SOUTHERN PLAINS
TRANSPORTATION CENTER

Surface Resistivity Testing for Quality Control of Concrete Mixtures

Julie Ann Hartell, Ph.D.
Cody Shults

SPTC17.1-07-F

Southern Plains Transportation Center
201 Stephenson Parkway, Suite 4200
The University of Oklahoma
Norman, Oklahoma 73019

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Technical Report Documentation Page

1. REPORT NO. SPTC 17.1-07	2. GOVERNMENT ACCESSION NO.	3. RECIPIENTS CATALOG NO.
4. TITLE AND SUBTITLE Surface Resistivity Testing for Quality Control of Concrete Mixtures		5. REPORT DATE December 30, 2018 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Hartell, Julie Ann; Shults, Cody		8. PERFORMING ORGANIZATION REPORT
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Civil and Environmental Engineering Oklahoma State University 207 Engineering South Stillwater, OK 74078		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 1-570968 / G10001773
12. SPONSORING AGENCY NAME AND ADDRESS Southern Plains Transportation Center 201 Stephenson Pkwy, Suite 4200 The University of Oklahoma Norman, OK 73019		13. TYPE OF REPORT AND PERIOD COVERED Final October 2017 – September 2018 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTEs		

16. ABSTRACT

The purpose of this study is to investigate the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures. The methodology proposed will enable the development of a method based on resistivity criteria to identify the water-to-cement ratio of a given mixture whether the mixture contains a certain type of supplementary cementitious material. The objectives of the experimental study are to perform an experimental parametric investigation to determine the time-resistivity behavior of typical concrete mixtures used in pavement and infrastructure construction and determining the efficacy of resistivity testing in differentiating key mixture components. It was found that resistivity testing is sensitive to water-to-cement ratio, with some exceptions, and sensitive to supplementary cementitious replacement. The preliminary results will aid in the development of a new quality control and assurance criteria for concrete mixture approval in addition to currently used test methods and specifications.

17. KEY WORDS Concrete, Resistivity, Silica Fume, Blast Furnace Slag, Portland Cement		18. DISTRIBUTION STATEMENT No restrictions. This publication is available at www.sptc.org and from the NTIS.	
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 50	22. PRICE

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgements

The authors would like to thank the Southern Plains Transportation Center for providing funding to carry-out this research project. The authors would like to thank the dedication of OSU research assistants Evan Karunaratne, Hang Zeng, Dakota Brewster, Manuel Jimenez, James Jurgens, and Rebecca Dempewolf for their help in research activities.

SURFACE RESISTIVITY TESTING FOR QUALITY CONTROL OF CONCRETE MIXTURES

Final Report

December 2018

Julie Ann Hartell, Ph.D., Assistant Professor

Cody Shults, Graduate Research Assistant

Southern Plains Transportation Center

201 Stephenson Pkwy, Suite 4200

The University of Oklahoma

Norman, OK 73019

Table of Contents

List of Figures

List of Tables

Executive Summary

Several properties of fresh and hardened concrete are routinely tested to verify the quality of the construction material indicative of certain mixture ingredients or properties; however, there is still a level of uncertainty when it comes to validating water-to-cement ratio (w/c) or the presence of beneficial supplementary cementitious materials. Both these parameters are prescribed to attain a required level of durability in accordance with an exposure class. Thus far, there is no simple utilitarian test method which can assess such parameters within a routine quality control and assurance program.

The purpose of this study is to investigate the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures. The methodology proposed will enable the development of a method based on resistivity criteria to identify the water-to-cement ratio of a given mixture whether the mixture contains a certain type of supplementary cementitious material. This preliminary study will aid in the development of a new quality control and assurance criteria for concrete mixture approval in addition to currently used test methods and specifications. This would allow infrastructure owners and stakeholders to produce high quality and durable concrete. The objectives of the experimental study are to perform an experimental parametric investigation to determine the time-resistivity behavior of typical concrete mixtures used in pavement and infrastructure construction and determining the efficacy of resistivity testing in differentiating key mixture components.

1 INTRODUCTION

Several properties of fresh and hardened concrete are routinely tested to verify the quality of the construction material indicative of certain mixture ingredients or properties; however, there is still a level of uncertainty when it comes to validating water-to-cement ratio (w/c) or the presence of beneficial supplementary cementitious materials. Both these parameters are prescribed to attain a required level of durability in accordance with an exposure class. Thus far, there is no simple utilitarian test method which can assess such parameters within a routine quality assurance and control plan.

Gulrez and Hartell investigated the problematic and determined a preliminary simple method based on resistivity properties of concrete for mixture containing no supplementary cementitious materials and a Class-C fly ash. The method could be used as part of a quality control and quality assurance program to validate the actual mixture design parameters of concrete poured during construction. The test method is based on surface resistivity testing which has the added value of being low-cost, user-friendly, quick and non-destructive. [1]

Figure 1-1 shows the instrument (resistivity meter) used for this study along with its test principle. The test method is based on the Wenner probe method initially developed for geotechnical purposes. First, the four water saturated probes are placed on the surface of a concrete cylinder (along its longitudinal axis). The two outer probes produce a small alternating current traveling through the concrete medium (Figure 1-1). Meanwhile, the two inner probes connected to a voltmeter, measure the voltage response to current flow. [2] The measuring device will display the apparent resistance of the concrete cylinder tested. It is determined from equation 1 obtained from the measured voltage and knowledge of current amplitude, probe spacing, and specimen dimensions. To determine the true resistivity of the concrete, the value recorded can be factorized to compensate for specimen geometry by multiplying the value with a factor based on a ratio of the sample's cross-sectional area to its length [3].

$$\rho = \frac{2\pi sV}{I} \quad \text{(Eq. 1)}$$

Where,

ρ: apparent resistivity (ohm-cm)

S: spacing between probes (cm)

V: measured voltage (volts)

I: amplitude of alternating current (amps)

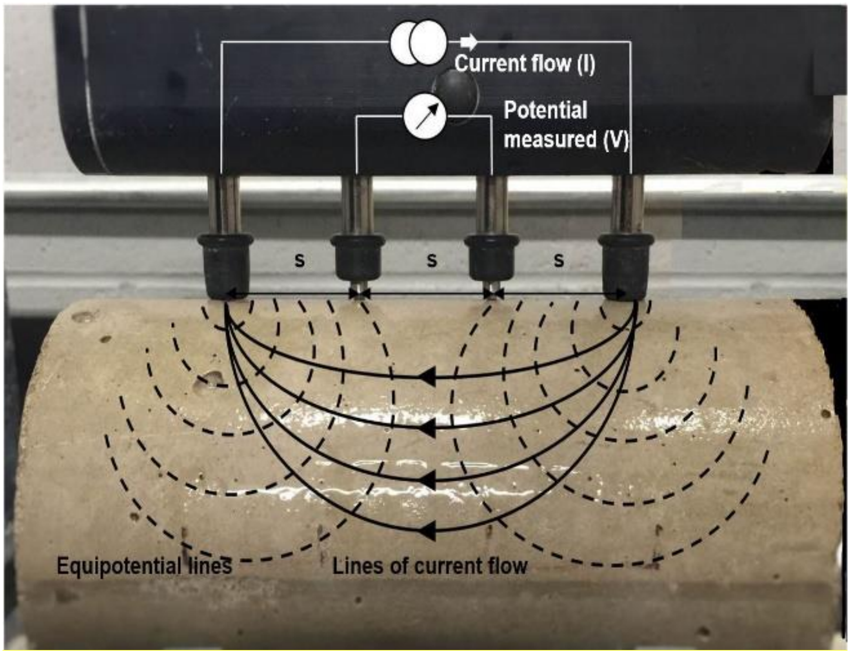

Figure 1-1: Schematic representation of the principles of resistivity testing.

Due to its sensitivity to the chemical and physical characteristics of a cementitious material, nondestructive electrical methods such as surface resistivity and bulk resistivity are gaining popularity in the cement and concrete industry. Previous studies demonstrated the existence of a correlation between the conventional method for durability assessment of concrete mixtures, the rapid chloride permeability test (RCPT), and electrical conductivity testing. The latter method was deemed accurate and reliable for determining the corrosion performance of a concrete mixture depending on its performance in resisting ionic flow. [4-6] One can use a simple classification table, derived from the RCPT standard method of testing (ASTM C1202), to estimate the

chloride ion penetration level based on the result of a surface resistivity test. [4] These studies led to the development of AASHTO TP 95: Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration [7] and AASHTO TP 119: Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test [8]. Moreover, resistivity testing has been found to be less expensive to perform in comparison to RCPT; therefore, providing motivation for implementation of the method in routine control activities.
Furthermore, previous studies have demonstrated that the w/cm ratio, various supplementary cementitious materials and their combinations used in the concrete mixtures have their own rate of surface resistivity development. (4,9). This fundamental principle was utilized for this study to develop the QC/QA tool based on specified mixture design criteria. A time-dependent resistivity model was developed to identify the water-to-cement ratio of a given mixture and the presence of Class-C fly ash, commonly used in Oklahoma, in the mixture. This enabled the development of a flowchart for use as a mixture design QC/QA tool. The method was trialed for fifteen mixtures of varying mixture design and material source. With a 95% interval of confidence, the method successfully validated 67% percent of mixtures for fly ash content. The validation of concrete mixtures to identify w/cm at day-28 was 100% and 93% accurate for "No fly ash" and "Fly ash" concrete mixtures respectively. [1]
This simple tool may help to verify the quality of a placed concrete and provide assurance that it meets the parameters of the accepted mixture design. As such, it would help control durability problems, prevent premature repair cost, and increase the service life of concrete structures. However, further investigation is required to validate the statistical criteria against multiple material sources and field trial testing prior to use and implementation. Result obtained thus far, serve as a guiding platform which may be expanded to incorporate other cementitious materials such as silica fume and granulated blast furnace slag for example.

The purpose of this study is to investigate the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures. The methodology proposed will enable the development of a method based on resistivity criteria to identify the water-to-cement ratio of a given mixture whether the mixture contains a certain type of supplementary cementitious material. This will aid in the development of a new quality control and assurance criteria for concrete mixture approval in addition to currently used test methods and specifications. This would allow infrastructure owners and stakeholders to produce high quality and durable concrete. The objectives of the experimental study are to perform an experimental parametric investigation to determine the time-resistivity behavior of typical concrete mixtures used in pavement and infrastructure construction and determining the efficacy of resistivity testing in differentiating key mixture components.

2 EXPERIMETAL PROGRAM

2.1 Materials

In this study, 75 concrete mixtures were made in the laboratory (ASTM C192). [10] The concrete mixtures varied in water-to-cementitious materials (w/cm) (0.40, 0.45, and 0.50 w/cm). The mixtures also varied in the amount of supplementary cementitious used: 0%, 5%, 20% fly ash; 0%, 2%, 8% silica fume; and 0%, 5%, 40% slag cement. The proportions of the concrete mixtures used in this study are listed in Tables 2-1 to 2-5. The aggregate proportions were kept constant while the water content was varied to achieve the desired water-to-cementitious materials ratio. For each mixture listed in the tables, one series was prepared with no admixtures; a second series was prepared with the addition of an air-entraining agent to achieve a percent air content of approximately 6%; and, a third series was prepared with the addition of both air-entraining and water-reducing agents to evaluate the impact of admixture addition on resistivity testing.

The aggregate that was used in the preparation of the concrete mixtures was a #57 crushed dolomite coarse aggregate and a natural sand fine aggregate (ASTM C33). [11] The two cement types used were a type-I and a type-III (ASTM C150). [12] Three supplementary cementitious materials were tested, a class-C fly ash (ASTM C618), a slag cement (ASTM C989), and silica fume (ASTM C1240). [13-15] Chemical admixtures were also used in select mixtures, an air entrainer (MasterAir AE 90) and a water reducer (ADVA Cast 600).

Concrete mixture batching, mixing, and casting was completed at the Bert Cooper Engineering Laboratory in the mixing room facilities which was temperature controlled. All relevant ASTM standardized procedures were followed in aggregate preparation, mixing, casting, and material quality in order to maximize reproducibility. All cylindrical samples (Ø4” x 8”) per mixture design were cast from a single batch in order to decrease potential error due to mixture design variations. For this study, six replicates were made for each mixture type and the total number of samples cast was 450. Cylindrical samples were prepared in two equal layers and were consolidated by rodding. After 24 hours of curing in their molds, the samples were demolded and placed in a limewater tank stored in a temperature controlled room (ASTM C511). [16] For this study, immersion curing was selected since it is the common method of curing within the state of Oklahoma making study outcomes relevant for this state.

Table 2-1: Concrete mixture design details of Type-I cement mixtures with no SCMs

Mixture	w/cm	Water (lb/yd^3)	Cement (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Paste (%)
1	0.40	245	611	1850	1250	28.1%
2	0.45	275	611	1850	1250	29.4%
3	0.50	306	611	1850	1250	30.8%

Table 2-2: Concrete mixture design details of Type-III cement mixtures with no SCMs

Mixture	w/cm	Water (lb/yd^3)	Cement (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Paste (%)
1	0.40	245	611	1850	1250	28.1%
2	0.45	275	611	1850	1250	29.4%
3	0.50	306	611	1850	1250	30.8%

Table 2-3: Concrete mixture design details of Type-I cement mixtures with Class-C Fly Ash

Mixture	w/cm	Fly Ash (%)	Water (lb/yd^3)	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Paste (%)
1	0.40	5%	245	580.4	30.6	1850	1250	28.1%
2	0.45	5%	275	580.4	30.6	1850	1250	29.4%
3	0.50	5%	306	580.4	30.6	1850	1250	30.8%
4	0.40	20%	245	488.8	122.2	1850	1250	28.1%
5	0.45	20%	275	488.8	122.2	1850	1250	29.4%
6	0.50	20%	306	488.8	122.2	1850	1250	30.8%

Table 2-4: Concrete mixture design details of Type-I cement mixtures with Silica Fume

Mixture	w/cm	Silica Fume (%)	Water (lb/yd^3)	Cement (lb/yd^3)	Silica Fume (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Paste (%)
1	0.40	2%	245	598.8	12.2	1850	1250	28.1%
2	0.45	2%	275	598.8	12.2	1850	1250	29.4%
3	0.50	2%	306	598.8	12.2	1850	1250	30.8%
4	0.40	8%	245	562.1	48.9	1850	1250	28.1%
5	0.45	8%	275	562.1	48.9	1850	1250	29.4%
6	0.50	8%	306	562.1	48.9	1850	1250	30.8%

Table 2-5: Concrete mixture design details of Type-I mixtures with Slag Cement

Mixture	w/cm	Slag Cement (%)	Water (lb/yd3)	Cement (lb/yd3)	Slag Cement (lb/yd3)	Coarse Aggregate (lb/yd3)	Fine Aggregate (lb/yd3)	Paste (%)
1	0.40	5%	245	580.4	30.6	1850	1250	28.1%
2	0.45	5%	275	580.4	30.6	1850	1250	29.4%
3	0.50	5%	306	580.4	30.6	1850	1250	30.8%
4	0.40	40%	245	366.6	244.4	1850	1250	28.1%
5	0.45	40%	275	366.6	244.4	1850	1250	29.4%
6	0.50	40%	306	366.6	244.4	1850	1250	30.8%

2.2 Testing Procedure

For this study, surface resistivity testing was performed in accordance with AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. The values recorded were not factorized; therefore, they correspond to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample [17]. Table 2-6 provides the performance classification of results in accordance with chloride ion permeability. [17] In accordance with the method, the probe placement location onto the surface of the cylinder was marked immediately following demolding to ensure that each measurement was taken at the same location throughout the testing process.

Table 2-6: Equivalent Surface Resistivity Values for Chloride Ion Permeability Classification

Chloride Ion Permeability	Surface Resistivity Test Result (28-day value) (kΩ-cm)
High	< 12
Moderate	12-21
Low	21-37
Very Low	37-254
Negligible	> 254

To ensure the lowest possible variability in the measurements, special care was taken of the surface conditions of the samples. Once removed from the limewater tank for testing, the surface of the cylinder was lightly sprayed with tap water to remove any excess salts that had accumulated on the surface. The surfaces of the cylinders were kept moist while not letting so much water accumulate on the surface that the flow of current passes through it. During testing, the samples were kept in a temperature and humidity controlled laboratory environment. The resistivity probes were also kept in the same temperature and humidity controlled room in order to minimize the effect of temperature fluctuation on the measurements. All measurements taken were taken by the same resistivity probe and same probe spacing of 1.5” in order to minimize the variability of the measurements taken.   For each cylinder, 6 resistivity tests were performed in time: at the time of demolding (day-1), day 3, day 7, day 14, day 21, and day 28. The results shown in the results section are average values for each day of the six sample replicates.

Figure 2-1: Example of surface resistivity test setup and resistivity probe.

3 RESULTS AND DISCUSSION

The purpose of the study was to perform an experimental parametric investigation to determine time-resistivity behavior of typical concrete mixtures used in pavement and infrastructure construction. The average results obtained for all mixtures prepared with varying water-to-cementitious ratios (w/cm) and varying percentage of supplementary cementitious material (SCM) can be found in tabular format in Appendix A. Also shown are the same mixtures made with the addition of an air-entraining admixture and the addition of air-entraining and water-reducing admixtures. The following sections compare each mixture parameter (cement type, w/cm, SCM type and content and admixture addition) to determine their influence on a resistivity results and whether they may impact the outcome of a test.

3.1 Analysis on the Influence of Water-to-Cement Ratio

Figure 3-1 demonstrates the resistivity behavior in time for standard mixtures of varying w/cm (0.40, 0.45 and 0.50) prepared with a type I cement only. First, after 28 days of curing, these mixtures would be classified as highly permeable to chloride ionic flow according to AASHTO T 358. As seen in Figure 3-1 at 56 days, the mixtures could be considered as moderately susceptible to chloride ion permeation; however, they do not present further appreciable gain in resistivity with increase in maturity.

Based on the measurements obtained, it would seem that mixtures prepared with a 0.45 w/cm and 0.50 w/cm depict the same resistivity trend in time. The results of a statistical hypothesis test (Table 3-1), Student's t-test, which compares the means after 28 days of curing, support that seen in Figure 3-1. According to Gulrez and Hartell (2018), there should be a distinguishable difference between measurements. [1] In this case, it would seem that the resistivity results obtained are slightly lower than anticipated. This may affect result comparison and interpretation for the rest of the study; still, based on past studies, conclusive interpretations may be achieved.

Figure 3-2 demonstrates the resistivity in time for samples of varying w/cm prepared with a Type-III cement only. For both 0.40 w/cm and 0.45 w/cm, the values obtained at 28-day testing would qualify the mixtures as moderately susceptible to chloride ion permeability. In time, the mixtures do not demonstrate a substantial gain in resistivity; therefore, it may not necessarily achieve a higher category of resistance to chloride ionic flow. As for the influence of w/cm on the measurement, the results of the statistical tests in Table 3-1 demonstrate that the difference between the 0.40 w/cm and 0.45 w/cm is not significant while the 0.5 w/cm is significant, in comparison to the other two mixtures.

Mixtures of varying w/cm were also prepared with 20% cement replacement with class-C fly ash. The resistivity results in time are depicted in Figure 3-3. Short term, the values obtained are lower than that obtained for the mixtures without fly ash, classifying them with a high chloride ion permeability, even the 0.4 w/cm mixture. However, the gain in resistivity differs than that previously observed. There is an increase in resistivity gain which demonstrates potential for the mixture to further increase in resistivity value with continued hydration and pozzolanic activity. Due to this observed behavior, it has been recommended to test mixtures prepared with SCMs at a later maturity, such as 91 days. [17, 18] However, the increase in test duration is not favorable to the industry, where rapid results are generally required.

As previously reported in Gulrez and Hartell, there is a noticeable difference in resistivity value between all three w/cm evaluated for fly ash mixtures (Table 3.1). [1] Similarly, for mixtures prepared with 8% silica fume, the differences in resistivity results are also significant when comparing mixtures of different w/cm. This is favorable for mixture performance evaluation and identification of causal parameters based on the obtained range in values.

On that note, seen in Figure 3-4, the addition of silica fume increased the resistivity by 339.3%, 405.5% and 327.3% for mixtures of 0.4, 0.45 and 0.5 w/cm respectively in comparison to their controls. This substantial increase contributed to better classification as mixtures of low chloride ion permeability. Furthermore, the slope in resistivity over time is the greatest of all mixtures evaluated. This demonstrates the benefits of silica fume addition in terms of resistance to ionic flow. Looking at the trend in resistivity gain, it is similar for all three mixtures of varying w/cm.   The difference is visible at a young age and it is statistically distinct after 28-days of curing (Table 3-1).

A similar conclusion could not be attained for the mixtures prepared with 40% replacement with slag cement (Figure 3-5).   In fact, the trend in resistivity gain is the same along with its values at all ages (Table 3-1).   Still, the mixtures demonstrated a low chloride ion permeability classification at 28-day with the potential for resistivity gain in time, reaching very-low classification for all mixtures of varying w/cm.

In general, based on the results obtained, the effects of water-to cementitious materials ratio could not be clearly distinguishable after 28-days of curing. AASHTO T 358, recommends to conduct the surface resistivity test after 28 days of curing' however it is well known that the benefits of pozzolanic reaction on microstructure refinement takes place with increased maturity.   Based on the observable 56-day trends, mixtures prepared with optimal SCM contents demonstrated this potential.

However, apart for mixtures prepared with silica fume, the impact of w/cm seems to be overshadowed by SCM addition.   Does this mean that one could achieve a "durable" mixture by simply adding SCMs and not paying great attention to water content? Based on the result, a 0.5 w/c mixture containing only 2% silica fume replacement would outperform a standard 0.4 w/c mixture, i.e. the recommended w/c for corrosion protection in an aggressive environment according to ACI 318 guidelines.   Further investigation on the meaning of these results in terms of transport properties and durability performances is required.

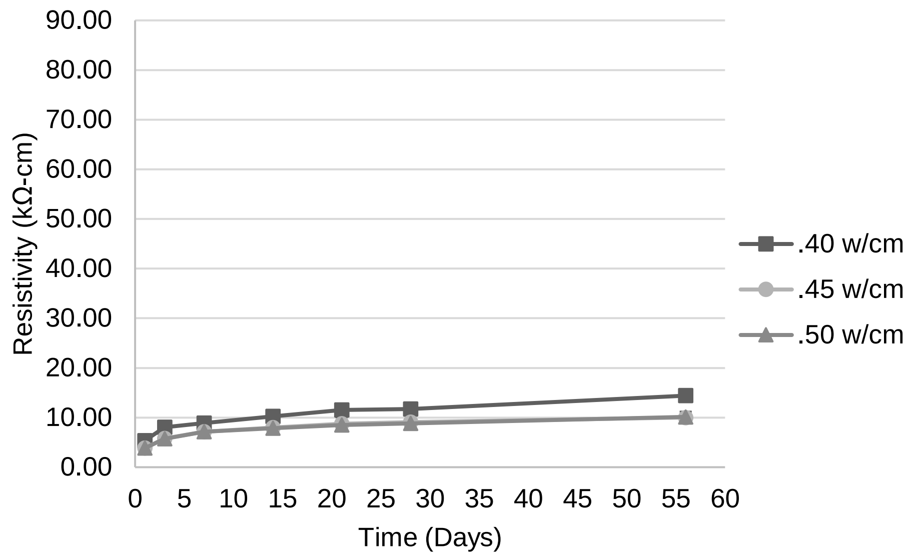

Figure 3-1: Mean resistivity values in time for mixtures of varying w/cm prepared with Type I cement, no SCMs and no admixtures

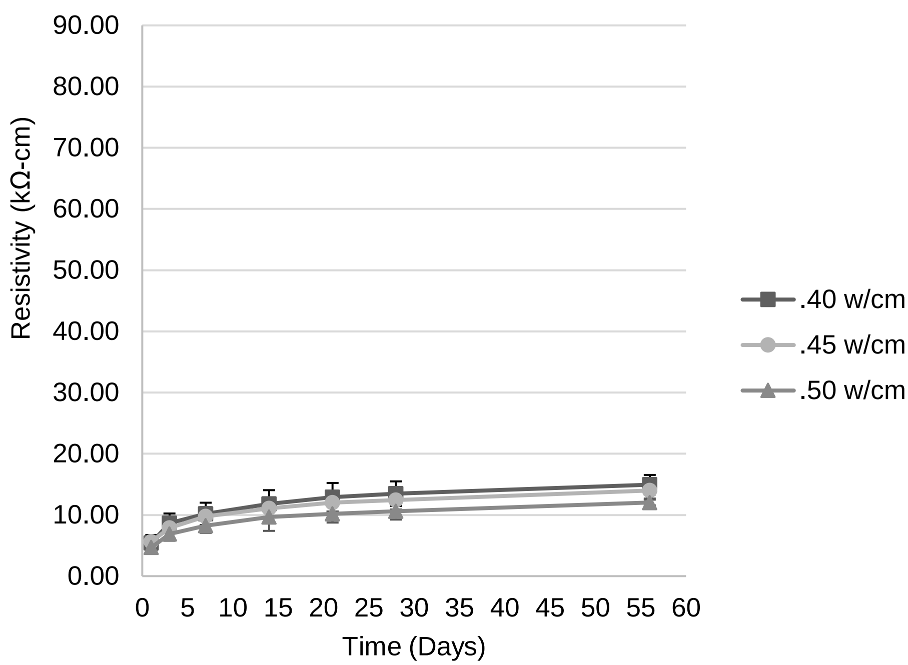

Figure 3-2: Comparison of variation of w/c for mixtures prepared with Type III cement.

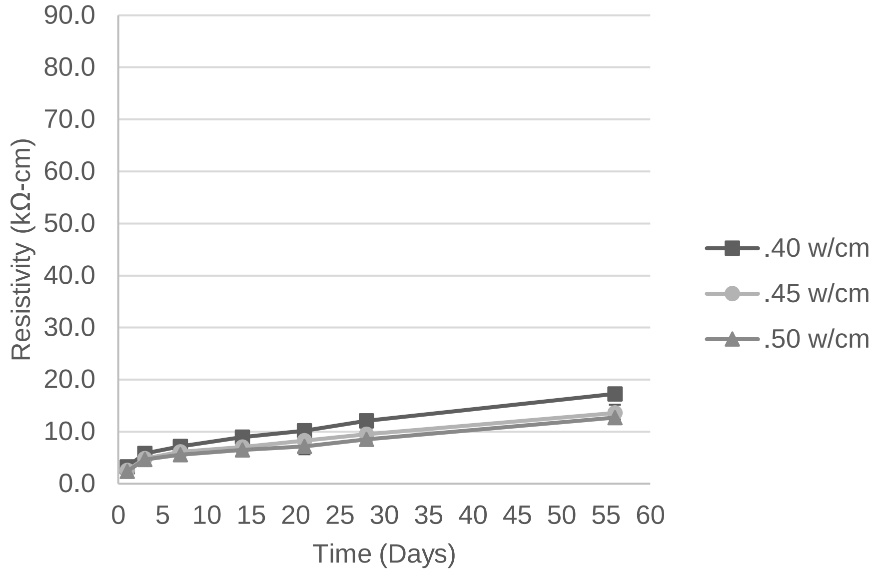

Figure 3-3: Comparison of variation of w/c for mixtures prepared with Type I cement and 20% Class-C Fly Ash.

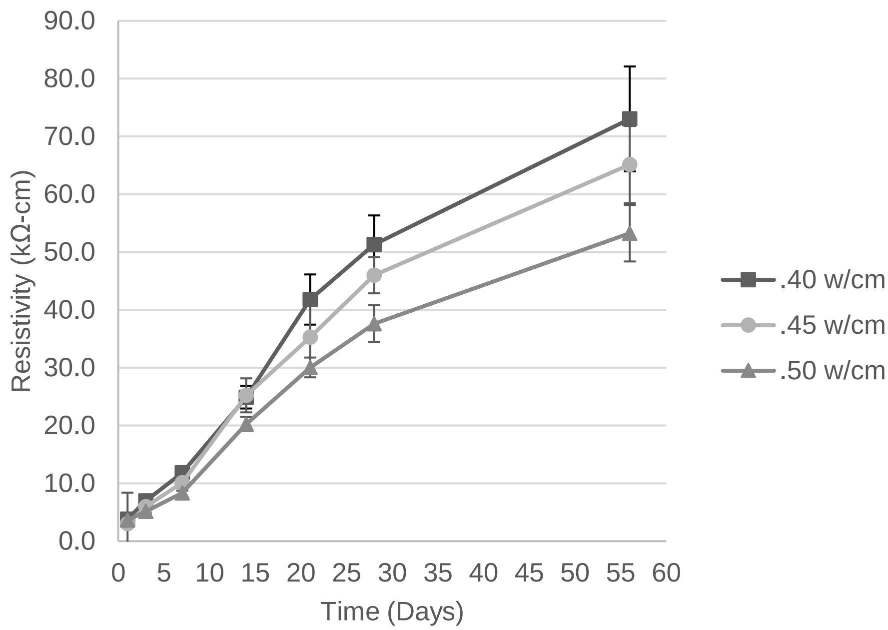

Figure 3-4: Comparison of variation of w/c for mixtures prepared with Type I cement and 8% Silica Fume.

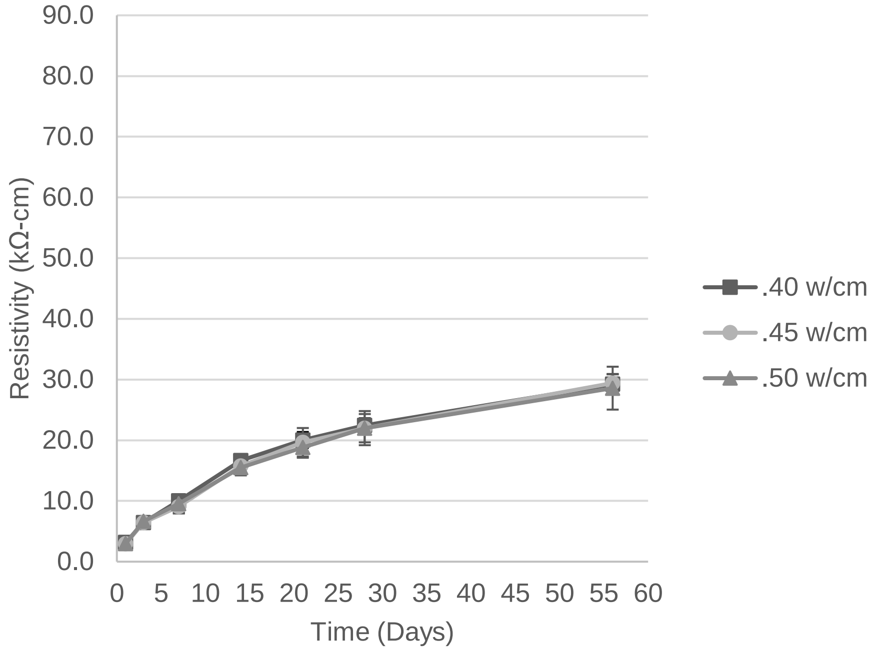

Figure 3-5: Comparison of variation of w/c for mixtures prepared with Type I cement and 40% Slag Cement.

Table: 3-1: Statistical comparison of mean 28-day resistivity values for mixtures of varying w/cm prepared with Type I cement, Type III cement, varying SCMs and no admixtures.

	ANOVA	Student T-test		
	0.40/0.45/0.50	0.40/0.45	0.40/0.50	0.45/0.50
Standard Mixture with Type-I Cement Only				
p-values	1.43E-07	2.42E-05	7.58E-08	0.461
Mixture with Type-III Cement Only				
p-values	9.94E-05	0.079	1.83 E-04	0.001
Mixture with 20% Fly Ash				
p-values	4.71E-09	9.85E-06	5.25E-08	0.004
Mixture with 8% Silica Fume				
p-values	1.31E-08	0.001	4.92E-07	3.40E-06
Mixture with 40% Slag Cement				
p-values	0.688	0.457	0.380	0.991

3.2 Analysis on the Influence of SCM Addition

3.2.1 Effect of Class-C Fly Ash Addition

At an early age, the resistivity value is lowest for samples with a high percent fly ash replacement (20%). The mixture containing no fly ash recorded the highest resistivity. However, it would seem that the curves converge towards day-28 as the mixtures containing a higher percentage of fly ash gain resistivity at a higher rate in comparison to that of the control mixtures containing no SCMs. Thus, after 28 days of continuous curing, it is not possible to distinguish the mixtures based on SCM content (Table 3-2). This is in agreement with that previously found by Gulrez and Hartell (2018). [1]

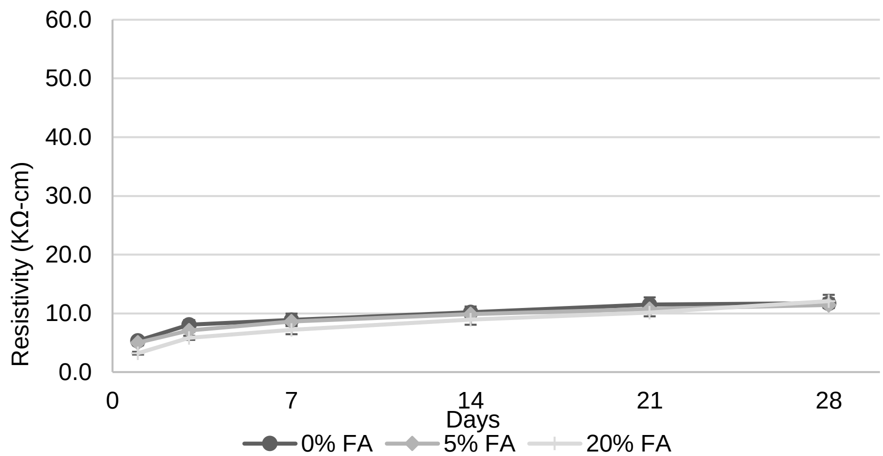

Figure 3-6: Comparison of variation of percent SCM for mixtures prepared with Type I cement, Class-C fly Ash and 0.4 w/cm

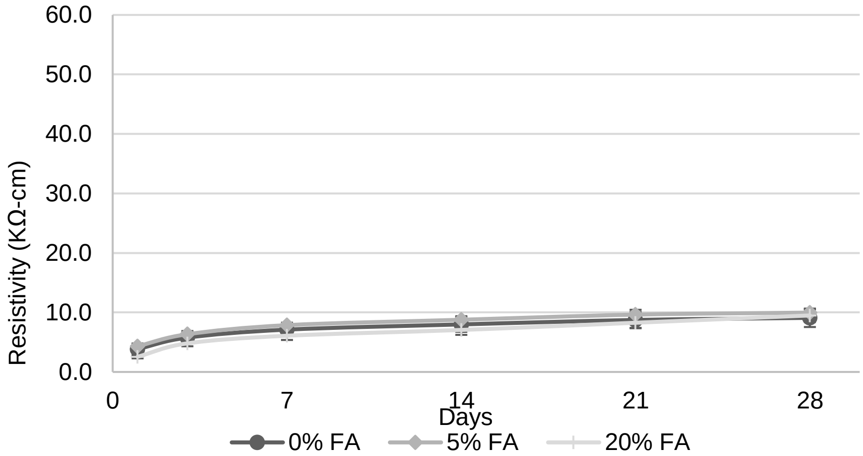

Figure 3-7**:** Comparison of variation of percent SCM for mixtures prepared with Type I cement, Class-C fly ash and 0.45 w/cm

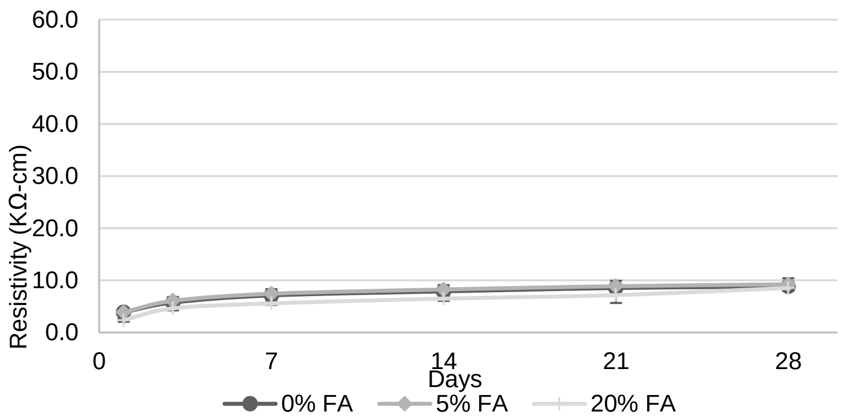

Figure 3-8: Comparison of variation of percent SCM for mixtures prepared with Type I cement, Class-C fly ash and 0.50 w/cm

Table: 3-2: Statistical comparison of mean 28-day resistivity values for mixtures of varying SCM percent content (none, low percentage and high percentage) prepared with Type I cement, Class-C fly ash and containing no admixture

	ANOVA	Student T-test		
	0%/low%/high%	0%/low%	0%/high%	Low%/high%
0.40 w/cm				
p-values	0.049	0.153	0.235	0.021
0.45 w/cm				
p-values	0.055	0.025	0.324	0.091
0.50 w/cm				
p-values	0.033	0.174	0.099	0.025

3.2.2 Effect of Silica Fume Addition

Looking at the early-age behavior, 1 to 7 days, there are no notable differences between mixtures containing silica fume and no SCM. Thereafter, initiation of pozzolanic reactions increases the rate of resistivity gain in time. The trend demonstrates an increase in resistivity gain with an increase in silica fume percent replacement.

Unlike the behavior seen for the fly ash mixture, the “convergence” effect occurs at a much earlier age. On day 1, the mixtures prepared with the SCM did record lower values than that of the OPC mixtures. This was also seen for the fly ash mixtures. However, the gain in resistivity at an early age is more considerable creating a convergence within the first week of continuous curing. This behavior does not permit early age distinction but aids thereafter. As such, silica fume addition can be discernable based on its resistivity test result at 28-days. Moreover, based on the visual comparison of standard deviations between sample means demonstrated in Figures 3-9 to 3-11, there is a potential to differentiate the mixtures as early as 14 days of continuous moist curing.

Here, a minor addition of silica fume (2%) resulted in a significant increase in 28-day resistivity value: 49.6%, 63.7%, 48.9% percent change for the 0.40w/cm, 0.45 w/cm and 0.50 w/cm mixtures respectively. The increase in value was sufficient to statistically discern both mixtures from each other (Table 3-3). As for a high percentage replacement by weight (8%), the 28-day values substantially increased by 339.3%, 405.5% and 327.3% with respect to the increasing w/cm. This increase in resistivity demonstrates the benefits of silica fume addition through pore refining of the cementitious matrix.

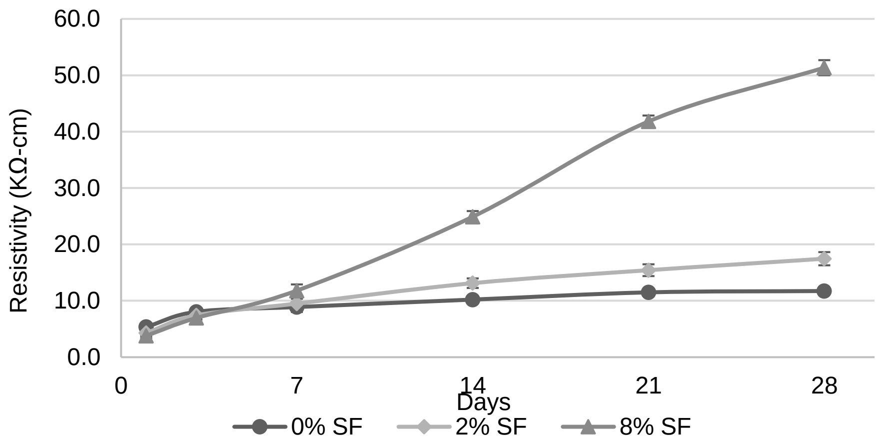

Figure 3-9**:** Comparison of variation of percent SCM for mixtures prepared with Type I cement, silica fume and 0.40 w/cm.

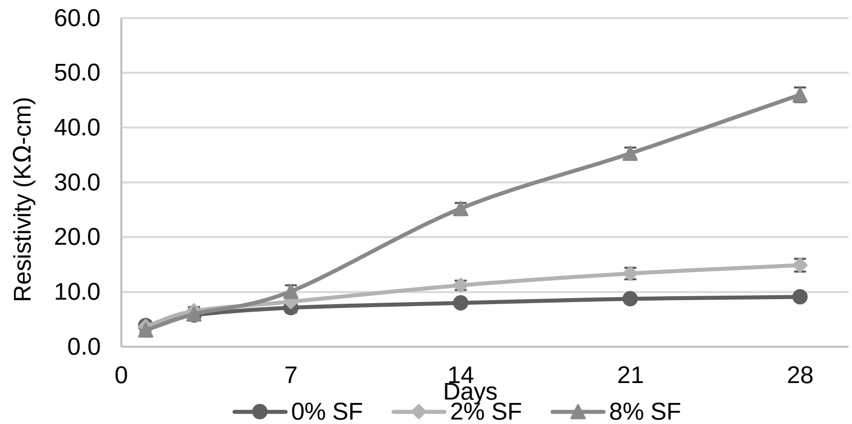

Figure 3-10**:** Comparison of variation of percent SCM for mixtures prepared with Type I cement, silica fume, and 0.45 w/cm

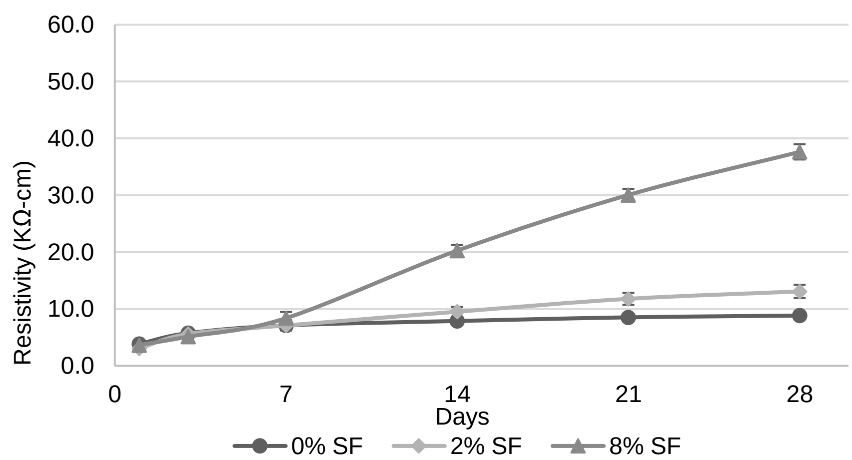

Figure 3-11: Comparison of variation of percent SCM for mixtures prepared with Type I cement, silica fume, and 0.50 w/cm.

Table: 3-3: Statistical comparison of mean 28-day resistivity values for mixtures of varying SCM percent content (none, low percentage and high percentage) prepared with Type I cement, silica fume and containing no admixture

	ANOVA	Student T-test		
	0%/low%/high%	0%/low%	0%/high%	Low%/high%
0.40 w/cm				
p-values	5.51E-17	2.19E-07	3.49E-12	3.25E-11
0.45 w/cm				
p-values	6.69E-18	3.82E-06	1.69E-13	5.16E-12
0.50 w/cm				
p-values	4.03E-18	2.16E-09	9.56E-13	5.58E-12

3.2.3 Effect of Slag Cement Addition

Mixtures fabricated with the slag cement behaved similarly to that of silica fume mixtures, where a noticeable “convergence” occurred at an early age, within the first few days of curing (Figures 3-12 to 3-14) Thereafter, there is an increase in resistivity in time but, not as prominent as that observed for the silica fume mixtures.

Based on the comparative results of the sample means recorded at 28-day (Student’s T-test) shown in Table 3-4, a low percentage of slag cement replacement (5%) made a discernable impact on the measurement. Here, the relatively low increase in resistivity (11.1%, 22.0%, 30.7% for the 0.40 w/cm, 0.45 w/cm, 0.50 w/cm mixtures respectively) was sufficient. As previously stated for silica fume addition, the impact of low percentage replacement is significant making resistivity testing acceptable for distinguishing mixtures containing slag cement from mixtures containing no SCM.

Although not to the extent as that observed for the silica fume mixtures, 40% replacement with slag cement did contribute to increasing the 28-day resistivity value by 92.3%, 141.8% and 150.0% for the 0.40 w/cm, 0.45 w/cm and 0.50 w/cm mixtures respectively. Again, the benefits of SCM addition are well demonstrated with this increase in resistivity.

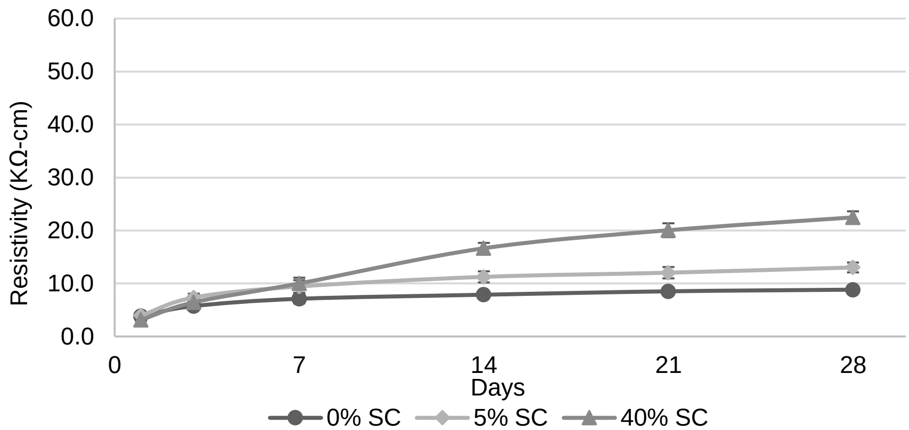

Figure 3-12: Comparison of variation of percent SCM for mixtures prepared with Type I cement, slag cement and 0.40 w/cm.

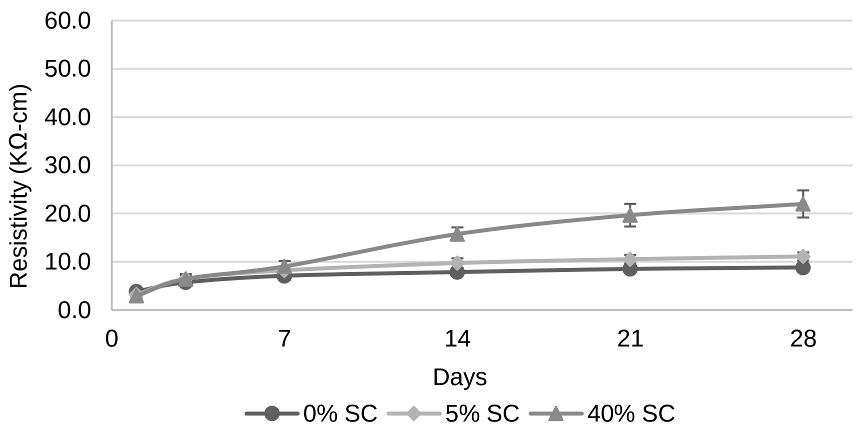

Figure 3-13: Comparison of variation of percent SCM for mixtures prepared with Type I cement, slag cement and 0.45 w/cm.

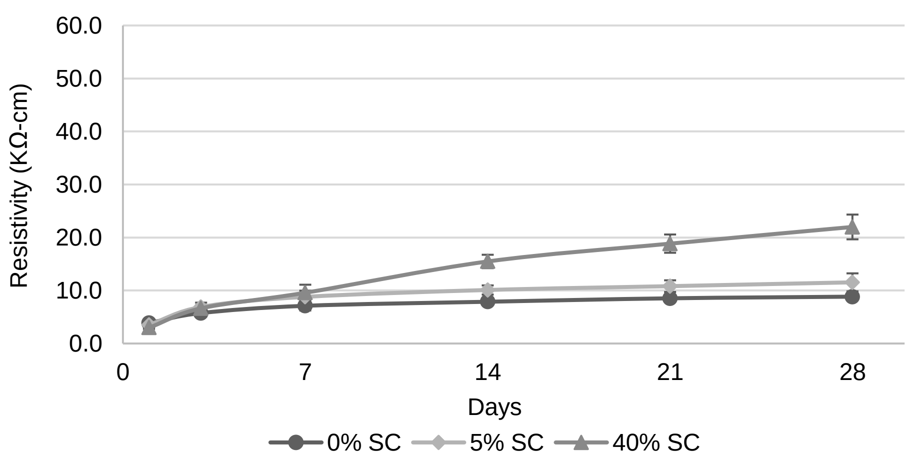

Figure 3-14: Comparison of variation of percent SCM for mixtures prepared with Type I cement, slag cement and 0.50 w/cm

As seen in Table 3-4, the difference in 28-day resistivity value between the low and high percent is statistically different. Looking at the trend in resistivity gain over time, there may be a distinguishable behavior with respect to percentage of slag cement replacement. This behavior is also seen for the silica fume mixtures. Further research into the effects of percent SCM addition is recommended to aid in the development of a potential model for mixture design optimization and resistivity predictions. However, other parameters such as chemical admixture addition may influence the outcome of a resistivity test. For this purpose, the following section investigates the influence of common admixtures such as air-entertainers and high-range water-reducers.

Table: 3-4: Statistical comparison of mean 28-day resistivity values for mixtures of varying SCM percent content (none, low percentage and high percentage) prepared with Type I cement, slag cement and containing no admixture

	ANOVA	Student T-test		
	0%/low%/high%	0%/low%	0%/high%	Low%/high%
0.40 w/cm				
p-values	3.30E-16	4.94E-04	4.72E-12	2.53E-11
0.45 w/cm				
p-values	5.56E-13	2.23E-04	2.48E-09	5.47E-09
0.50 w/cm				
p-values	9.67E-14	2.39E-05	1.23E-10	6.91E-09

3.3 Analysis on the Influence of Admixture Addition

3.3.1 Influence on Ordinary Portland Cement Mixtures

Looking at the resistivity curves demonstrated in Figures 3-15 to 3-17, the shapes of the curves are similar. In fact, there are no recorded differences for mixtures of low w/cm. In section 3.1, it was reported that the value obtained for the 0.45 w/cm mixture was slightly lower than that expected which could explain reported results of the comparison analysis for this w/cm. The 0.45 w/cm mixtures containing admixtures recorded similar resistivity values. However, the mixture containing no admixtures recorded slightly lower resistivity values which was sufficient to make it statistically different from its counterparts. However, this trend continues for the mixture of higher w/cm (0.50) making all three mixtures statistically different from each other as reported in Table 3-5.

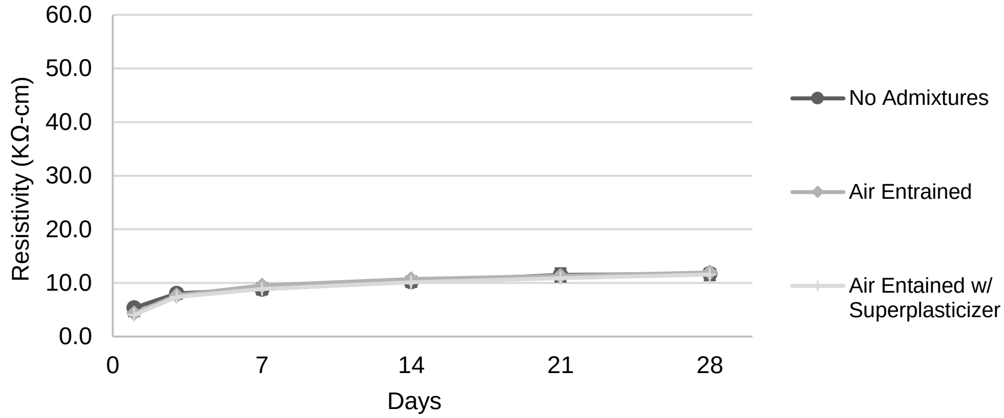

Figure 3-15: Comparison of addition of admixtures for mixtures prepared with Type I cement and 0.40 w/cm

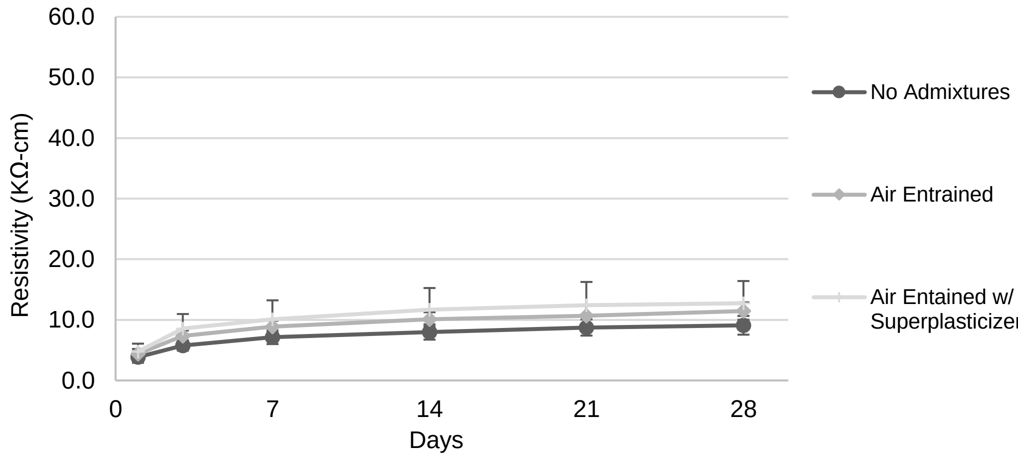

Figure 3-16: Comparison of addition of admixtures for mixtures prepared with Type I cement and 0.45 w/cm

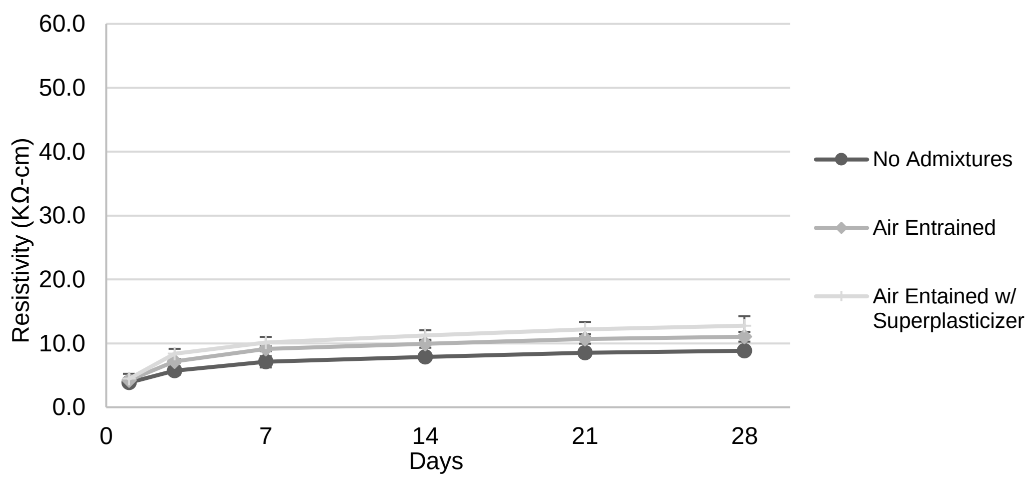

Figure 3-17: Comparison of addition of admixtures for mixtures prepared with Type I cement, and a w/c of 0.50

Table: 3-5: Statistical comparison of mean 28-day resistivity values for mixtures of varying admixture content (none, with air-entrainer and with air-entrainer plus water-reducer) prepared with Type I cement, containing no SCMs

	ANOVA	Student T-test		
	NO/AE/AE+WR	NO/AE	NO/AE+WR	AE/AE+WR
0.40 w/cm				
p-values	0.550464	0.352	0.676	0.343
0.45 w/cm				
p-values	0.000407	2.69 E-04	0.001	0.140
0.50 w/cm				
p-values	4.94E-09	6.25E-07	2.86E-07	4.85 E-04

3.3.2 Influence on Class-C Fly Ash Mixtures

As that seen for the standard Portland cement mixtures, the influence of admixture addition for mixtures prepared with fly ash resulted in a slight increase in resistivity value making it significant for this comparative analysis (Table 3-6). On average, there is a small percent difference of 6.0% and 15.9% for mixtures containing an air entrainer and an air entrainer with a water-reducer respectively. This behavior is seen in Figures 3-18 to 3-20. Here, the low coefficients of variation (COV) recorded for these mixtures may have contributed to the outcome of this comparative analysis. With a slightly a higher COV (but still acceptable, with reference to the standard method AASHTO T-358) the impact of admixture addition would have been insignificant. This fact is also observed for the other two mixture types prepared with silica fume and slag cement.

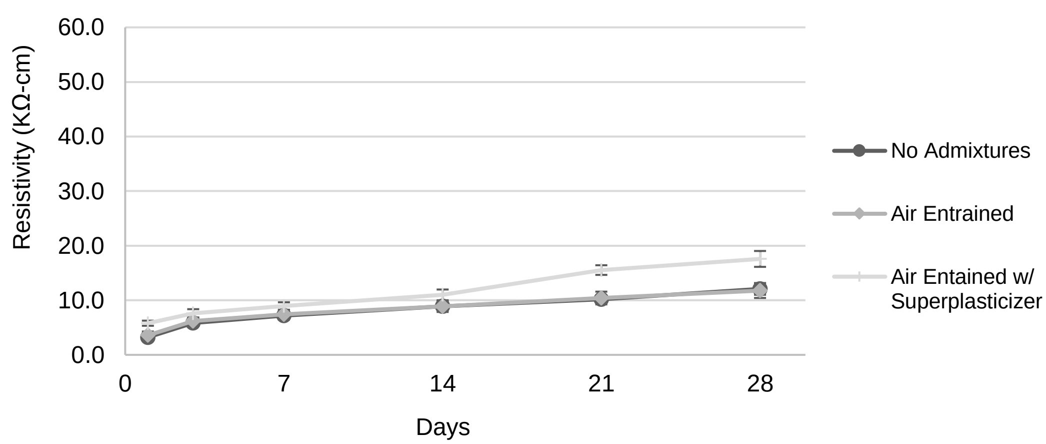

Figure 3-18 Comparison of addition of admixtures for mixtures prepared with Type I cement, 20% Class-C fly ash, and 0.40 w/cm

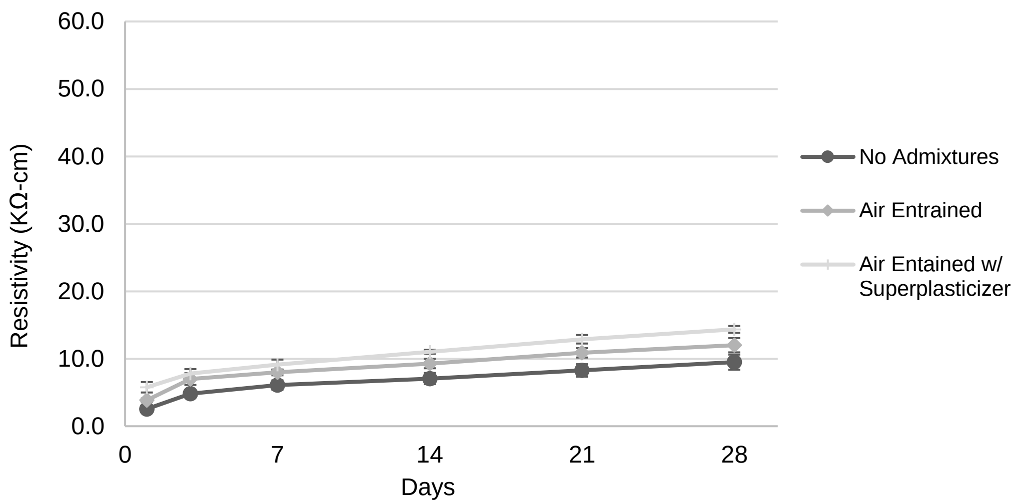

Figure 3-19. Comparison of addition of admixtures for mixtures prepared with Type I cement, 20% Class-C fly ash and 0.45 w/cm

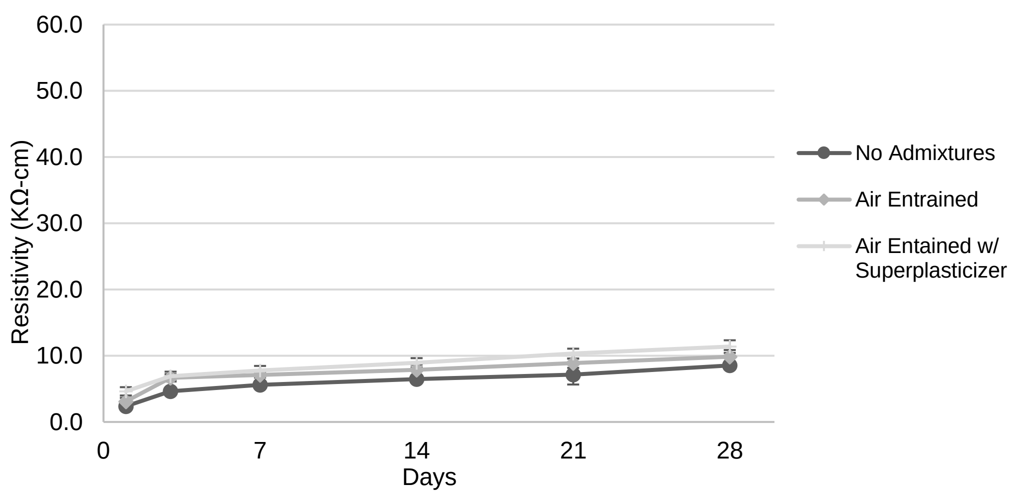

Figure 3-20. Comparison of addition of admixtures for mixtures prepared with Type I cement, 20% Class-C fly ash and 0.50 w/cm

Table: 3-6: Statistical comparison of mean 28-day resistivity values for mixtures of varying admixture content (none, with air-entrainer and with air-entrainer plus water-reducer) prepared with Type I cement, containing 20% fly ash.

	ANOVA	Student T-test		
	NO/AE/AE+WR	NO/AE	NO/AE+WR	AE/AE+WR
0.40 w/cm				
p-values	7.28E-09	0.395	2.58E-07	4.62E-07
0.45 w/cm				
p-values	7E-11	1.22E-05	2.93E-09	1.81E-06
0.50 w/cm				
p-values	4E-08	2.38E-04	1.8E-07	2.99E-04

3.3.3 Influence on Silica Fume Mixtures

Seen in Figures 3-21 to 3-23 and Table 3-7, the addition of admixtures for mixtures prepared with 8% silica fume did not impact the outcome of the resistivity test. Here, all mixtures are considered statistically similar to their respective counterpart for a given w/cm. As such, admixture addition does not seem to be a dominating factor potentially influencing the resistivity measurement.

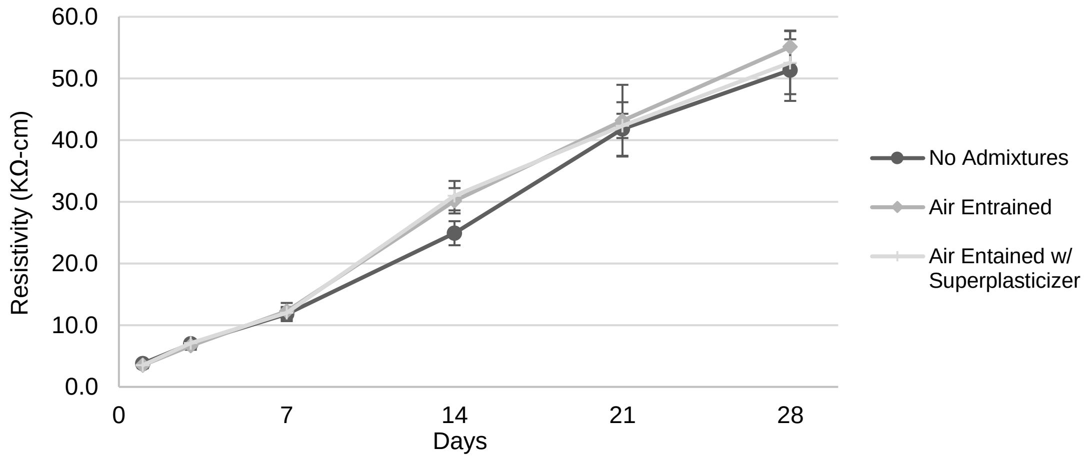

Figure 3-21: Comparison of addition of admixtures for mixtures prepared with Type I cement, 8% silica fume and 0.40 w/cm

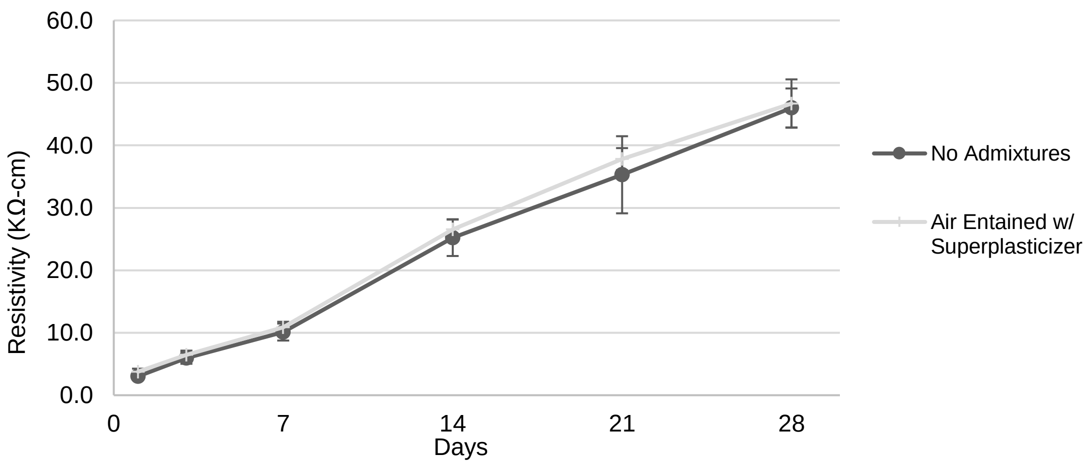

Figure 3-22: Comparison of addition of admixtures for mixtures prepared with Type I cement, 8% silica fume and 0.45 w/cm

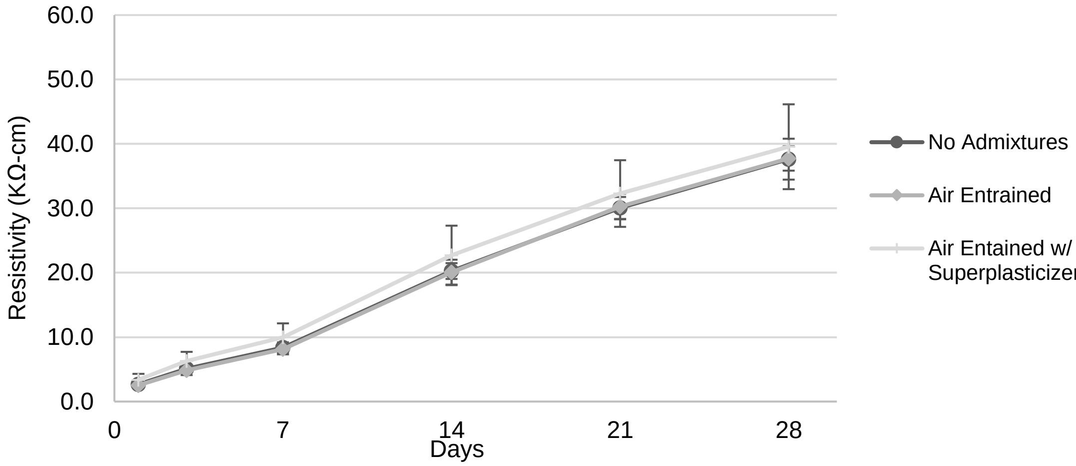

Figure 3-23: Comparison of addition of admixtures for mixtures prepared with Type I cement, 8% silica fume and 0.50 w/cm

Table: 3-7: Statistical comparison of mean 28-day resistivity values for mixtures of varying admixture content (none, with air-entrainer and with air-entrainer plus water-reducer) prepared with Type I cement, containing 8% Silica Fume.

	ANOVA	Student T-test		
	NO/AE/AE+WR	NO/AE	NO/AE+WR	AE/AE+WR
0.40 w/cm				
p-values	0.027805	0.008	0.428	0.054
0.45 w/cm				
p-values	-	-	0.504	-
0.50 w/cm				
p-values	0.258481	0.889	0.225	0.222

3.3.4 Influence on Slag Cement Mixtures

Unlike mixtures prepared with silica fume, the addition of admixtures seem to have a beneficial impact on the resistivity for slag cement concrete mixtures. Reported in Table 3-8, the presence of a high range water-reducer significantly changes the results outcome. As seen in Figures 3-23 to 3-26, the addition of a high-range water reducer resulted in a percent difference of 8.0%, 17.1%, 8.1% for mixtures of 0.40 w/cm, 0.45 w/cm and 0.50 w/cm respectively. This behavior is also seen for the fly ash mixtures but to a lesser extent. Again, the low COV obtained could have overshadowed the comparative analysis or, there is truly a slight gain in resistivity for mixtures containing a water-reducer.

Here, the effects of grain dispersion provided by the admixture may have an impact on increasing the measurement by permitting an increased in reaction kinetics. This beneficial aspect of water-reducers has been reported for other properties of concrete such as compressive strength. However, due to the limited sample size investigated, further research into this concept must be carried-out to determine the repeatability of this outcome at different admixture dosage ratios.

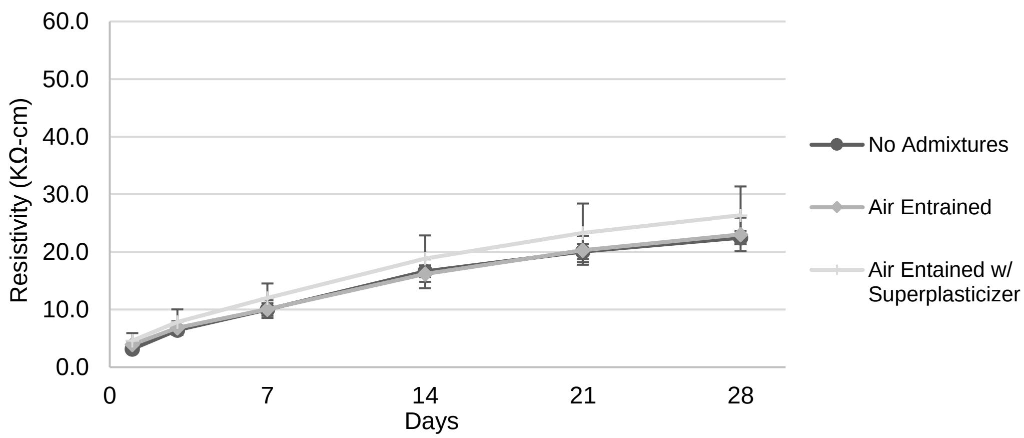

Figure 3-24: Comparison of addition of admixtures for mixtures prepared with Type I cement, 40% slag cement and 0.40 w/cm

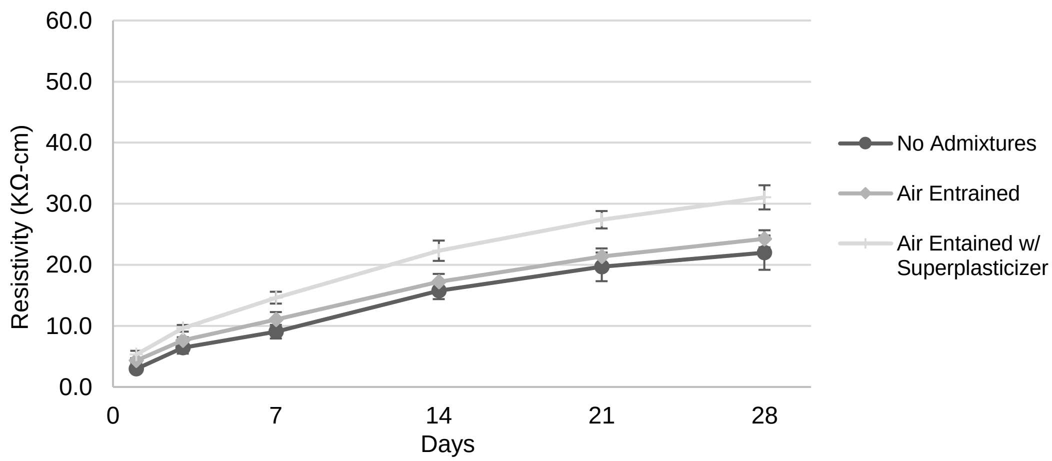

Figure 3-25: Comparison of addition of admixtures for mixtures prepared with Type I - cement, 40% slag cement and 0.45 w/c

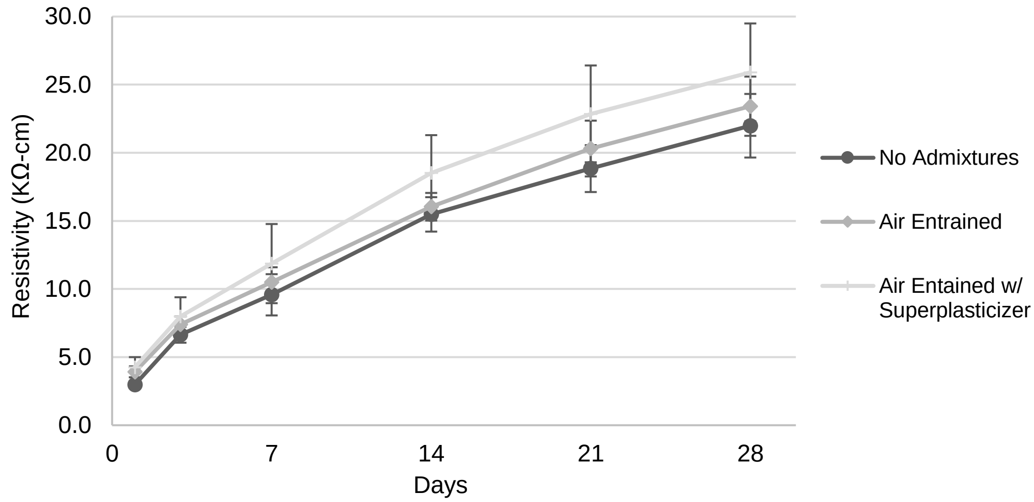

Figure 3-26: Comparison of addition of admixtures for mixtures prepared with Type I cement, 40% slag cement and 0.50 w/cm

Table: 3-8: Statistical comparison of mean 28-day resistivity values for mixtures of varying admixture content (none, with air-entrainer and with air-entrainer plus water-reducer) prepared with Type I cement, containing 40% slag cement.

	ANOVA	Student T-test		
	NO/AE/AE+WR	NO/AE	NO/AE+WR	AE/AE+WR
0.40 w/cm				
p-values	0.002	0.403	0.004	0.018
0.45 w/cm				
p-values	7.45E-10	0.005	1.47E-07	8.16E-08
0.50 w/cm				
p-values	7.01E-04	0.052	0.001	0.016

4 CONCLUSION

The purpose of this study is to investigate the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures. It was found found that the method is sensitive to supplementary cementitious material addition and may provide an indication of water-to-cement ratio and presence of admixtures. Though, this study is based on a comparative analysis of 28-day resistivity testing results as that prescribed by AASHTO T358.

First, in terms of chloride ion permeability classification as prescribed in AASHTO 358, looking at the resistivity value alone on a given day (e.g. 28), may not be an adequate parameter for evaluating the durability performance of a concrete mixture design. The benefits of SCM addition, like fly ash, have been well demonstrated in the industry; however, their potential is not demonstrated within a 28-day curing period. Depicted in this study, the resistivity value increases in time for mixtures containing SCMs and it has been recommended to determine a more realistic resistivity potential of a mixture at a later age (56 to 91 days); thus, early-age testing may not be adequate for the purpose of classification of mixtures.

This fact would make the method impractical for DOT's to perform as part of a quality control / quality assurance program; since it would double the amount of concrete samples taken at a job site: one set for performing 56-day resistivity and one set for performing 28-day compressive strength. A meaningful method of evaluation must be determined for early age assessment. The results in this study demonstrates this potential for identification of mixture design parameters. Here, the presence and potential content of SCMs can be distinguished based on the trend in resistivity gain in time and its 28-day value.

For mixtures containing no SCMs, there is a partial impact of water-to-cement ratio on the resistivity result. Here, the spread in results is so low that minute variation in water content can affect the measurement thus rendering difficult w/cm prediction. In terms of admixture addition, its presence seems to provide minimal impact.

Similar results were obtained for mixtures prepared with fly ash. The latent pozzolanic reactions overshadows result interpretation at an early age. In fact, a mixture containing no SCMs recorded higher values than its fly ash counterpart. But, the demonstrated rate in resistivity gain over time provided an indication of longterm resistivity gain.   On the other-hand, w/cm was distinguishable.

W/cm distinction was also observed for the silica fume mixtures evaluated.   Even in low replacement concentrations, silica fume addition demonstrated its high impact on resistivity which is also discernable with percent replacement and within 28-days of moist curing. This is a positive fact for early age assessment of mixtures.
However, w/cm distinction was not possible for mixtures prepared with slag cement. Here, further assessment of slag cement and water-to-cement ratio is recommended by replicating the study with a greater sample size to increase confidence level.

A similar conclusion can be made in terms of admixture addition, the low differences but, statistically distinct, would affect the resistivity test by slightly increasing its value. However, this was not seen for mixtures prepared with silica fume. Thus, further analysis with an increased sample size is recommended to increase the reliability of the comparative analysis.

5 REFERENCES

[1] Gulrez, W. and Hartell, J. (2018). “New Method for Quality Control and Compliance of Concrete Mixture Design by Using Surface Resistivity Testing “.   Proceedings TRB Annual Meeting 2018.

[2] ACI 228.2R-13, “Report on Nondestructive Test Methods for Evaluation of Concrete in Structures”.   ACI Committee 228, American Concrete Institute. Farmigton Hills, MI, 2013, 86 pp.

[3] Morris, W., Moreno, E.I. and Sagues, A. A., “Practical Evaluation of Resistivity of Concrete in Test Cylinders using a Wenner Array Probe”, Cement and Concrete Research, Vol. 26, No. 12, pp. 1779-1787, 1996

[4] Kessler, R. J., Powers, R. G., Vivas, E., Paredes, M. A., and Virmani, Y. P. (2008). “Surface Resistivity as an Indicator of Concrete Chloride Penetration Resistance.” *Proc., Concrete Bridge Conference*, St. Louis, Missouri, 20.

[5] Rupnow, T., and Icenogle, P. (2012). “Surface Resistivity Measurements Evaluated as Alternative to Rapid Chloride Permeability Test for Quality Assurance and Acceptance.” *Transportation Research Record: Journal of the Transportation Research Board* (2290), 30-37.

[6] Spragg, R. P., Castro, J., Nantung, T., Paredes, M., and Weiss, J. (2012). “Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders.” *Advances in Civil Engineering Materials*, 1(1),1-17.

[7] AASHTO TP 95. (2014). Standard Test Method for Surface Resistivity of Concrete’s Ability to Resist Chloride Ion Penetration. *American Association of State Highway and Transportation Officials*, Washington, DC, 10.

[8] AASHTO TP 119, Standard Test Method for Electrical Resistivity of Concrete Cylinder Tested in a Uniaxial Resistance Test. *American Association of State Highway and Transportation Officials*, Washington, DC, 2017, 15.

[9] Nadelman, E. I., and Kurtis, K. E. (2014) "*A Resistivity-Based Approach to Optimizing Concrete Performance*." Concrete International, 36(5), 50-54.

[10] ASTM C192-16a. (2016). *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM International, West Conshohocken, PA.*

[11] ASTM C33-18 (2018). Standard Specification for Concrete Aggregates. ASTM International, West Conshohocken, PA.

[12] ASTM C150-18 (2018). *Standard Specification for Portland Cement.* ASTM International, West Conshohocken, PA.

[13] ASTM C618-17a. (2017). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA.
ASTM C192/C192M-16a. (2016). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA.

[14] ASTM C1240-15. (2015). Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, West Conshohocken, PA.

[15] ASTM C989/C989M-18. (2018). Standard Specification for Slag Cement for Use in Concrete and Mortars, ASTM International, West Conshohocken, PA.

[16] ASTM C511-13. (2013). "Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes," ASTM International, West Conshohocken, PA.

[17] AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*.

APPENDIX A

Surface Resistivity Results

Table A-1: Surface resistivity results for Type-I concrete mixtures with no SCM and no admixtures.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm	Average	5.4	8.1	8.9	10.2	11.5	11.7
0.40 w/cm	COV	5.0	5.0	6.0	4.7	5.3	3.6
0.45 w/cm	Average	3.9	5.8	7.1	8.0	8.7	9.1
0.45 w/cm	COV	12.2	7.5	7.9	7.9	7.7	8.5
0.50 w/cm	Average	3.9	5.7	7.1	7.9	8.5	8.8
0.50 w/cm	COV	3.1	5.9	6.2	3.4	2.6	3.4

Table A-2: Surface resistivity results for Type-I concrete mixtures with no SCM and added air entrainment.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm	Average	4.3	7.7	9.5	10.7	11.3	11.9
0.40 w/cm	COV	8.3	1.8	4.4	2.7	3.3	2.7
0.45 w/cm	Average	4.4	7.4	8.9	10.1	10.7	11.5
0.45 w/cm	COV	9.1	6.0	5.5	5.9	7.7	6.2
0.50 w/cm	Average	4.2	7.2	9.2	9.9	10.7	11.0
0.50 w/cm	COV	2.6	1.7	2.1	3.1	3.5	3.4

Table A-3: Surface resistivity results for Type-I concrete mixtures with no SCM and added air entrainment and superplasticizer.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm	Average	4.0	7.4	8.9	10.1	10.9	11.6
0.40 w/cm	COV	10.9	8.8	8.9	8.7	6.1	7.6
0.45 w/cm	Average	4.8	8.6	10.1	11.7	12.4	12.7
0.45 w/cm	COV	13.9	14.2	15.6	15.4	15.5	14.4
0.50 w/cm	Average	4.5	8.4	10.1	11.2	12.2	12.8
0.50 w/cm	COV	8.8	4.8	4.3	3.6	4.8	5.8

Table A-4: Surface resistivity results and statistical analysis for Type-III concrete mixtures with no SCM and no admixtures.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm	Average	5.4	8.7	10.2	11.8	12.9	13.5
0.40 w/cm	COV	12.0	9.0	8.9	9.5	9.1	7.5
0.45 w/cm	Average	5.7	7.9	9.8	11.1	12.0	12.5
0.45 w/cm	COV	6.7	5.4	7.8	6.3	6.1	6.3
0.50 w/cm	Average	4.7	6.9	8.3	9.7	10.2	10.6
0.50 w/cm	COV	5.6	8.1	7.2	11.7	7.1	6.4

Table A-5: Surface resistivity results for Type-I concrete mixtures with Class C Fly Ash and no admixtures.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% FA	Average	5.0	7.1	8.6	9.9	10.7	11.4
0.40 w/cm - 5% FA	COV	4.8	2.1	1.9	1.2	1.8	2.1
0.45 w/cm - 5% FA	Average	4.3	6.3	7.9	8.8	9.6	10.0
0.45 w/cm - 5% FA	COV	4.4	4.3	2.7	3.4	4.3	2.7
0.50 w/cm - 5% FA	Average	3.9	6.1	7.4	8.3	8.9	9.2
0.50 w/cm - 5% FA	COV	6.7	6.1	5.9	5.1	5.9	6.3
0.40 w/cm - 20% FA	Average	3.2	5.8	7.2	8.9	10.2	12.1
0.40 w/cm - 20% FA	COV	3.7	2.9	5.1	4.8	3.2	4.5
0.45 w/cm - 20% FA	Average	2.6	4.8	6.1	7.1	8.3	9.5
0.45 w/cm - 20% FA	COV	5.1	5.2	5.9	5.9	5.6	5.9
0.50 w/cm - 20% FA	Average	2.4	4.6	5.6	6.5	7.2	8.5
0.50 w/cm - 20% FA	COV	6.8	4.3	2.5	3.4	10.6	3.3

Table A-6: Surface resistivity results for Type-I concrete mixtures with Class C Fly Ash and added air entrainment.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% FA	Average	3.9	7.0	8.5	9.7	10.6	11.3
0.40 w/cm - 5% FA	COV	7.5	2.6	3.1	2.1	2.2	2.8
0.45 w/cm - 5% FA	Average	4.0	7.6	9.5	10.6	11.5	12.1
0.45 w/cm - 5% FA	COV	7.3	4.0	5.2	5.1	5.3	5.3
0.50 w/cm - 5% FA	Average	3.6	7.1	9.1	10.1	10.4	11.1
0.50 w/cm - 5% FA	COV	6.3	4.8	6.1	7.0	4.0	5.5
0.40 w/cm - 20% FA	Average	3.6	6.2	7.4	8.9	10.4	11.8
0.40 w/cm - 20% FA	COV	9.8	5.2	5.0	5.6	5.6	5.7
0.45 w/cm - 20% FA	Average	3.9	7.0	8.0	9.3	10.9	12.0
0.45 w/cm - 20% FA	COV	3.4	6.3	2.8	3.8	3.2	4.4
0.50 w/cm - 20% FA	Average	3.1	6.7	7.1	7.9	8.9	9.9
0.50 w/cm - 20% FA	COV	8.7	4.2	2.9	5.1	3.9	5.2

Table A-7: Surface resistivity results for Type-I concrete mixtures with Class C Fly Ash and added air entrainment and superplasticizer.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% FA	Average	7.0	9.3	11.0	12.3	13.9	14.1
0.40 w/cm - 5% FA	COV	5.8	4.9	4.9	4.6	5.0	5.0
0.45 w/cm - 5% FA	Average	5.6	7.3	9.1	10.1	11.1	11.8
0.45 w/cm - 5% FA	COV	8.5	8.1	7.3	7.6	8.2	7.7
0.50 w/cm - 5% FA	Average	6.4	7.8	9.5	10.8	11.7	12.3
0.50 w/cm - 5% FA	COV	5.9	4.7	3.0	5.8	6.1	4.9
0.40 w/cm - 20% FA	Average	5.8	7.6	9.0	11.0	17.6	15.5
0.40 w/cm - 20% FA	COV	4.1	5.0	3.8	4.5	4.2	2.8
0.45 w/cm - 20% FA	Average	5.8	7.8	9.1	11.0	12.9	14.4
0.45 w/cm - 20% FA	COV	6.7	4.2	4.2	1.3	2.4	1.7
0.50 w/cm - 20% FA	Average	4.6	6.9	7.8	8.9	10.3	11.4
0.50 w/cm - 20% FA	COV	6.7	5.1	4.2	3.9	3.7	4.2

Table A-8: Surface resistivity results for Type-I concrete mixtures with Silica Fume and no added admixtures.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 2% SF	Average	4.3	7.4	9.5	13.1	15.4	17.5
0.40 w/cm - 2% SF	COV	9.1	6.9	5.6	5.9	4.1	6.1
0.45 w/cm - 2% SF	Average	3.7	6.5	8.2	11.2	13.4	14.9
0.45 w/cm - 2% SF	COV	5.9	8.6	7.0	7.7	6.4	9.1
0.50 w/cm - 2% SF	Average	3.1	5.6	7.1	9.5	11.8	13.1
0.50 w/cm - 2% SF	COV	4.5	4.5	4.6	5.7	3.8	3.3
0.40 w/cm - 8% SF	Average	3.8	7.0	11.8	24.9	41.8	51.4
0.40 w/cm - 8% SF	COV	5.8	4.9	4.8	3.9	5.2	4.9
0.45 w/cm - 8% SF	Average	3.0	6.0	10.1	25.2	35.3	46.0
0.45 w/cm - 8% SF	COV	6.6	7.7	6.7	5.8	8.8	3.4
0.50 w/cm - 8% SF	Average	3.7	5.1	8.4	20.3	30.1	37.6
0.50 w/cm - 8% SF	COV	5.0	3.7	4.9	3.0	2.8	4.2

Table A-9: Surface resistivity results for Type-I concrete mixtures with Silica Fume and added air entrainment.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 2% SF	Average	3.9	7.2	9.2	12.6	15.5	17.2
0.40 w/cm - 2% SF	COV	8.3	10.6	6.7	3.7	6.3	6.8
0.45 w/cm - 2% SF	Average	3.7	6.9	8.6	10.6	14.6	16.4
0.45 w/cm - 2% SF	COV	7.9	6.6	3.7	4.4	5.1	5.0
0.50 w/cm - 2% SF	Average	3.3	6.4	8.0	9.6	12.9	14.1
0.50 w/cm - 2% SF	COV	7.0	7.1	7.4	8.5	6.5	6.5
0.40 w/cm - 8% SF	Average	3.5	6.7	12.3	30.2	43.2	55.1
0.40 w/cm - 8% SF	COV	4.8	4.9	5.5	3.4	6.7	2.4
0.45 w/cm - 8% SF	Average	4.7	9.0	16.7	41.2	60.6	76.4
0.45 w/cm - 8% SF	COV	8.8	7.1	6.3	6.3	4.8	5.3
0.50 w/cm - 8% SF	Average	2.5	4.9	8.1	20.1	30.3	37.7
0.50 w/cm - 8% SF	COV	6.3	7.8	5.0	4.9	3.3	2.5

Table A-10: Surface resistivity results for Type-I concrete mixtures with Silica Fume and added air entrainment and superplasticizer.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 2% SF	Average	4.7	8.4	10.7	14.7	17.5	19.5
0.40 w/cm - 2% SF	COV	6.2	7.3	5.3	7.2	6.9	7.0
0.45 w/cm - 2% SF	Average	5.2	9.2	12.0	16.3	19.1	20.7
0.45 w/cm - 2% SF	COV	7.1	6.1	6.2	6.8	6.8	6.3
0.50 w/cm - 2% SF	Average	4.5	8.0	10.6	13.7	16.1	18.0
0.50 w/cm - 2% SF	COV	6.6	4.4	3.4	4.5	5.5	4.7
0.40 w/cm - 8% SF	Average	3.5	7.1	12.0	31.0	42.3	52.6
0.40 w/cm - 8% SF	COV	7.1	2.7	2.8	3.8	2.3	4.9
0.45 w/cm - 8% SF	Average	3.8	6.5	10.9	26.5	37.8	46.7
0.45 w/cm - 8% SF	COV	6.4	5.3	4.1	3.0	2.3	4.2
0.50 w/cm - 8% SF	Average	3.4	6.3	10.0	22.7	32.3	39.6
0.50 w/cm - 8% SF	COV	13.6	11.3	10.8	10.1	8.0	8.3

Table A-11 Surface resistivity results for Type-I concrete mixtures with Slag Cement and no added admixtures.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% SC	Average	4.0	7.4	9.4	11.3	12.0	13.0
0.40 w/cm - 5% SC	COV	5.8	4.9	6.3	4.6	4.5	3.6
0.45 w/cm - 5% SC	Average	3.2	6.5	8.2	9.8	10.6	11.1
0.45 w/cm - 5% SC	COV	4.7	4.3	4.4	5.0	4.1	3.8
0.50 w/cm - 5% SC	Average	3.5	6.9	8.8	10.1	10.8	11.5
0.50 w/cm - 5% SC	COV	7.4	6.0	6.6	4.3	5.1	7.4
0.40 w/cm - 40% SC	Average	3.2	6.5	10.0	16.7	20.1	22.5
0.40 w/cm - 40% SC	COV	3.2	4.0	5.4	3.1	3.2	2.5
0.45 w/cm - 40% SC	Average	3.0	6.5	9.1	15.8	19.7	22.0
0.45 w/cm - 40% SC	COV	8.1	7.7	6.2	4.4	5.9	6.4
0.50 w/cm - 40% SC	Average	3.0	6.6	9.6	15.5	18.8	22.0
0.50 w/cm - 40% SC	COV	4.4	4.4	7.9	4.1	4.6	5.3

Table A-12: Surface resistivity results for Type-I concrete mixtures with Slag Cement and added air entrainment.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% SC	Average	5.5	8.7	10.6	12.7	13.4	13.6
0.40 w/cm - 5% SC	COV	5.7	6.7	6.7	7.2	6.9	6.8
0.45 w/cm - 5% SC	Average	5.0	7.2	9.6	11.0	12.0	12.6
0.45 w/cm - 5% SC	COV	7.6	8.0	6.6	5.3	5.3	4.4
0.50 w/cm - 5% SC	Average	5.2	8.0	10.4	11.9	12.8	13.6
0.50 w/cm - 5% SC	COV	8.4	3.1	4.6	2.7	4.5	3.9
0.40 w/cm - 40% SC	Average	3.9	6.9	10.1	16.2	20.3	23.0
0.40 w/cm - 40% SC	COV	7.4	8.2	7.5	7.8	6.2	6.3
0.45 w/cm - 40% SC	Average	4.3	7.7	11.0	17.2	21.4	24.3
0.45 w/cm - 40% SC	COV	3.9	3.1	5.6	3.8	3.1	2.9
0.50 w/cm - 40% SC	Average	3.9	7.4	10.5	16.0	20.3	23.4
0.50 w/cm - 40% SC	COV	5.1	3.9	5.1	3.2	5.0	4.7

Table A-13: Surface resistivity results for Type-I concrete mixtures with Slag Cement and added air entrainment and superplasticizer.

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 5% SC	Average	4.5	7.5	9.6	11.2	12.2	13.0
0.40 w/cm - 5% SC	COV	9.7	8.6	8.6	7.0	6.9	7.4
0.45 w/cm - 5% SC	Average	5.7	9.0	11.7	13.4	15.0	15.9
0.45 w/cm - 5% SC	COV	6.1	5.6	2.5	1.9	2.7	3.2
0.50 w/cm - 5% SC	Average	5.3	8.5	10.9	12.5	13.6	14.4
0.50 w/cm - 5% SC	COV	5.3	3.6	4.0	3.8	4.6	4.4
0.40 w/cm - 40% SC	Average	4.6	7.8	12.0	18.8	23.3	26.4
0.40 w/cm - 40% SC	COV	14.4	14.2	10.5	10.7	10.9	9.5
0.45 w/cm - 40% SC	Average	5.3	9.6	14.6	22.3	27.4	31.1
0.45 w/cm - 40% SC	COV	5.6	2.8	3.3	3.7	2.6	3.2
0.50 w/cm - 40% SC	Average	4.3	8.0	11.9	18.5	22.9	25.9
0.50 w/cm - 40% SC	COV	8.7	8.8	12.2	7.5	7.8	6.9