a-d. It is noted that the measured BR matches the measured DOS, i.e. when DOS increases BR decreases and vice-versa. For all mixtures, BR increased with age even when the measurements were taken after wet weather. After about 7 months, fly ash mixtures had the lowest BR among all 4 mixtures. However, its DOS was also lower than the slag cement mixtures and hence the BR has to be corrected for DOS to make appropriate comparisons. The measurements will be continued till 1 year of exposure.

SUMMARY

The following summary is based on the mixtures and conditions evaluated in Phase A:

1. Unlike the strength test, the resistivity test, regardless of the conditions evaluated, cannot detect a change in *w/cm* of 0.10 when the paste volume is kept constant between the mixtures.
2. Resistivity test results correlate well with RCPT test results and classified mixtures in the same order.
3. Surface resistivity test results are about 10-20% lower than bulk resistivity test results.
4. At the end of conditioning the general ranking of the bulk resistivity test results: SCB < LW=PS < MR=MRVS < SC < AC. Resistivity of concrete specimens subject to condition MR was 13% higher than condition LW. Resistivity of concrete specimens subject to condition AC was much higher than condition LW due to the higher DOH. Condition AC is appropriate

for fly ash mixtures due to their slower reactivity. Condition PS had very similar resistivity as condition LW even after correcting for DOS. Conditions SC and SCB gave much lower bulk resistivity when corrected for their lower DOS. This is due to their lower DOH.

5. The measured DOS was close to 100% for non-air-entrained concrete mixtures after conditioning except for condition SC. Therefore, vacuum saturation did not increase DOS and so thus did not impact the resistivity.
6. Variability of the various test methods were as follows: BR < SR < BR (S1) < BC < RCPT. Bulk resistivity of the whole specimen had a COV similar to that of the compressive strength test. Among the different conditions there was little difference except for condition SCB which appeared to have higher variation.
7. The use of vacuum saturation did not improve the precision of the resistivity test results.
8. There is no need to cut 2 in. thick disk specimens to measure bulk resistivity. Using the whole 8 in. specimen resulted in lower variation. Disk specimens gave similar resistivity as whole cylindrical specimens as long as appropriate correction factors are used.
9. There was no difference in measured BR of the top and middle disk specimens.
10. Replicate batches showed higher difference in SR, BR test results than strength, but lower than RCPT.
11. The DOS in service varied between concrete mixtures. Varying DOS can impact chloride ingress and freeze thaw resistance. This aspect needs to be studied in depth.

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Table 1 Chemical Characteristics Of Cementitious Materials

Material	Type II	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 2 Proposed 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
0.55PCMA	0.55 PC	5	>3000
0.45FAMA	0.45 25% fly ash	5	1000-2000
0.40SLMA	0.40 50% slag cement	5	<1000
0.50SLMA	0.50 50% slag cement	5	<1000
0.40SLHA	0.40 50% slag cement	8	<1000

Table 3 Mix Proportions and Test Results

Mix Designation	**0.55PC**	**0.45FA**	**0.40SL**	**0.40SLR**	**0.50SL**
Yield Adjusted Proportions					
Total Cementitious	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 1/2	8	6 3/4	6	7 3/4
ASTM C138, Density, lb/ft^3	147.8	149.0	149.8	150.6	148.6
ASTM C138, Gravimetric Air, %	1.6	1.4	1.7	1.2	1.3
ASTM C231, Pressure Air, %	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

Table 4 Resistivity, RCPT, and Bulk Conductivity Test Results

	0.55PC				**0.45FA**				**0.40SL**				**0.50SL**			
Condition	SR, Ω-m	BR, Ω-m	RCPT, Coulombs	BC, mS/m	SR, Ω-m	BR, Ω-m	RCPT, Coulombs	BC, mS/m	SR, Ω-m	BR, Ω-m	RCPT, Coulombs	BC, mS/m	SR, Ω-m	BR, Ω-m	RCPT, Coulombs	BC, mS/m
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
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
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
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

Table 5 Bulk Resistivity Normalized to Condition LW

	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 6 Impact of Conditioning on the Measured Degree of Saturation

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
AC	107%	103%	92%	104%	**100%**
LW	103%	103%	98%	97%	**99%**
PS	100%	102%	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 7 Bulk Resistivity Corrected to Constant Temperature (77°F) and DOS (100%) with the last Column Showing Values Normalized to Condition LW

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
AC	48	269	209	243	**1.56**
MR	48	151	202	173	**1.13**
LW	41	141	166	159	**1.00**
PS	36	135	156	141	**0.93**
SCB	22	95	112	99	**0.66**
SC	23	98	106	114	**0.68**

Table 8 Bulk Resistivity of 2 in. disk Specimen after Vacuum Saturation After Conditioning with the last Column Showing Values Normalized to Condition LW

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
AC	46	267	242	223	**1.49**
MR	55	161	218	190	**1.13**
LW	42	142	186	174	**1.00**
SC	37	99	134	105	**0.67**

Table 9 Measured Coefficient of Variation (averaged over 4 mixtures) of the Various Tests and Conditions

	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%**

Table 10 Impact of Vacuum Saturation on the Measured Coefficient of Variation of Bulk Resistivity

	BR (before VS)	BR (after VS)
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%**

Table 11 Ratio of Measured BR of Top 2 in. Disk Specimen to the Whole Specimen

	0.55PC	0.45FA	0.40SL	0.50SL	Average (SCM mixtures)
MRVS	1.07	0.93	0.94	0.86	0.91
LW	1.02	0.98	1.00	0.96	0.98
MR	1.00	1.02	0.97	0.92	0.97
SC	0.90	0.82	0.85	0.75	0.81
SCB	0.79	0.94	0.93	0.93	0.93
PS	1.00	0.89	0.90	0.82	0.87
AC	1.04	0.91	0.95	0.92	0.93
	1.03	0.96	0.96	0.92	

Table 12 Ratio of Measured BR of Disk (2-4 in. from the Top) to the Top 2 in. Disk Specimen

	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 13a-c Ratio of Measured Electrical Property After VS to Before VS (a) Bulk Resistivity; (b) RCPT; (c) Bulk Conductivity

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
LW	N/A	1.02	1.08	0.99	1.03
MR	1.13	1.02	1.04	0.96	1.01
SC	0.93	0.61	0.64	0.59	0.61
AC	1.01	1.03	0.95	0.99	0.99

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
LW	0.96	0.96	1.09	0.94	1.00
MR	0.96	1.08	1.00	1.08	1.05
SC	1.51	1.48	1.39	1.49	1.45
AC	1.02	0.88	1.09	1.03	1.00

	0.55PC	**0.45FA**	**0.40SL**	**0.50SL**	**Average (SCM mixtures)**
LW	0.96	0.93	1.01	0.95	0.96
MR	1.12	1.01	0.89	1.10	1.00
SC	1.32	1.51	1.30	1.47	1.42
AC	1.05	0.91	1.09	1.14	1.05

Table 14 Change in Measured Electrical Test Results of Whole and Disk Specimens due to Rebatching Mixture 0.40SL

Condition	**SR**	**BR**	**BR (S1)**	**RCPT**	**BC**
MRVS	1.12	1.14	1.14	0.8	0.86
LW	1.14	1.18	1.17	0.74	0.76
SC	1.09	1.12	1.19	0.84	0.86

Table 15 Impact of VS of a whole Cylinder Vs a 2 in. Disk Specimen

	BR change		**Mass change**	
	Whole	**Disk**	**Whole**	**Disk**
0.55PC	9.5%	13.5%	0.02%	0.02%
0.45FA	1.7%	2.1%	0.00%	0.08%
0.40SL	4.8%	4.4%	0.02%	0.06%
0.50SL	2.4%	-3.7%	0.00%	0.10%

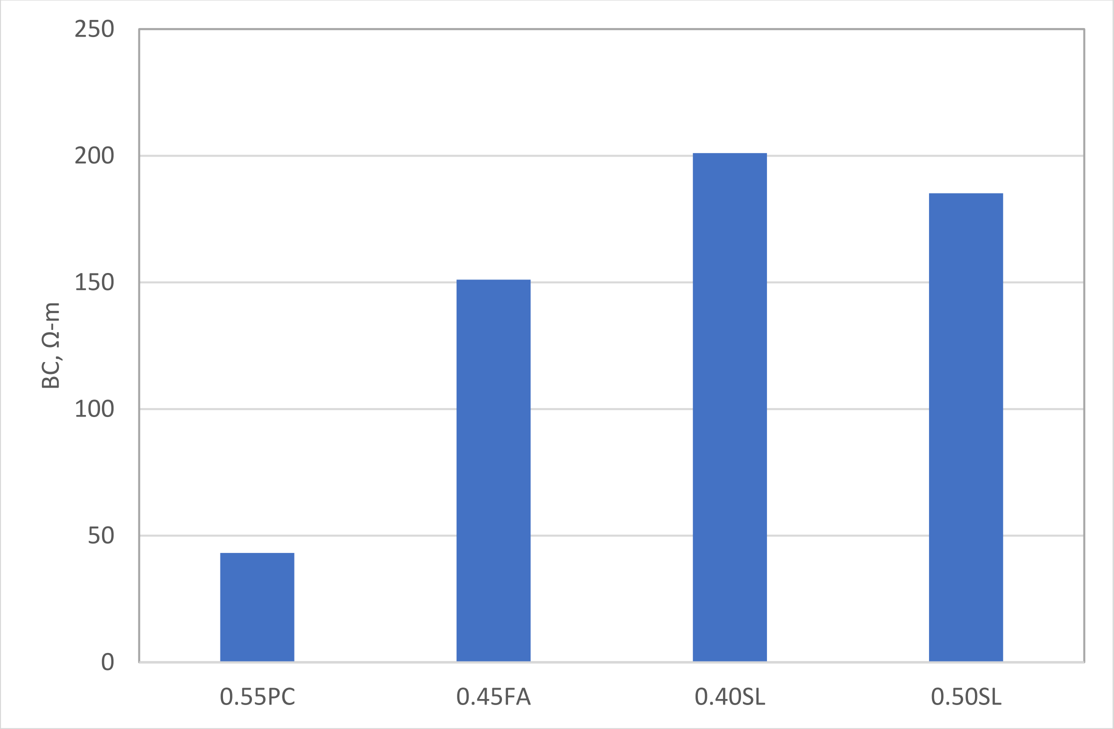


Fig.1. Bulk Resistivity Averaged over all Conditions Except SC and AC

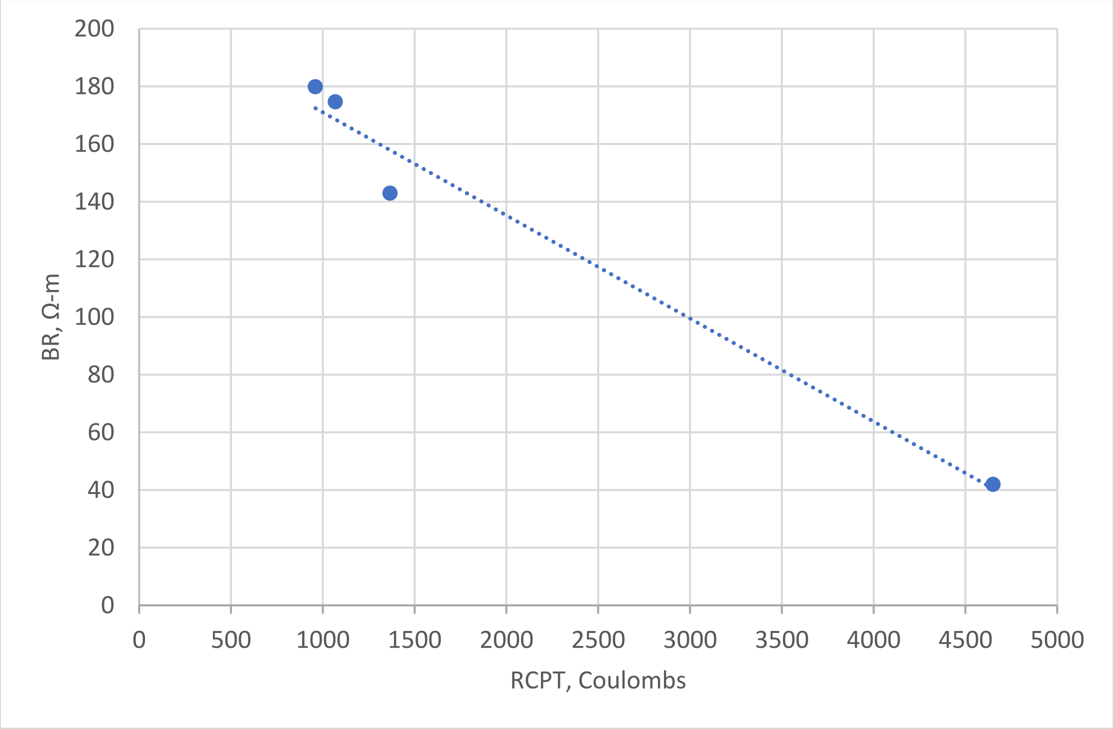


Fig. 2. Bulk Resistivity and RCPT results after 56 days of Lime Water Conditioning

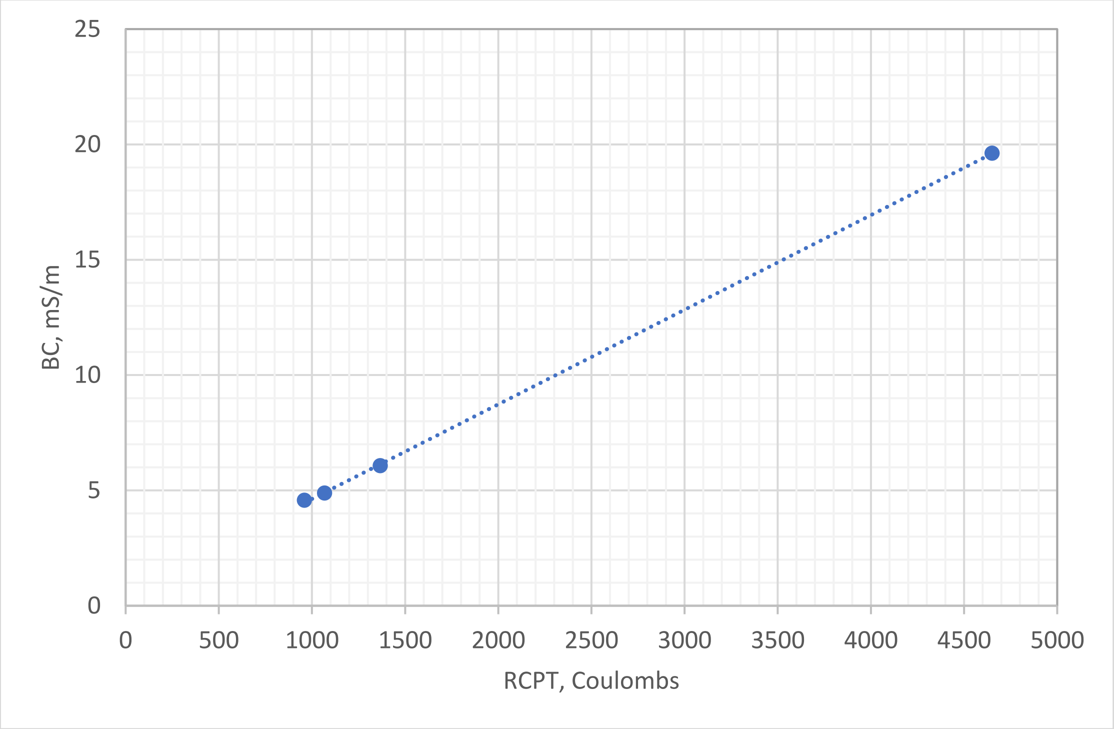


Fig. 3. Bulk Conductivity (Modified ASTM C1760) and RCPT results after 56 days of Lime Water Conditioning

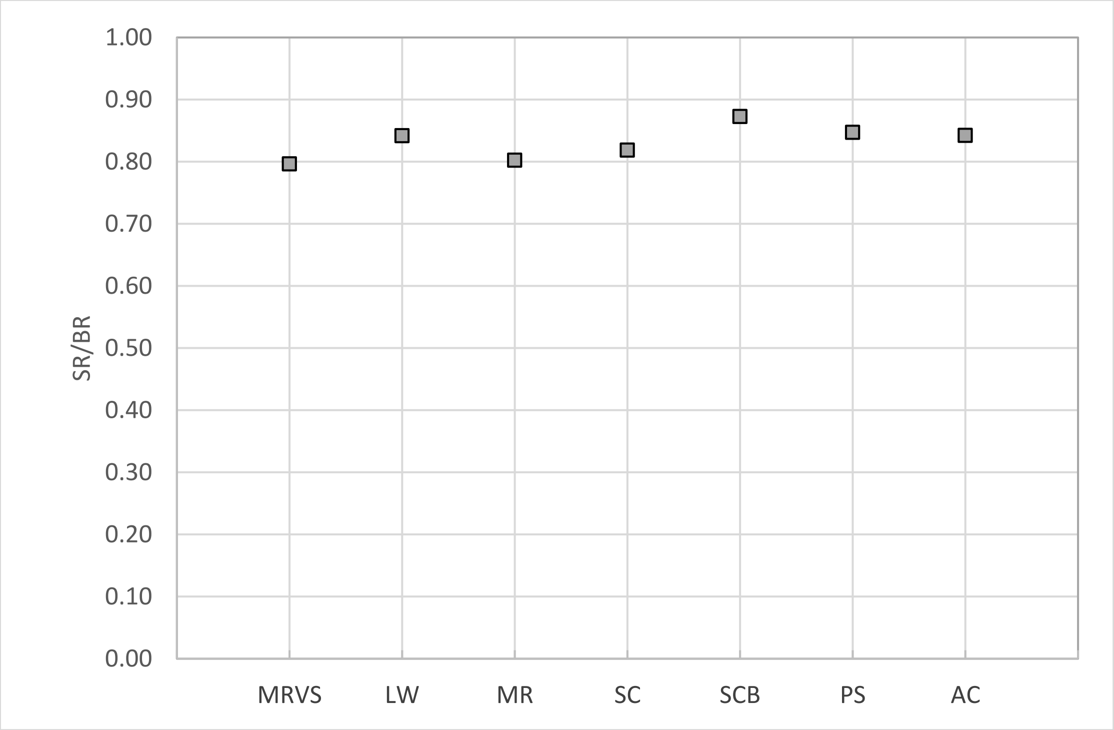
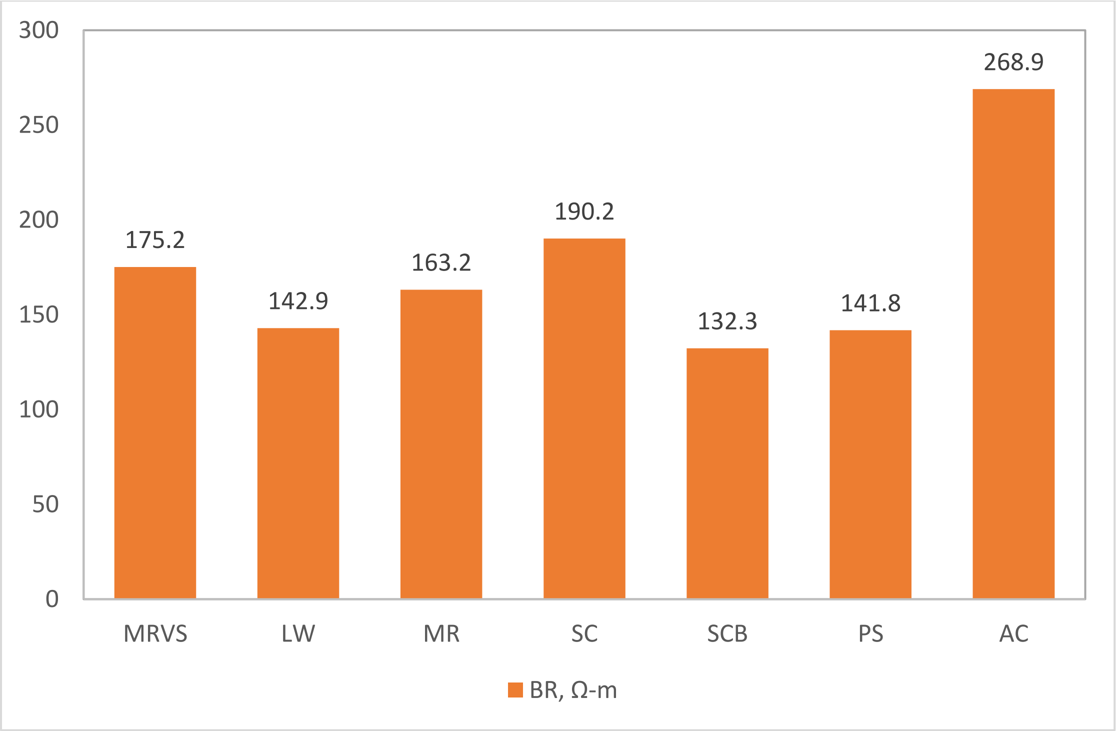


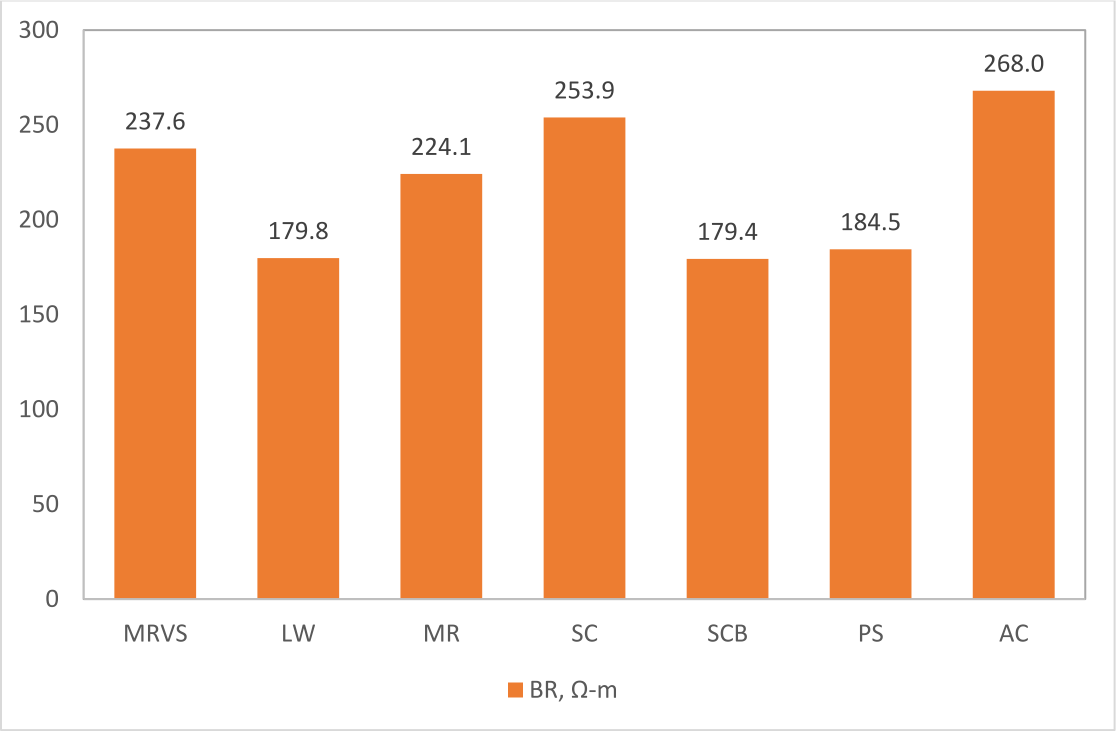
Fig.4. Ratio of Surface to Bulk Resistivity Averaged Over the 4 Mixtures


60
50
40
30
20
10
0
52.9
41.9
50.6
44.4
32.6
38.0
47.6
MRVS
LW
MR
SC
SCB
PS
AC
BR, Ω-m

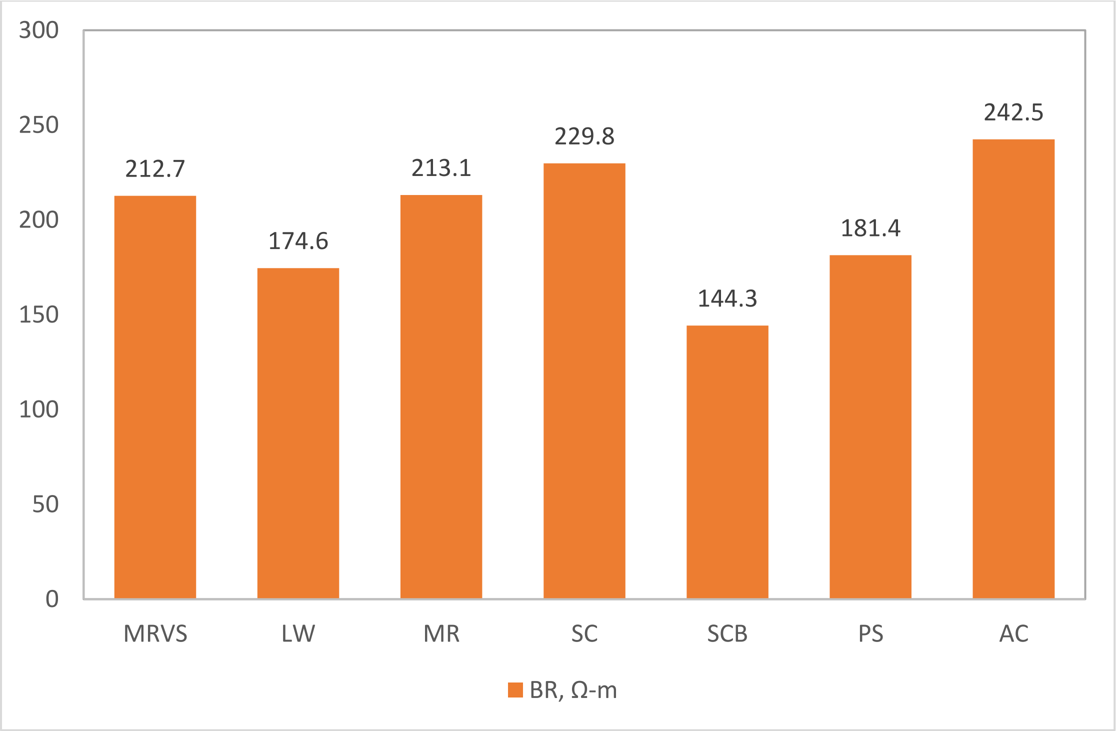
(a)


300
250
200
150
100
50
0
175.2
142.9
163.2
190.2
132.3
141.8
268.9
MRVS
LW
MR
SC
SCB
PS
AC
BR, Ω-m

(b)



(c)



(d)

Figure 5. BR of (a) 0.55PC (b) 0.45PC (c) 0.40SL50 (d) 0.50SL50 for all Conditions

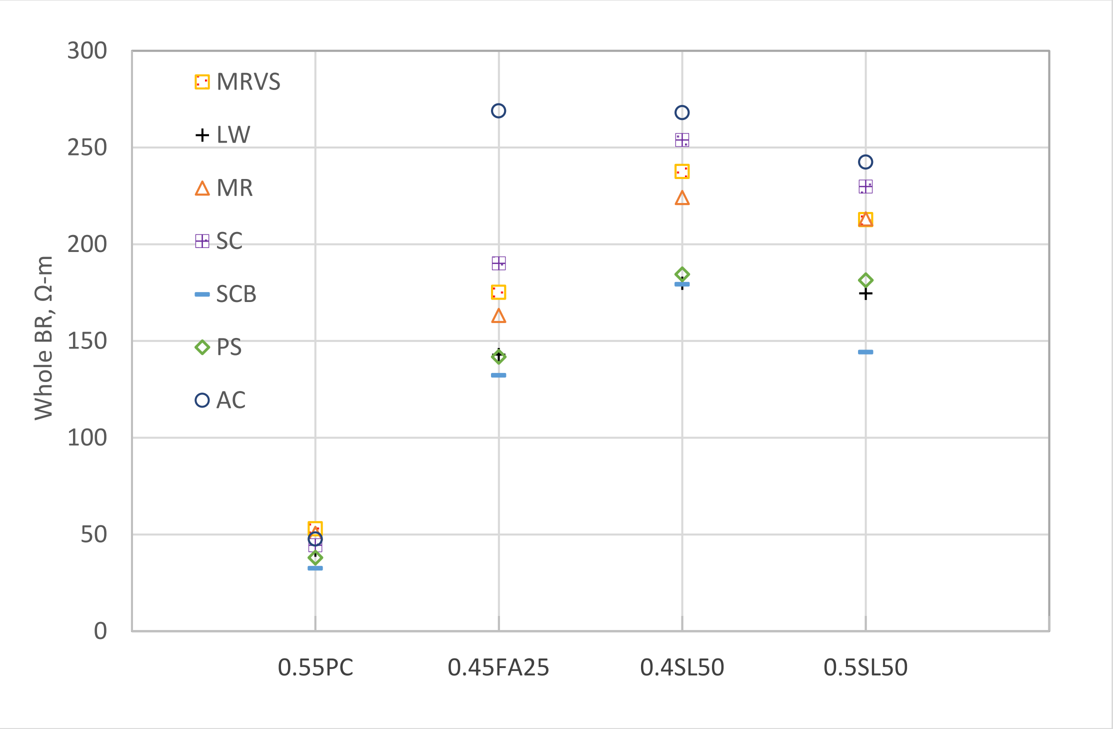
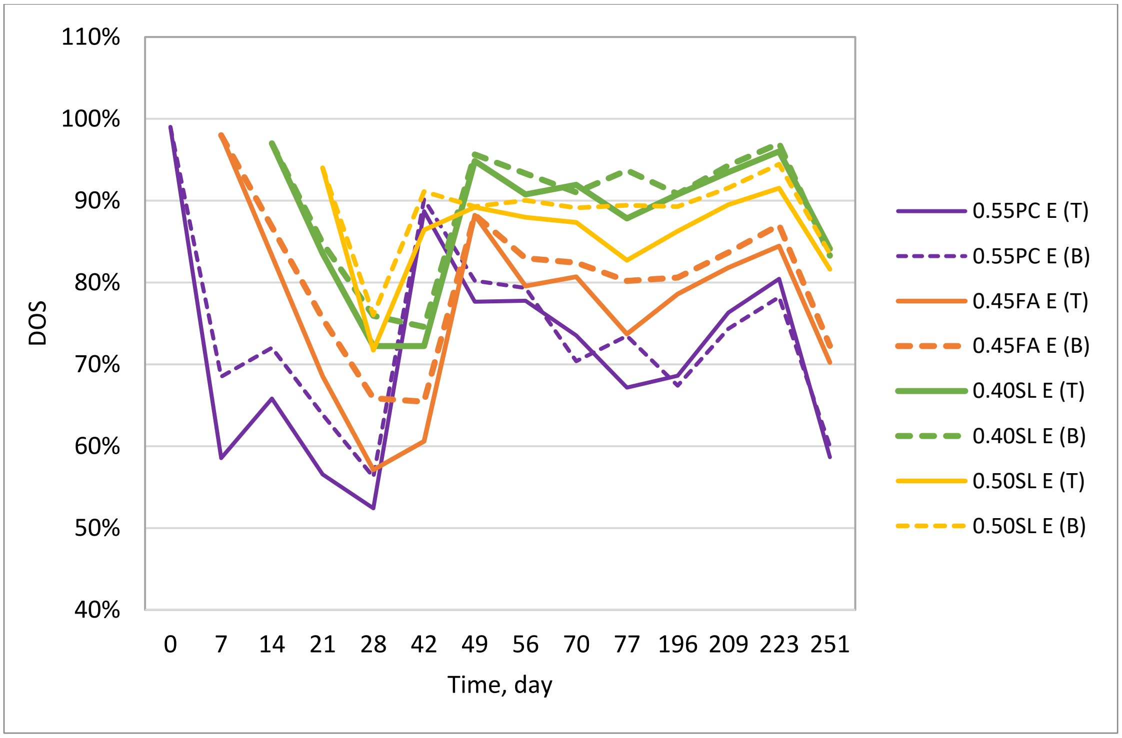
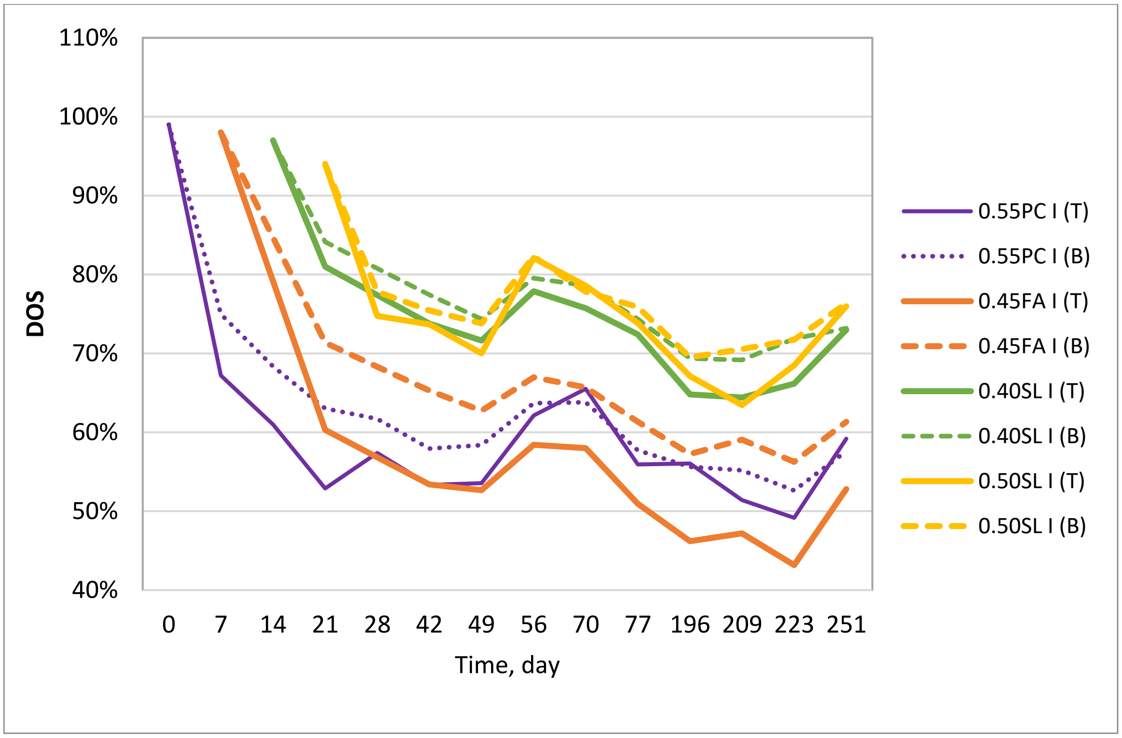


Fig. 6. Measured Bulk Resistivity of Various Conditions and Mixtures

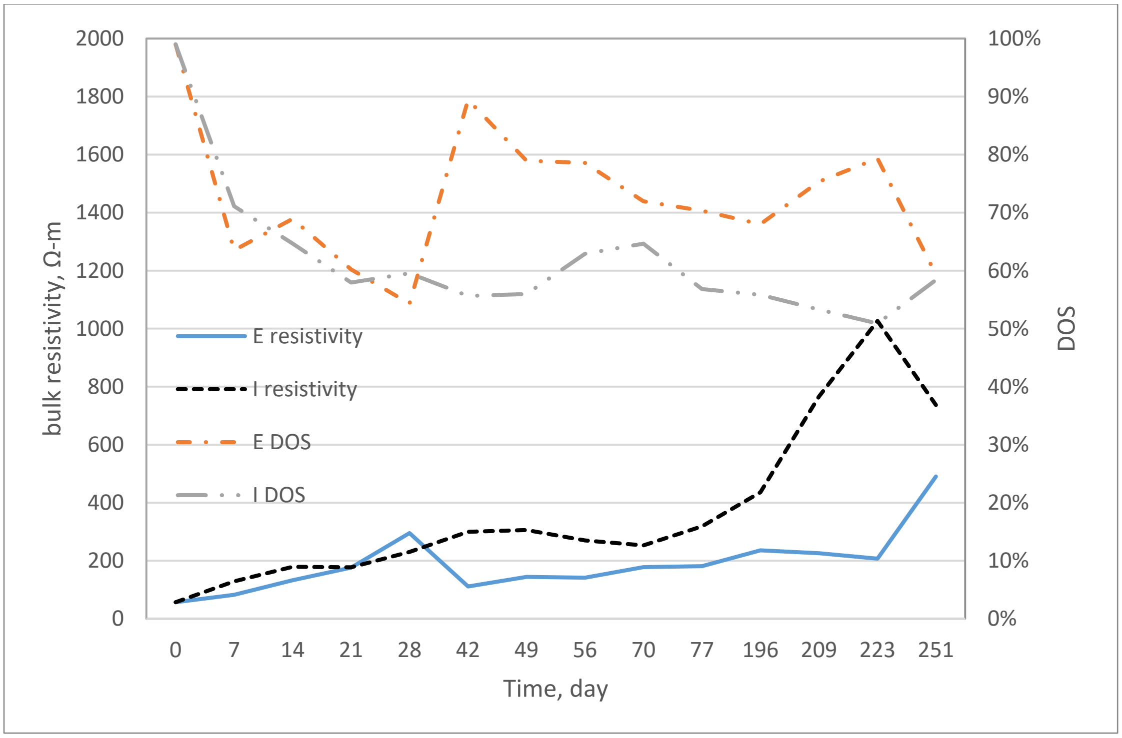


(a)

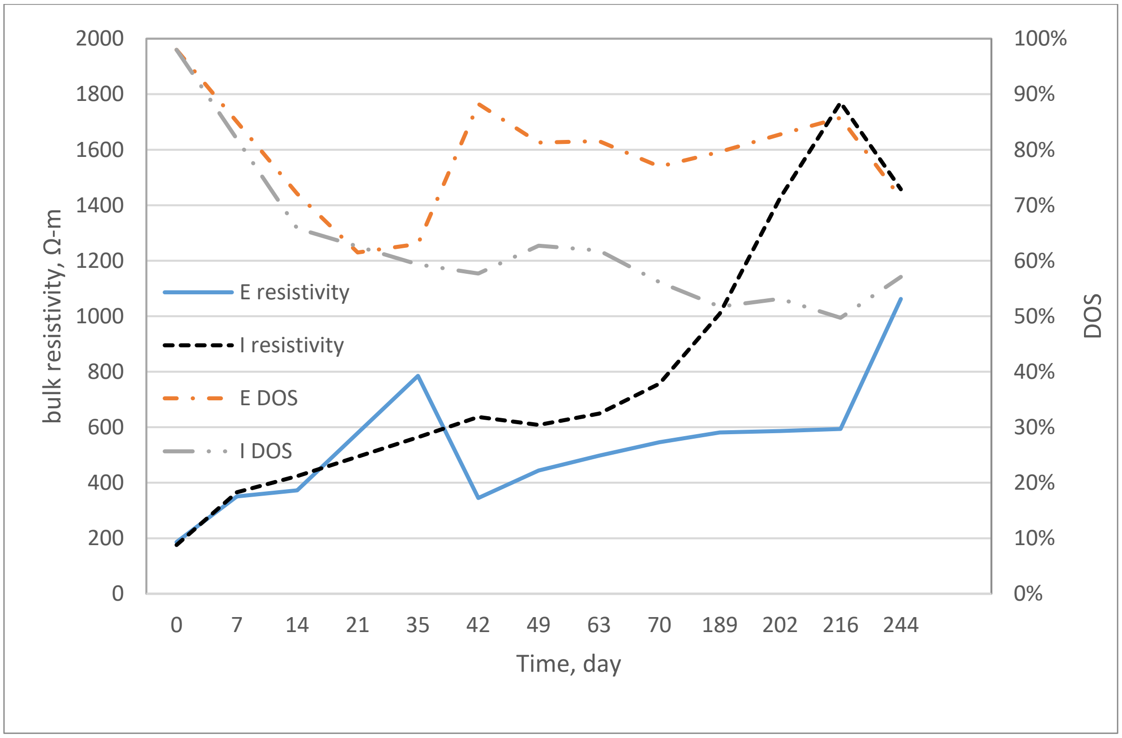


(b)

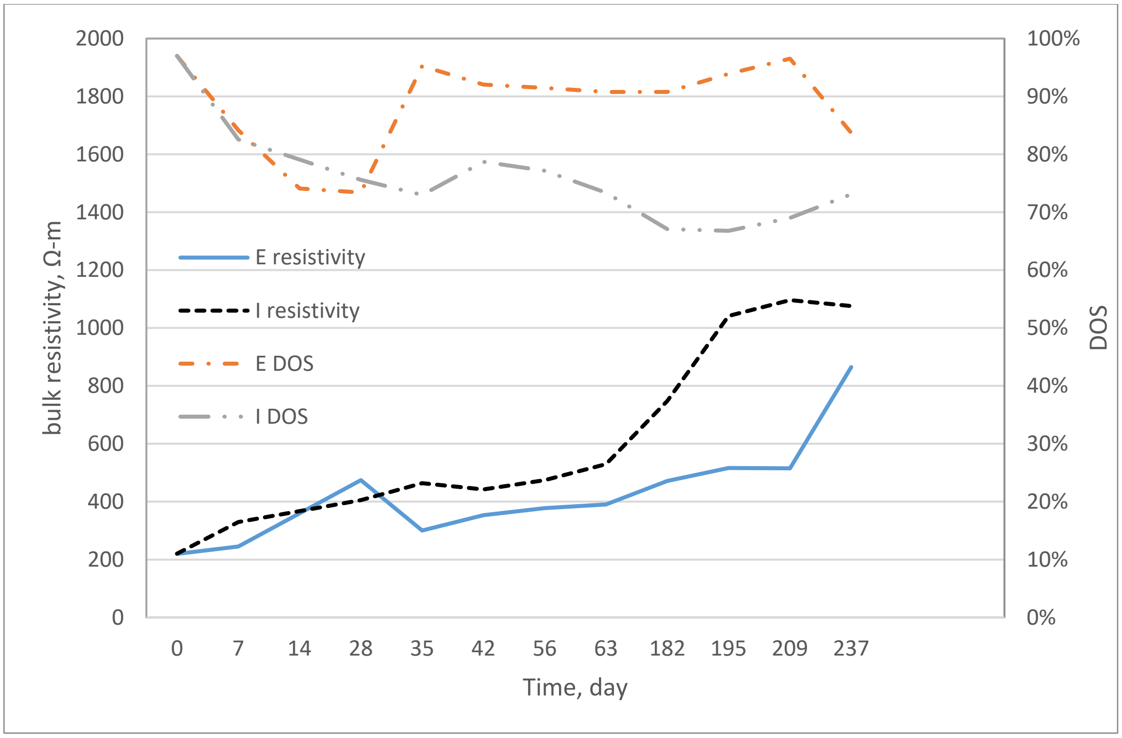
Fig. 7a-b. Change in DOS of Disk Specimens Subject to Exposure (a) Outdoor (b) Indoor


2000
1800
1600
1400
1200
1000
800
600
400
200
0
bulk resistivity, Ω-m
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
DOS
E resistivity
I resistivity
E DOS
I DOS
0
7
14
21
28
42
49
56
70
77
196
209
223
251
Time, day

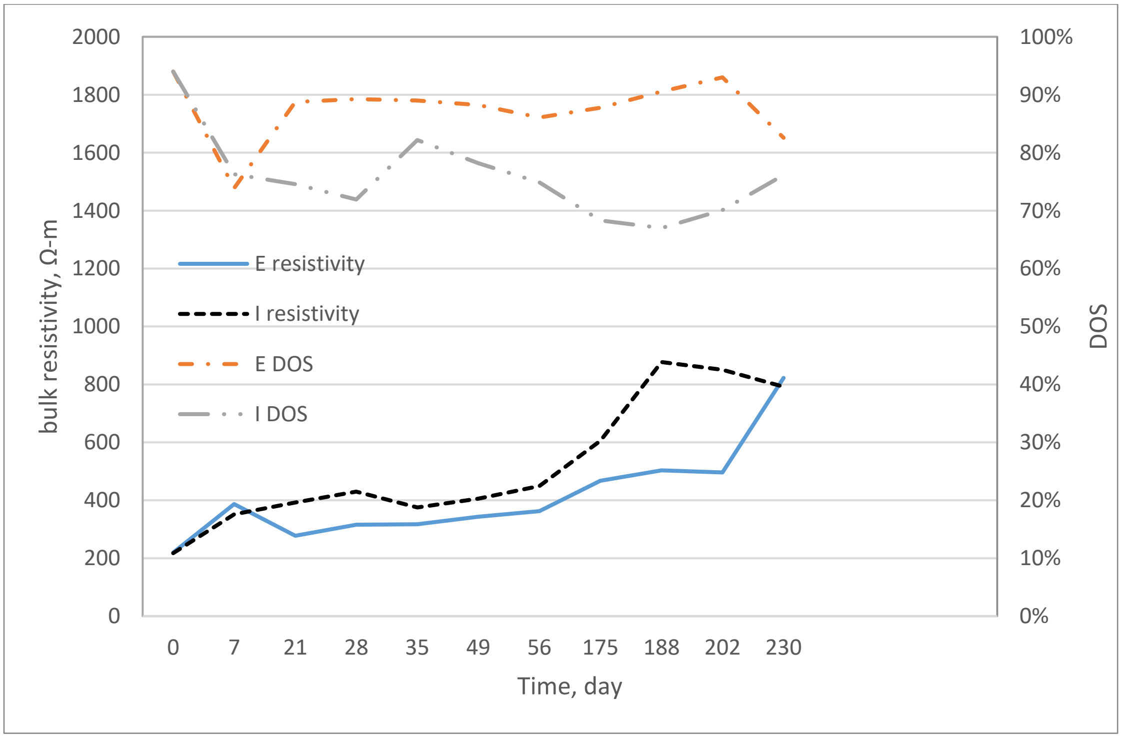
(a)


2000
1800
1600
1400
1200
1000
800
600
400
200
0
bulk resistivity, Ω-m
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
DOS
E resistivity
I resistivity
E DOS
I DOS
0
7
14
21
35
42
49
63
70
189
202
216
244
Time, day

(b)



(c)



(d)

Fig. 8a-d. Change in DOS and BR of Disk Specimens Subject to Outdoor and Indoor Exposures (A) 0.55PC (b) 0.45FA25 (c) 0.40SL50 (d) 0.50SL50