RESEARCH

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INVESTIGATION OF CONCRETE ELECTRICAL RESISTIVITY AS A PERFORMANCE-BASED TEST

Prepared For:

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Research Division

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16. Abstract

The purpose of this research project was to identify the extent that concrete resistivity measurements (bulk and/or surface) can be used as a performance based lab test to improve the quality of concrete in Utah bridge decks. By allowing UDOT to specify a required resistivity, concrete bridge deck quality will increase and future maintenance costs will decrease. This research consisted of two phases: the field phase and the lab phase. In the field phase, concrete samples were gathered from local concrete producers in Utah. These concrete samples were made with common concrete mixes used in bridge decks across the state of Utah. Testing multiple different mix designs allowed the research team to investigate several variations of concrete constituents, for instance, water to cement ratio, common Utah supplementary cementitious materials, curing type, and aggregate type. Mechanical and durability testing was performed on concrete of different ages. These tests included strength, surface resistivity, bulk resistivity, rapid chloride permeability, and freeze and thaw tests. In the lab phase, one of the field mixes was chosen as the control mix. This mix was then duplicated in the lab in order to see the performance differences of each mix in the controlled and field experiments. In addition, changes were made to the lab control mix, to see the effect of different materials on the resistivity and durability of concrete.

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UNIT CONVERSION FACTORS

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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

FHWA	Federal Highway Administration
RCPT	Rapid chloride permeability test
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

This study investigates the potential for adopting the surface resistivity test as a performance based method for estimation of chloride penetrability of concrete. The intent is to determine if it is feasible or advisable to replace the current test method—the rapid chloride penetrability test (RCPT)—with the simpler and faster surface resistivity test method. It was also desired to investigate the bulk resistivity test, which was less preferable than surface resistivity but also a potential improvement over RCPT in terms of ease and duration of test. To that end, the researchers tested dozens of concrete mixtures in both the laboratory and the field. Mixtures included a variety of water-to-cementitious materials ratios (*w/cm*), chemical admixtures, mineral admixtures, fibers, aggregates, and other factors. The intent of including such a wide variety of mixture components was to elucidate the effects of these components on the correlation between RCPT and surface resistivity.

Test results in most cases showed a close correlation between the surface resistivity test and RCPT, in terms of chloride penetrability classifications. When the two classifications did not match exactly, the classification based on surface resistivity was conservative in most cases. Overall, classifications based on surface resistivity were either identical to those based on RCPT or were one class worse. In comparison, classifications based on bulk resistivity were typically farther away from those based on RCPT, and were in many cases non-conservative. This means that the bulk resistivity test may suggest a better performance than is likely to actually occur.

Test results suggest that most admixtures will affect chloride penetrability. However, the effects are generally well correlated between tests, meaning that the improvements or reductions in penetrability can be reliably measured. However, some aggregates—specifically lightweight aggregates and conductive heavyweight aggregates may result in spurious readings of the resistivity tests. Additions of metakaolin or some chemical admixtures may have similar effects. Practitioners should perform qualification testing when these materials are used, so that they can better understand the correlation between RCPT and resistivity tests in such cases.

1.0 INTRODUCTION

1.1 Problem Statement

Corrosion is an issue in every reinforced concrete structure. Bridge decks are of particular importance because they are subject to heavy traffic, salts, and environmental effects. Corrosion of the reinforcing steel deteriorates the bridge deck, greatly increasing the amount of maintenance needed to keep the bridge operative. Improving the resistance of the bridge deck to chloride ingress is one way to keep maintenance levels low and ideally extend bridge deck service life and decrease the maintenance cost. One way to extend bridge deck service life is to use a test, such as the rapid chloride permeability test or the resistivity based test, that measures resistance to chloride ingress. While the rapid chloride permeability test (RCPT) is well accepted, it is time consuming and expensive. Electrical resistivity testing is rapidly becoming a replacement for the RCPT.

1.2 Objectives

The purpose of this research project was to evaluate bulk and surface resistivity methods and determine if they can be used as performance based tests for bridge deck concrete. The other objective was to determine an acceptable resistivity for performance specifications of concrete bridge decks.

1.3 Scope

In the field phase, samples of concrete mixtures used for bridge decks were gathered from local concrete producers in Utah. In the lab phase, different concrete was casted in the lab in order to see the performance differences of each mix in the controlled environment. Then, Mechanical and durability testing was performed on the concrete mix samples at different ages.

1.4 Outline of Report

The report is organized in 5 sections:

- Section 2 presents background information related to measuring the chloride permeability of concrete;
- Section 3 discusses research methods and data collection;
- Section 4 presents the results and analysis; and
- Section 5 lists the conclusions, recommendations, and implementation.

2.0 BACKGROUND

2.1 Overview

Both durability and strength are factors that define the performance of a concrete. Generally, the definition of penetrability is "the ease with which fluids, both liquids and gases, can enter into or move through the concrete" (Savas 1999). Factors that affect penetrability are water to cement ratio (W/CM), aggregate size, pore size, and pore distribution (Savas 1999). The key to creating a durable concrete is allowing the concrete to achieve an impermeable pore structure (Swamy 1996, Bryant et al. 2009). Several tests and methods can measure concrete durability, for instance, the rapid chloride permeability test, the surface resistivity method, and the bulk resistivity method.

2.2 Motivation

The American Concrete Institute (ACI) defines durability of concrete as "its ability to resist weathering action, chemical attack, abrasion, and other conditions of service" (ACI 116 R). In general, the five factors that influence durability are:

1. Design: type of materials, concrete mix design, material conditions, and proportions and thickness of concrete cover over reinforcing steel.
2. Construction practices: mixing, delivering, discharging, consolidating, finishing, and curing conditions.
3. Hardened concrete properties: compressive strength and penetrability.
4. Environmental exposure conditions: sulfate attack, freeze-thaw cycle, and alkali-silica reaction.
5. Loading conditions: type of loading, loading duration, and crack width and depth.

The concrete electrical resistivity method is a non-destructive method that is faster and easier to implement than other methods that measure concrete penetrability. By specifying concrete resistivity in new structures, the Utah Department of Transportation (UDOT) can increase the standard quality of concrete by controlling concrete penetrability economically. Less permeable concrete means less deterioration in future bridges (Figure 2.1).

(a) (b)

Figure 2.1 (a) Common bridge deterioration caused by corrosion, (b) bridge deterioration with deterioration of the support

2.3 Rapid chloride permeability test (RCPT)

One of the necessary factors in determining concrete performance is chloride penetrability, which measures the resistance of a concrete to chloride penetration. The American Society for Testing and Materials (ASTM) standardized a test which measures this property of concrete. This standard (ASTM C1202-12), which uses electrical flow to measure the resistance of concrete to chloride ion penetration, is entitled Rapid Chloride Permeability Test (RCPT).

"This test method consists of monitoring the amount of electrical current passed through 50-mm thick slices of 100-mm nominal diameter cores or cylinders during a 6-h period. A potential difference of 60 V DC is maintained across the ends of the specimen, one of which is immersed in a sodium chloride solution, the other in a sodium hydroxide solution. The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration" (ASTM C1202, 2012). The relationship between chloride ion penetrability and charge passed is shown in Table 2.1. The test setup is shown in Figure 2.2 and cells used in the RCP test are shown in Figure 2.3.

Table 2.1 Chloride Ion Penetrability Based on Charge Passed (ASTM C1202 2012)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

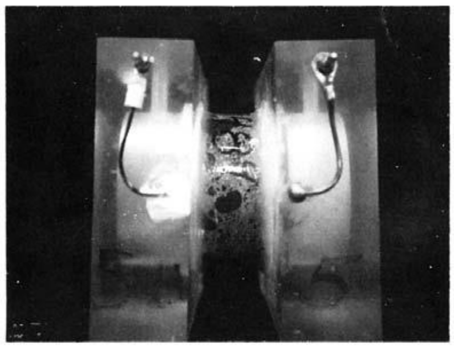


Figure 2.2 RCPT specimen ready for test (ASTM C1202)

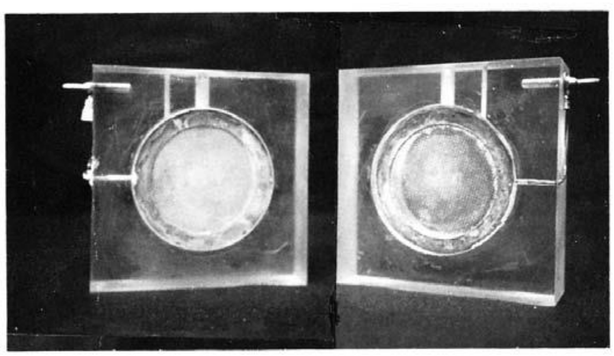


Figure 2.3 RCPT cell (ASTM C1202)

2.4 Surface Resistivity (Wenner method)

This test is according to Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T 358-15). There are two major reasons that engineers evaluate surface electrical resistivity of concrete. First, the long-term durability of concrete, especially in severe environments, depends on the quality of concrete between the rebar and the exterior surface since all deteriorating factors attack concrete from its surface. Second, the nature of surface electrical resistivity is non-destructive, which gives us opportunities to test concrete almost everywhere, even in sensitive structures such as nuclear power plants where coring is not an option.

Originally, geologists invented the surface resistivity measurement technique for investigating soil strata (Wenner 1980, Millard et al. 1989). There are four electrodes (probes) in the Wenner method, which are situated in a straight line with equal spacing between each probe. As shown in Figure 2.4, the two inner probes measure the electrical potential and the two exterior probes apply an Alternating Current (AC) into the concrete. The equation for measuring surface electrical resistivity of a semi-infinite, homogeneous concrete is shown in Equation 1.

$$\rho = 2\pi a \frac{V}{I}$$ **Equation 1**

Where:

V = electrical potential (Volts)

I = electrical current (Amps)

a = probe spacing (cm)

Probe spacing must be determined very accurately and carefully since small probe spacing could lead to a high degree of scatter, which is due to the presence or absence of aggregate with high resistivity. On the other hand, probe spacing that is too large could lead to inaccuracies due to constriction of the current field by the specimen’s edges (Millard et al. 1989).

Figure 2.6 shows the Giatec Scientific Inc. instrument for measuring surface resistivity that was used in this research. Sengul and Gjørv (2008) show that there is a good correlation between chloride diffusivity and electrical conductivity of concrete as shown in Figure 2.5.

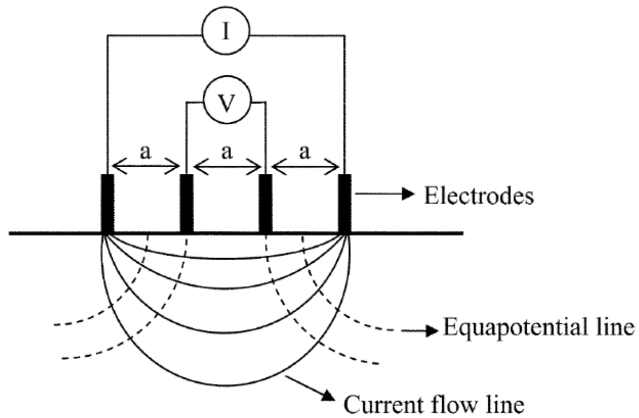


Figure 2.4 Schematic representation of surface resistivity test (Sengul and Gjørv 2008)

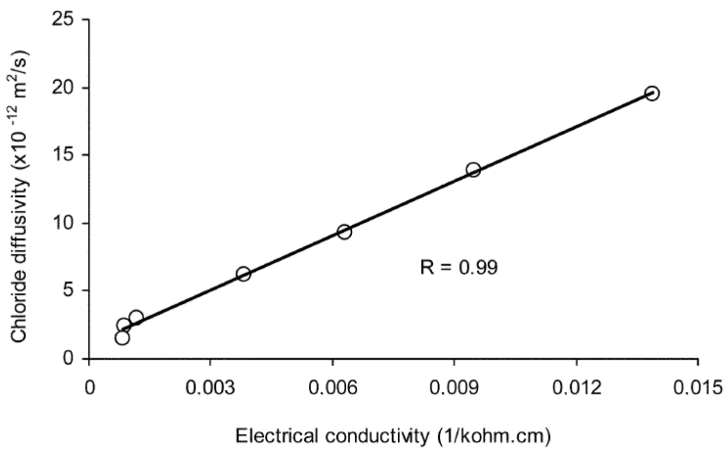


Figure 2.5 Relationship between chloride diffusivity and electrical conductivity for concrete tested using the four-electrode method (Sengul and Gjørv 2008)

Figure 2.6 Surface resistivity measurement device (Giatec Scientific, Inc.)

There are four difficulties when using the Wenner method (Millard et al. 1989):

1. Steel bars should not be in the affected depth of applied current flow (see Figure 2.4); otherwise, the measured resistivity will be significantly lower in comparison to the real resistivity of concrete (Millard and Gowers 1991).
2. As a specimen becomes semi-infinite, probe spacing must be chosen carefully in order to give accurate and consistent results.
3. The connection of probes directly to the surface of concrete is important, and any resistance between these two should be eliminated. Saturated wooden bars, sponges, or contact gel can remove this unwanted resistance.
4. Error happens when concrete has two different surface layers with different resistivity. This can occur when salt ingresses into the surface of concrete or when recently wetted concrete has a carbonated surface, which results in an increase of resistivity (Millard and Gowers 1991).

Most of these apply to in-situ resistivity measurements rather than laboratory measurements.

2.5 Bulk Resistivity

This test is according to “Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete” (ASTM C1760-12). The procedure used to find electrical resistivity using the bulk resistivity method measures the voltage between the two ends of a concrete cylinder as a small AC current is applied to a concrete cylinder. Two conductive plates apply the electrical current, as shown in Figure 2.7 and Figure 2.8. Concrete electrical resistivity can be calculated using Equation 2.

$$\rho = \frac{A}{L} \times Z \qquad \textbf{Equation 2}$$

Where:

A = cross-sectional area of cylinder

L = length of the specimen

Z = impedance that occurs due to the resistance of concrete

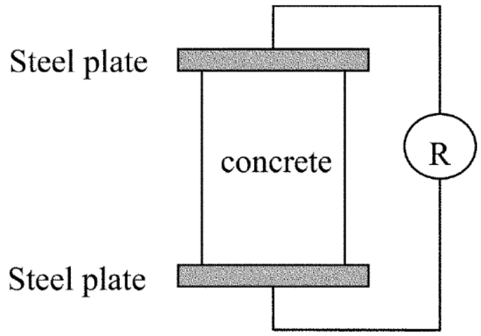


Figure 2.7 Bulk resistivity method (Sengul and Gjørv 2008)

Figure 2.8 Bulk resistivity measurement device (Giatec Scientific, Inc.)

Both alternating current (AC) and direct current (DC) can be used in the bulk resistivity method. Since cement pore water contains electrolytes, the passage of direct current through concrete during a bulk resistivity test will cause polarization, which creates a potential that resists the applied potential (Monfore 1968). The potential for polarization depends on the ions present and the materials that make up the electrodes. Polarization causes a reaction in electrodes, which can cause a thin layer of oxygen, hydrogen, or another gas to form on the electrodes. This layer resists the applied current. (Monfore 1968). Cyclic direct current can prevent polarization effects.

Polarization can be avoided at frequencies more than 50 Hz, because in high frequencies the capacitive reactance of concrete is much larger than its electrical resistivity (Neville 1995). Sengul and Gjørv (2008) clearly showed that there is a good correlation between chloride diffusivity and electrical conductivity when using the bulk method for concrete, as shown in Figure 2.9. This relationship is similar to that of surface resistivity.

Both pore structure characteristics and pore solution chemistry effect electrical conductivity of concrete (Monfore 1968). Both of these factors are a function of admixtures, temperature, cement type, W/CM ratio, etc. (Savas 1999).

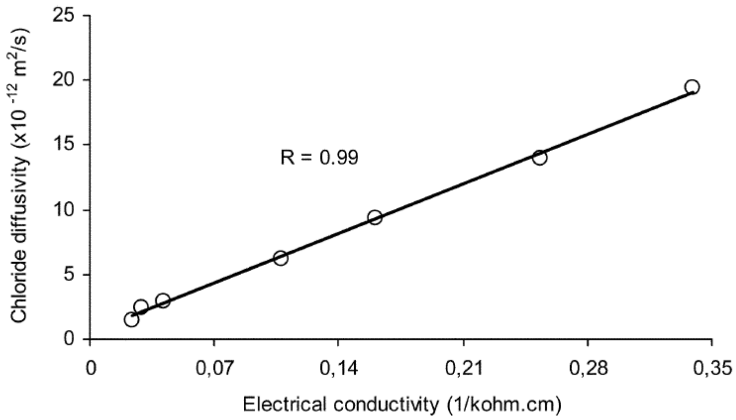


Figure 2.9 Relationship between chloride diffusivity and electrical conductivity for concrete tested using the two-electrode method (Sengul and Gjørv 2008)

2.6 Admixtures

Adding chemical admixtures, for instance adding calcium nitrite (which can be found in corrosion inhibitor admixtures), can affect pore solution chemistry of concrete (Wee et al. 2000, Chini et al. 2003). Calcium nitrite increases the conductivity of concrete, but it does not increase the rate of chloride ingress (Savas 1999).

Adding Supplementary Cementitious Materials (SCMs) to a concrete mixture improves particle packing, which leads to finer and discontinuous pore structures (Neville 1995). SCM's secondary hydration products block the pore system of concrete and makes it discontinuous. Therefore, the final concrete has lower penetrability and higher durability (Chini et al. 2003).

2.7 Temperature

According to ASTM C1202-12, the solution temperature should remain between 20°C and 25°C during the RCP test. As temperature increases, the reported result of the RCP test shows a higher penetrability than the real penetrability of concrete (Bassouni et al. 2006). Electrical resistivity decreases with increase in air temperature as shown in Figure 2.10.

2.8 Cement Type

Different cements have different chemical compositions, and the quantity of ions present in each cement differs from mix to mix. Consequently, electrical resistivity of concrete is closely related to cement type (Neville 1995). Figure 2.11 clearly shows that using different cement could lead to different resistivity.

2.9 Water to Cement Ratio

W/CM ratio represents the amount of water that is evaporable and paste porosity in concrete (Neville 1995). A concrete with a higher W/CM ratio will have more continuous pore systems in addition to having larger pore sizes. Thus, a high W/CM ratio leads to a more permeable concrete and a higher electrical conductivity (Ahmed et al. 2009).

W/CM ratio affects electrical resistivity of concrete in two ways:

1. Since water is a conductive material, a higher W/CM ratio causes a decrease of resistivity (Neville 1995).
2. Electrical resistivity of concrete is dependent on the volume of pores and the connectivity degree, both of which increase in higher W/CM ratio concretes (Andrade 2010).

The W/CM ratio effect can be seen in Figure 2.12.

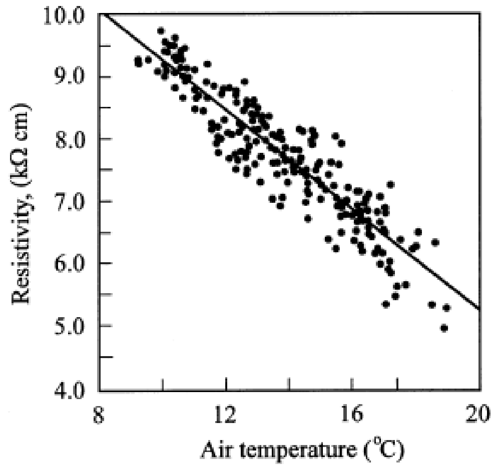


Figure 2.10 Relationship between measured resistivity and air temperature (Gowers and Millard 1999)

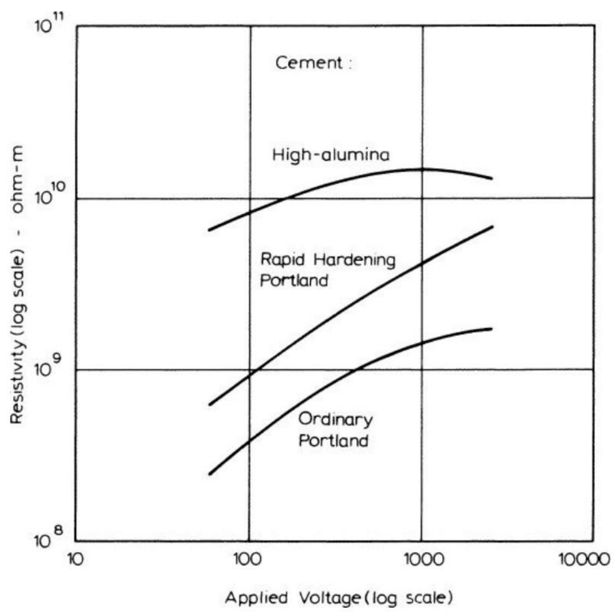


Figure 2.11 Relation between resistivity and applied voltage of different cement concretes with *w/cm* = 0.49 (Neville 1995)

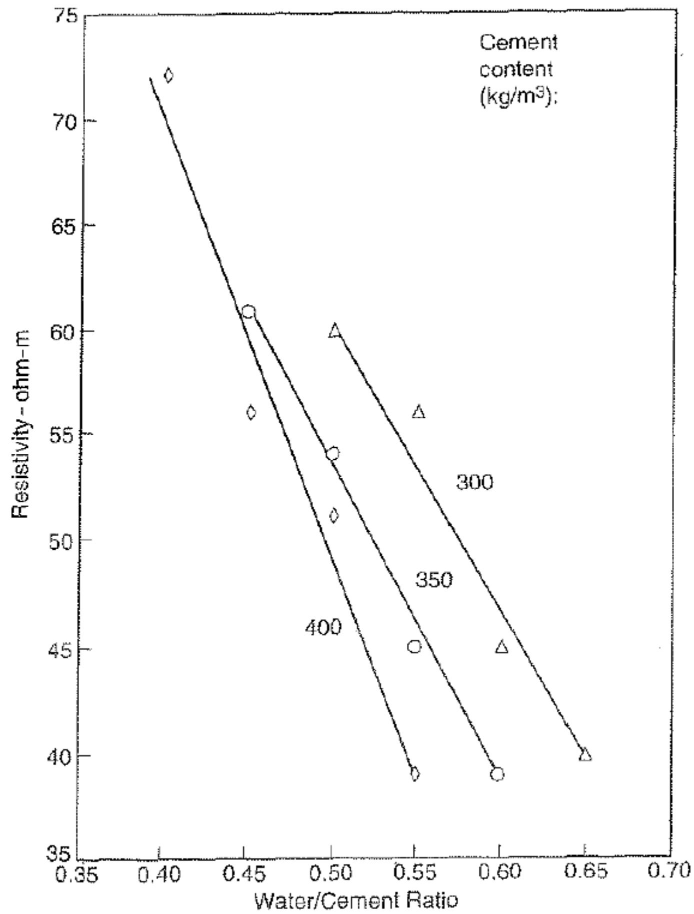


Figure 2.12 Relation between electrical resistivity and W/CM ratio at 28 days with different cement contents (Neville 1995)

2.10 Summary

One objective of this research was to compare field and laboratory mixtures in the state of Utah in order to evaluate the use of resistivity as a quality control measure for bridge deck concretes. In order to standardize and understand the resistivity method, the research team first had to establish variables that could affect the resistivity test. Below are variables that can potentially affect the test:

- Mineral admixtures (e.g., fly ash, silica fume, slag, metakaolin)
- Chemical admixtures (e.g., water reducers, retarders, accelerators, corrosion inhibitors)
- Aggregate type and size (e.g., normal weight, lightweight, heavyweight)

- Paste fraction
- Water-to-cement ratio (*w/cm*)
- Curing methods (e.g., air-cured, water-cured, steam-cured)
- Surface wetting
- Temperature
- Degree of saturation

3.0 RESEARCH METHODS

3.1 Overview

This section describes the research methods and data collection, including concrete mixture proportions, specimen preparation, and test methods.

3.2 Testing Program

In the field phase, 50 cylinders and 3 freeze thaw prisms samples were made from each concrete mixture. In the lab phase, those numbers decreased to 20 cylinders and 3 freeze thaw prisms per concrete mixture. The experimental programs used for each mixture are listed below:

1. Compressive strength
2. Rapid chloride permeability test
3. Surface electrical resistivity test
4. Bulk electrical resistivity test
5. Slump
6. Air content
7. Unit weight
8. Freeze and thaw

3.3 Mixing instructions

Below are the steps that were used to cast concrete:

1. Rinsed the mixer with water
2. Removed any excess (puddled) water from the mixer, the mixer was damp, not wet;
3. Added coarse and fine aggregate to mixer, gradually, and added about quarter of the mix water;
4. Mixed for about 1-2 minutes;
5. Started adding the cement/fly ash/slag and water to the mixer as it was mixing (I added the cement using a scoop and added some of the water after each 2- scoops of cement);

6. After all of the cement and water have been added, the air entrainment admixture was added;
7. Mixed for 1-2 minutes;
8. If it looked like the mixture had a low slump, some water reducer was added;
9. Mixed for 2 minutes;
10. If applicable, I added the other admixtures/steel fiber and mixed for at least 2 minutes;
11. Checked slump, unit weight, air content;
12. Cast specimens (2 layers with 25 times of rodding and 10-15 times of tapping)

3.4 Compressive strength test

All the compression test procedures were performed according to ASTM C39. Three samples for each concrete age—7, 14, 28 and 56 days—were sulfur caped and tested at the recommended loading rate of 352-528 lb/s. Some of the samples were tested with rubber ends due to lack of time. Most of the fracture types were cone and shear, and if a cylinder had an unusual fracture type, it was ignored in accordance with ASTM C39. The average strength of the three samples was reported as the compressive strength of that particular mix at that age. Figure 3.1 shows the compression test apparatus. This apparatus is FX-600F/LA-270 from FORNEY.

Figure 3.1 Compression test machine

3.5 Rapid chloride permeability test

All rapid chloride penetrability tests were performed according to ASTM C1202-12. This test required sample preparation before beginning the RCPT test. In the sample preparation phase, a two-inch slice was cut from the middle of the cylinder and then saturated under pressure for at least one day. The cuts were made using a saw. After the saturation period, the surfaces were dried and sealed in the machine. The RCPT machine consists of two half-cells: one filled with 3.0% NaCl and the other one filled with 0.3 Mole of NaOH. Since temperature can affect this test, the temperature in the NaOH cell was monitored during this test. The temperature during testing had to be less than 90°C to prevent possible boiling of the solution, which could damage the cells. The objective of running this test was to measure the amount of charge passed in coulombs during the 6-hour period of the test. Figure 3.2 shows the RCP test cell while measuring the current and monitoring the temperature in the NaOH cell.

Table 3.1 shows each chloride ion penetrability category at each age. The PROOVE-it by GERMAN INSTRUMENTS used to measure rapid chloride permeability test in this research.

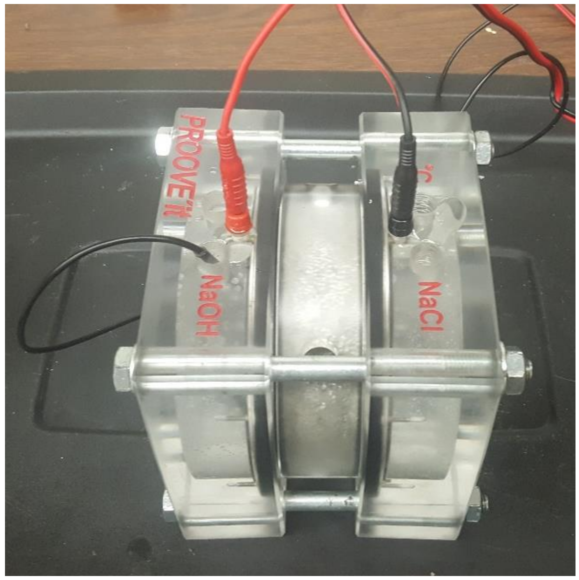


Figure 3.2 RCPT measurement cell with connections made (ASTM C1202)

Table 3.1 Chloride ion penetrability classification for RCPT (ASTM C1202)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

3.6 Surface electrical resistivity

Surface electrical resistivity uses the Wenner method to measure surface electrical resistivity of concrete. This test is according to Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T 358-15). A low frequency alternating current (AC) goes through the two outer probes and the drop in voltage is measured by the two inner probes. The sample used in this test was cured under water. Before beginning this test, the concrete cylinder was surface dried and then placed in the apparatus as shown in Figure 3.3. The results of this experiment showed that it is best to run this test immediately after surface drying the cylinder and it is helpful to put conductive gel on each probe so the probes can connect better to the surface of the cylinder. The apparatus calculates the resistivity in four perpendicular directions, averages all the measurements, and comes up with one resistivity number. One concrete cylinder from each concrete mix was selected to run this test throughout the aging of the concrete. The probe distance was fixed in all the stages of testing and it was 4 cm. The Surf by GIATEC SCIENTIFIC used to measure surface electrical resistivity test in this research. Table 3.2 shows the relation of chloride penetrability classification and surface electrical resistivity at 23°C.

Figure 3.3 Surface resistivity measurement fixture

Table 3.2 Chloride permeability classification based on surface resistivity (Kessler 2005)

Chloride Penetrability	Resistivity (kΩ.cm)
High	<10
Moderate	10-15
Low	15-25
Very low	25-200
Negligible	>200

3.7 Bulk electrical resistivity

The PROOVE-it by GERMAN INSTRUMENTS used to measure bulk electrical resistivity uses Equation 3 to measure the electrical conductivity. This test is according to “Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete” (ASTM C1760-12). Electrical conductivity is the reciprocal of resistivity.

$$\sigma = \frac{K \times I_1 \times L}{(V \times D^2)}$$ **Equation 3**

Where:

Σ = bulk electrical conductivity, mS/m (milliSiemens per meter)

K = Conversion factor = 1273.2

I_1 = current at 1 min, mA

L = average length of specimen, mm

V = Voltage

D = Average diameter of specimen, mm

Table 3.3 shows the relation of chloride penetrability classification and Bulk electrical resistivity (Thomas 2016, Thomas 2018).

Table 3.3 Chloride penetrability classification based on bulk resistivity (Thomas 2016, Thomas 2018)

Chloride Penetrability	**Resistivity (kΩ.cm)**
High	<5
Moderate	5-10
Low	10-20
Very low	20-200
Negligible	>200

3.8 Slump test

A slump test was conducted according to the standard test method for slump of hydraulic-cement concrete (ASTM C143). Slump is one of the fresh concrete properties. As shown in Figure 3.4, the concrete had a slump of 2.5 inches.

3.9 Air content

The air test, like the slump test, is a fresh concrete property and there are multiple ways to find the air content of concrete. Two methods were used in this research. The standard test method for air content of freshly mixed concrete by the volumetric method (ASTM C173) was used for lightweight concrete. The air content of normal and heavyweight concrete was measured by the pressure method (ASTM C231). The apparatus used for the pressure method and the volumetric method are shown in Figure 3.5 and Figure 3.6 respectively.

Figure 3.4 Slump test

Figure 3.5 Pressure air meter

Figure 3.6 Volumetric air meter

3.10 Unit weight

This test was performed according to the standard test method for density (Unit Weight) Yield, and Air Content (Gravimetric) of Concrete (ASTM C138).

3.11 Freeze and thaw

The freeze thaw test was performed according to the standard test method for resistance of concrete to rapid freezing and thawing (ASTM C666). Two prisms with dimensions of 3 in. by 4 in. by 16 in. were made to conduct this test. The prisms were cured under water. This test was done after at least 14 days of curing. In this test, the relative dynamic modulus of elasticity was measured and the durability factor was calculated. The numerical value of the relative dynamic modulus of elasticity is calculated as follows (Equation 4):

$$P_c = \frac{n_1^2}{n^2} \times 100$$

Equation 4

Where:

P_c = relative dynamic modulus of elasticity, after c cycles of freezing and thawing in percent,

N = fundamental transverse frequency at 0 cycles of freezing and thawing

n_1 = fundamental transverse frequency after *c* cycles of freezing and thawing

The durability factor can be calculated as follows (Equation 5):

$$DF = \frac{PN}{M}$$ **Equation 5**

Where:

DF = durability factor of the test specimen

P = relative dynamic modulus of elasticity at N cycles, %

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less

M = specified number of cycles at which the exposure is to be terminated

There are two different procedures for the freeze thaw test. Procedure A is done by rapidly freezing and thawing the concrete in water, and procedure B is done by rapidly freezing the concrete in air and thawing it in water. The research group chose procedure A, rapid freezing and thawing. Within-laboratory durability Factor Precision for Averages of Two or More Beams in procedure A is shown in Table 3.4. Figure 3.7 shows the freeze and thaw machine.

Table 3.4 Within-laboratory durability factor precision for averages of two or more beams under ASTM C666 Procedure A

Range of Average Durability Factor	Number of Beams Averaged									
	2		3		4		5		6	
	Standard Deviation[A]	Acceptable Range[A]	Standard Deviation[A]	Acceptable Range[A]	Standard Deviation[A]	Acceptable Range[A]	Standard Deviation[A]	Acceptable Range[A]	Standard Deviation[A]	Acceptable Range[A]
0 to 5	0.6	1.6	0.5	1.3	0.4	1.1	0.4	1.0	0.3	0.9
5 to 10	1.1	3.1	0.9	2.5	0.8	2.2	0.7	2.0	0.6	1.8
10 to 20	4.2	11.8	3.4	9.7	3.0	8.4	2.7	7.5	2.4	6.8
20 to 30	5.9	16.7	4.8	13.7	4.2	11.8	3.7	10.6	3.4	9.7
30 to 50	9.0	25.4	7.4	20.8	6.4	18.0	5.7	16.1	5.2	14.7
50 to 70	10.8	30.6	8.8	25.0	7.6	21.6	6.8	19.3	6.2	17.6
70 to 80	8.2	23.1	6.7	18.9	5.8	16.4	5.2	14.6	4.7	13.4
80 to 90	4.0	11.3	3.3	9.2	2.8	8.0	2.5	7.2	2.3	6.5
90 to 95	1.5	4.2	1.2	3.5	1.1	3.0	0.9	2.7	0.9	2.4
Above 95	0.8	2.2	0.6	1.8	0.5	1.5	0.5	1.4	0.4	1.3

[A] These numbers represent the (1S) and (D2S) limits as described in Practice C 670.

Figure 3.7 Freeze-thaw test chamber

Figure 3.8 shows the test apparatus used to measure the relative dynamic modulus of elasticity. One end of the prism was connected to an accelerometer and the other side was struck with a hammer. The prism was supported in the middle by a metal rope. A dynamic signal analyzer measured the strike and relative dynamic modulus of elasticity. The dynamic signal analyzer 35670A by HEWLETT PACKARD (hp) was used for doing this test.

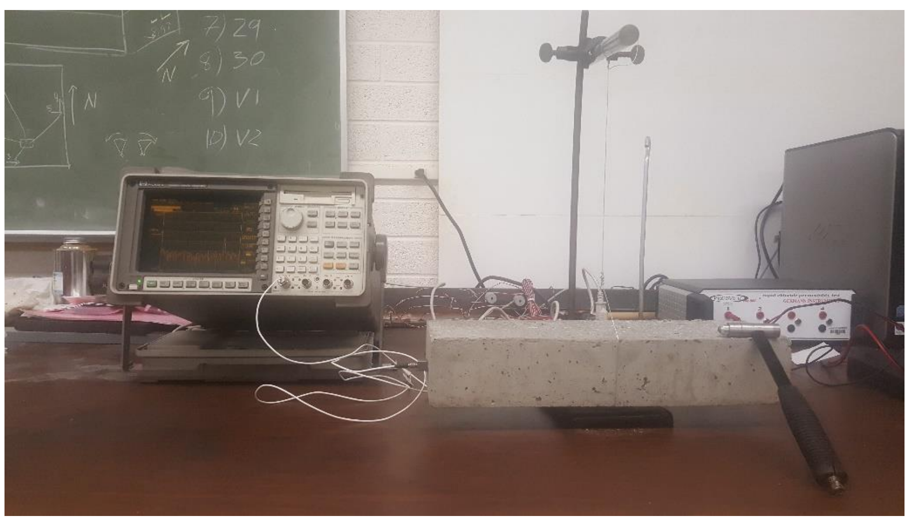


Figure 3.8 Resonant frequency test setup

3.12 Mix designs

In the field phase, eleven different mixes were cast in the laboratory environment. Mix design properties are shown in Table 3.4. A more detailed table for each field mix design gathered in this phase can be found in APPENDIX A: DETAILED FIELD MIXTURE DESIGNS AND RAW DATA. All amounts are for one cubic yard of concrete under dry conditions. D4 0.42 was chosen to be the control mix for the lab phase. Different chemical admixtures, different aggregate, slag cement, and steel fiber were used in this phase.

The design strength, weight, water to cement ratio, and company that made each type of concrete in the field phase can be determined from the name of the mix as follows: the first letter of each name represents the company who made it, the following number represents the design strength, an L represents a lightweight mix (no L means it is not lightweight), and the last number is the water to cement ratio. For instance, A4L 0.44 means the concrete was cast in company A and is a 4 ksi design mix with lightweight aggregate. In addition, the water to cement ratio is 0.44.

Some supplementary cementitious materials (SCMs) and admixtures were tested in the lab phase to observe their effect on resistivity. For instance, slag cement is ground granulated blast-furnace slag (GGBFS) which is a byproduct of iron manufacturing and is often used as a pozzolan. Fly ash which is also a SCMs, is a byproduct from burning pulverized coal in electric power plant. Fly ash enhances strength, resistance to segregation, and ease of pumping. Metakaolin is a calcined product of the clay mineral kaolinite. Metakaolin particles are smaller than cement, but larger than Silica fume. A mixture of cement and Metakaolin will reduce the pore size to about a tenth (Verein 2002). Silica fume is a byproduct of manufacturing silicon metal or ferrosilicon alloys. Silica fume is very fine and it is finer than cement. Silica fume helps the durability and strength of concrete. VCAS™ pozzolans are made from Vitrified Calcium Aluminio-Silicate material having low alkali content. This pozzolans is not cementations.

Several chemical admixtures were also investigated. Hycrete™ is a waterproofing and corrosion protection admixture for concrete. According to Hycrete website, this admixture reduces the penetrability of concrete and also makes a protective layer around the reinforcing steel. (Hycrete.com). MasterLife® CI 30 was used as a corrosion inhibiting admixture in the lab phase. This is a calcium nitrite based corrosion inhibiting admixture. MasterSet® AC 534 is an Accelerating Admixture. This admixture does not contain calcium chloride and it will accelerate the setting time of concrete. MasterMatrix® VMA 362 is a Viscosity-Modifying Admixture (VMA) used in this research. This admixture increases the resistance to segregation.

Table 3.5 Field mixture proportions

Mix Design	Design Strength (psi)	*w/cm*	Air (%)	Slump (in)	Cement (lb)	Fly Ash (lb)	Coarse Aggregate (lb)	Fine Aggregate (lb)	Water (lb)	Water Reducer (fl oz)	Air Entrainer (fl oz)	Accelerating Admixture (fl oz)	VMA	Hydration Controlling Admixture
D4 0.42	4000	0.42	5-7.5	3-6	489	122	1643	1320	254	4 oz/cwt	--	--	--	--
A4L 0.44	4000	0.44	5-7.5	4.5-7.5	564	141	1092	1069	310.4	7 (A, D) +14 (A, F)	9 oz/cwt	--	--	--
B5 0.37-	5000	0.368	5-7.5	4-8.5	639	160	1550	1030	292	19.18 + 47.94	3.6	127.84	--	--
B5 0.37+	5000	0.372	6	4-9	564	141	1615	1145	260	14.10 + 42.30	3.17	112.8	--	--
A5 0.4	5000	0.4	5-7.5	3-5	564	141	1689	1044	282.1	21	19	--	--	--
A5L 0.4	5000	0.4	4.5-7.5	3-5	564	141	1676	353(LW fines) +581(Sand)	278.7	20	10	--	--	--
B6L 0.37	6000	0.368	5-7.5	4-9	640	160	1155	971	292	16 + 52	3.6	128	--	--
A6 0.37	6000	0.37	5-7.5	4-9	602	150	1613	1084	280.4	15(A, D) + 90(A, F)	19	--	--	--
C10 0.32	10000	0.33	5-7.5	22	700	175	1014	1055(Sand) +499(Medium)	280	16 oz/cwt	0.55 oz/cwt	--	0.8 oz/100wt	0.6 oz/100wt

Table 3.6 Laboratory mixture proportions

Mix Design	Design Strength (psi)	W/CM	Air (%)	Cement (lb)	Fly Ash (lb)	Coarse Aggregate (lb)	Fine Aggregate (lb)	Water (lb)	Water reducer	Air entrainment	More information
Control (D4 0.42)	4000	0.42	5-7.5	489	122	1643	1320	254	4 oz/cwt	0.35 oz/cwt	--
Slag cement	4000	0.42	5-7.5	489	0	1643	1320	254	4 oz/cwt	0.35 oz/cwt	150 lb of Slag cement
Steel fiber	4000	0.42	5-7.5	489	122	1643	1320	254	4 oz/cwt	0.35 oz/cwt	40lbs/yd^3 of steel fiber
Water reducer	4000	0.42	5-7.5	489	122	1643	1320	254	till get 9 in slump	0.35 oz/cwt	--
Velocity Modifying Admixture	4000	0.42	5-7.5	489	122	1643	1320	254	4 oz/cwt	0.35 oz/cwt	8 fl oz/cwt of VMA
Accelerator (Master Set)	4000	0.42	5-7.5	489	122	1643	1320	254	4 oz/cwt	0.35 oz/cwt	28 fl oz/cwt of Accelerator
High Air	4000	0.42	9	489	122	1643	1320	254	4 oz/cwt	Till get 9% air	--
Low Air	4000	0.42	3	489	122	1643	1320	254	4 oz/cwt	Till get 3% air	--
Corrosion Inhibiting Admixture	4000	0.42	5-7.5	489	122	1643	1320	254	4 oz/cwt	0.35 oz/cwt	3 gal/yd^3 of Corrosion Inhibiting Admixture
Magnetite Aggregate	5000	0.42	2.5	458	--	3080	2648	260	--	--	It contains 153 lb of slag cement
Hematite Aggregate	5000	0.45	2.5	458	--	3230	2500	280	--	--	It contains 153 lb of slag cement
Internally Cured Concrete	4000	0.3	6	734	122	874 (N)+ 263 (L)	1643 (N)	254	6 oz/cwt	0.35 oz/cwt	N: Normal weight L: Lightweight
Fine Lightweight Replacement	4000	0.3	6	734	122	1643 (N)	778 (L)	254	6 oz/cwt	0.35 oz/cwt	N: Normal weight L: Lightweight
Full Lightweight Replacement	4000	0.3	6	734	122	1064 (L)	778 (L)	254	6 oz/cwt	0.35 oz/cwt	N: Normal weight L: Lightweight

Table 3.7 USU mixture proportions

Mix Design	Design Strength (psi)	W/CM	Air (%)	Cement (lb)	Coarse Aggregate Rock (lb)	Coarse Aggregate Pea Gravel (lb)	Fine Aggregate (lb)	Water (lb)	Water Reducer	Air Entrainment	More information
USU with Hycrete	4500	0.44	6	640	1490	250	1177	283	58 lq oz	3 lq oz	128 lq oz of Hycrete
USU without Hycrete	4500	0.44	6	640	1490	250	1177	283	58 lq oz	3 lq oz	--
20% Fly ash Replacement	4500	0.44	6	513	1490	250	1177	283	58 lq oz	3 lq oz	114 lb of Fly ash
20% Metakaolin Replacement	4500	0.44	6	513	1490	250	1177	283	58 lq oz	3 lq oz	102 lb of Metakaolin
20% Silica fume Replacement	4500	0.44	6	513	1490	250	1177	283	58 lq oz	3 lq oz	94 lb of Silica fume
20% V-CAS Replacement	4500	0.44	6	513	1490	250	1177	283	58 lq oz	3 lq oz	106 lb of V-CAS

Table 3.8 RCA mixture proportions

Mix Design	W/C	Air (%)	Cement (lb)	Course Aggregate (lb)	Coarse RCA (lb)	Fine Aggregate (lb)	Fine RCA (lb)	Water (lb)	More Info
0 % RCA	0.35	1.5	611	1634	0	1332	0	217	750 ml Water Reducer
30 % RCA-rock without RCA-Sand	0.35	1.5	611	1144	490	1332	0	217	750 ml Water Reducer
100 % RCA-rock without RCA-Sand	0.35	1.75	611	0	1634	1332	0	217	750 ml Water Reducer
30 % RCA-rock with RCA-Sand	0.35	1.75	611	1144	490	932	400	217	750 ml Water Reducer
100 % RCA-rock with RCA-Sand	0.35	1	611	0	1634	0	1332	217	750 ml Water Reducer
100 % RCA-rock without RCA-Sand	0.35	0.75	611	0	1634	0	1332	217	750 ml Water Reducer

3.13 Inter-laboratory Investigation

In order to investigate if different surface resistivity apparatuses would provide different results, a small inter-laboratory investigation was performed. Six samples were transported from the USU curing room to the UDOT fog room. All the samples were under water during transportation. They were in the UDOT fog room for five days in order to reach temperature and moisture content equilibrium. Some of the samples were made with normal weight aggregates and some were made with the heavy weight aggregates. The purpose of this investigation was to determine if the different machines would result in the same resistivity. In this investigation, each sample was tested at the same time with two machines side by side as shown in Figure 3.9. After the test was done on one machine, the same sample was tested on the other machine at the same orientation (±10°) and the results were compared.

Figure 3.9 Inter-laboratory comparison of surface resistivity

3.14 Summary

In this chapter, each test method was outlined and each individual mix design was presented. In the next chapter, data will be evaluated and the findings will be presented.

4.0 RESULTS

4.1 Overview

As discussed previously, the investigation was performed in several phases: (1) Evaluation of field mixtures, (2) evaluation of laboratory mixtures, (3) evaluation of mixtures used on USU campus, and (3) evaluation of mixtures with reclaimed concrete aggregate (RCA). This section presents the results of compressive strength, RCPT, surface resistivity, and bulk resistivity tests of concrete mixtures from these four project phases. The results are disseminated in the context of the suitability of resistivity-based methods as replacements for the RCPT.

4.2 Test results

Table 4.1 presents the average RCPT, surface resistivity, bulk resistivity, and compressive strength results for the nine field mixtures at 7, 14, 28, and 56 d. Also given in the figure are the chloride permeability classifications based on the information presented in Section 2. Similarly,

Table 4.2 presents the results for the eleven laboratory mixtures, Table 4.3 presents the results for the six USU mixtures, and Table 4.4 presents the results for the six RCA mixtures. Table 4.5 presents the results of the inter-laboratory variability study.

Table 4.1 Average RCPT, resistivity, and compressive strength results for field mixtures at 7, 14, 28, and 56 d (H = high, M = moderate, L = low, VL = very low, N = negligible)

	RCPT (C)				**Surface resistivity (kΩ.cm)**				**Bulk resistivity (kΩ.cm)**				**Compressive strength (psi)**			
	7 d	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**
D4 0.42	4963 H	3852 M	3255 M	2183 M	5.3 H	7.2 H	8.2 H	10.2 M	6.4 M	8.2 M	9.8 M	10.3 L	3862	4053	4567	4825
A4L 0.44	4952 H	3579 M	2257 M	1954 L	3.7 H	5.4 H	7.7 H	9.8 H	7.5 M	9.3 M	11.4 L	11.7 L	3009	5283	5437	5562
B5 0.37-	2722 M	2168 M	1634 L	1389 L	12.3 M	16.4 L	20.3 L	25.7 VL	11.4 L	14.2 L	18.9 L	16.9 L	4372	5874	7348	9000
B5 0.37+	2938 M	2241 M	1756 L	626 VL	7.4 H	13.5 M	19.3 H	27.8 VL	10.1 L	13.8 L	17.8 L	20.2 VL	4345	5234	6859	7950
A5 0.4	3461 M	2697 M	2432 M	1966 L	4.6 H	8.8 H	10.2 M	13.1 M	8.7 M	12.0 L	14.4 L	14.8 L	4301	4850	5369	6434
A5L 0.4	3586 M	2788 M	2591 M	2263 M	4.6 H	5.3 H	6.4 H	7.3 H	6.8 M	8.7 M	10.2 L	10.6 L	3403	4873	5663	5974
B6L 0.37	3877 M	3264 M	2863 M	2543 M	4.2 H	6.3 H	8.2 H	12.4 M	8.6 M	10.4 L	12.1 L	13.3 L	4637	5468	6125	7157
A6 0.37	3973 M	3312 M	2729 M	2426 M	5.5 H	7.6 H	8.7 H	10.3 M	8.3 M	10.5 L	13.0 L	13.7 L	4948	5926	6430	6890
C10 0.32	1956 L	1759 L	1289 L	917 VL	9.4 H	12.9 M	15.3 L	21.2 L	12.7 L	16.0 L	19.3 L	20.8 VL	5547	7689	9562	10993

Table 4.2 Average RCPT, resistivity, and compressive strength results for laboratory mixtures at 7, 14, 28, and 56 d (H = high, M = moderate, L = low, VL = very low, N = negligible)

	RCPT (C)				Surface resistivity (kΩ.cm)				Bulk resistivity (kΩ.cm)				Compressive strength (psi)			
	7 d	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**
Slag cement	4039 H	3168 M	2336 M	1437 L	4.4 H	5.9 H	10.5 M	16.8 L	5.2 M	7.3 M	8.6 M	9.5 M	3791	5935	7366	8863
Water reducer	3656 M	2319 M	1362 L	579 VL	6.5 H	13.6 M	20.6 L	20.8 L	10.1 L	14.2 L	17.5 L	18.9 L	2856	4495	5375	6067
VMA	2711 M	2243 M	1879 L	1422 L	6.9 H	12.3 M	17.3 L	20 L	8.8 M	13.8 L	16.7 L	20.8 VL	2869	4684	5628	6667
Master set	4261 H	3268 M	2136 M	1839 L	5.9 H	10.2 M	14 M	14.7 M	7.3 M	10.2 L	12.1 L	15.4 L	2923	4577	5541	6561
High air	2719 M	1681 L	835 VL	216 VL	9.6 H	20.8 L	25.7 VL	32.8 VL	6.1 M	8.9 M	11.7 L	15.8 L	2641	3664	4568	5253
Control-lab	3154 M	1717 L	954 VL	1 N	9.3 H	13.7 M	17.3 L	20.9 L	11.1 L	13 L	14.3 L	15.4 L	4923	5360	6113	7258
Low air	2833 M	1925 L	1368 L	1166 L	8.7 H	17.9 L	24.4 L	32.1 VL	7.5 M	11.8 L	15.4 L	17.6 L	4167	6147	7925	8965
Steel fiber	3248 M	2417 M	1357 L	686 VL	6.4 H	8.3 H	16.9 L	19.6 L	5.8 M	7.8 M	8.9 M	9.3 M	2365	3761	4729	5381
Magnetite	1867 L	723 VL	210 VL	4 N	7.7 H	10.9 M	14.1 M	8.5 H	9.1 M	13.4 L	16.7 L	20.2 VL	3331	4441	5627	6453
Hematite	1546 L	617 VL	87 N	4 N	3.5 H	1.7 H	3.6 H	14.2 M	7.4 M	10.5 L	14 L	16.0 L	5368	6937	8411	9637
Corrosion	3526 M	2562 M	1615 L	1193 L	6.3 H	11.2 M	18.1 L	19.4 L	4.8 M	5.9 M	8.1 M	9.5 M	3928	5398	6797	7909

Table 4.3 Average RCPT, resistivity, and compressive strength results for USU mixtures at 7, 14, 28, and 56 d (H = high, M = moderate, L = low, VL = very low, N = negligible)

	RCPT (C)				Surface resistivity (kΩ.cm)				Compressive strength (psi)			
	7 d	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**	**7 d**	**14**	**28**	**56**
USU with Hycrete	--	3104 M	4934 H	1043 L	8.6 H	12.6 M	15.8 L	40.1 VL	2459	3241	2921	3121
USU without Hycrete	1491 L	1759 L	3517 M	0 N	9.4 H	11.8 M	0 H	18.3 L	4466	5845	6453	6056
20% Fly ash Replacement	315 VL	138 VL	793 VL	0 N	10.3 M	14.4 M	20.5 L	35.7 VL	3802	3863	4803	4922
20% Metakaolin Replacement	2784 M	1661 L	1261 L	1184 L	14.7 M	54.4 VL	91.4 VL	127 VL	6387	6858	7835	7281
20% Silica fume Replacement	4902 H	1653 L	--	480 VL	16.6 L	47.5 VL	118 VL	235 N	4383	5312	5222	6591
20% V-CAS Replacement	7655 H	5615 H	677 VL	981 VL	8.2 H	15.4 L	27.5 VL	58 VL	3746	4367	3907	3832

Table 4.4 Average resistivity and compressive strength results for RCA mixtures at 7, 14, 28, and 56 d (H = high, M = moderate, L = low, VL = very low, N = negligible)

	Surface resistivity (kΩ.cm)			Compressive strength (psi)		
	7d	**14**	**28**	**7**	**14**	**28**
0 % RCA	12.2 M	16.2 L	20.9 L	8811	9506	9802
30% Coarse RCA	11.8 M	13.8 M	20.2 L	7960	8946	9087
100% Coarse RCA	11.5 M	14.2 M	17.6 L	8035	8598	8756
30% Coarse and Fine RCA	10.8 M	11.5 M	16.5 L	8297	8423	9038
100% Coarse and Fine RCA (1)	5.8 H	5.2 H	7.8 H	6291	6988	7350
100% Coarse and Fine RCA (2)	7.0 H	8.8 H	15.0 L	7053	8142	--

Table 4.5 Inter-laboratory variability of surface resistivity

Sample No.	1	2	3	4	5	6
UDOT Machine (kΩ.cm)	43.3	40.8	20	24.7	6.8	45.6
USU Machine (kΩ.cm)	44.4	45.9	21.1	24.3	7.3	44.5
Error (%)	2.46	12.42	5.5	1.6	7.4	2.34

4.3 Discussion

4.3.1 Field mixtures

Figure 4.1 shows the compressive strength development of field concrete mixtures. Compressive strength differences between mixtures resulted from variations in *w/cm*, curing condition, and inclusion of SCMs, but the compressive strength of all field mixtures exceeded the design strength after 28 d curing. 28-d compressive strengths ranged from as low as 4,000 psi to around 11,000 psi, which should be expected to provide a wide range of chloride penetrability. Figure 4.2 presents RCPT results for field mixtures. As expected, the charge passed during

RCPT decreased with time because of continued refinement of the concrete pore structure. Similar results were observed for surface resistivity (Figure 4.3) and bulk resistivity (Figure 4.4) measurements, except that reduced penetrability at later age manifests as an increase in resistivity with time.

In general, the RCPT, surface resistivity, and bulk resistivity results followed compressive strength. Mixtures with high compressive strength exhibited low charge passed during RCPT and high surface and bulk resistivity. Mixtures with lower compressive strength exhibited higher charge passed during RCPT and lower surface and bulk resistivity.

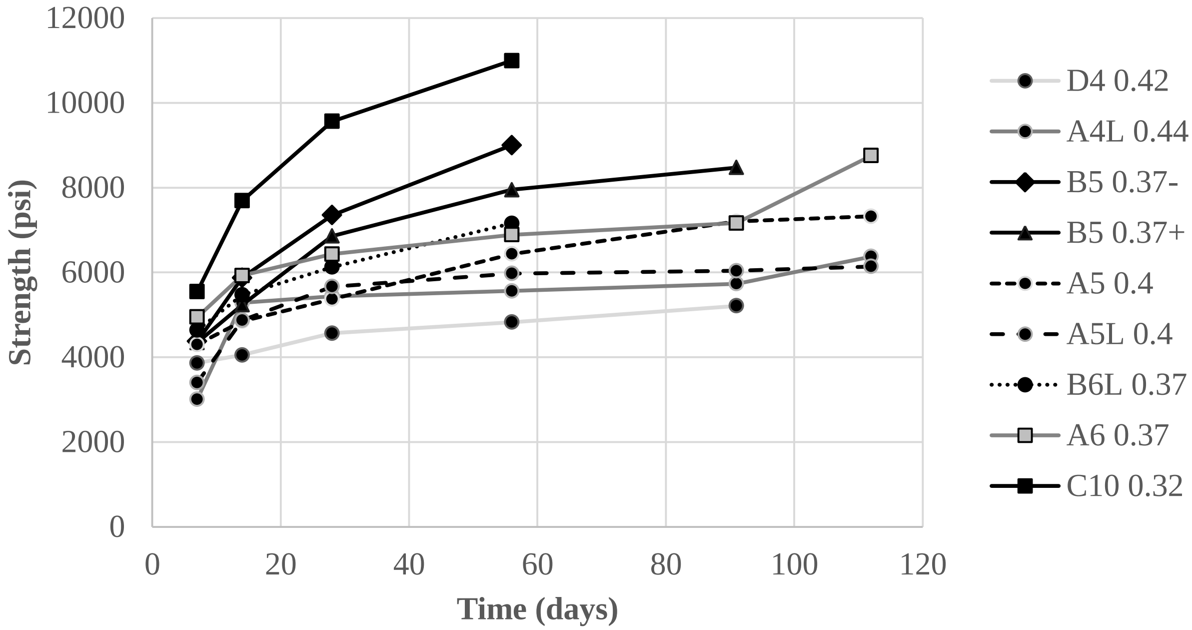


Figure 4.1 Compressive strength development of field mixtures

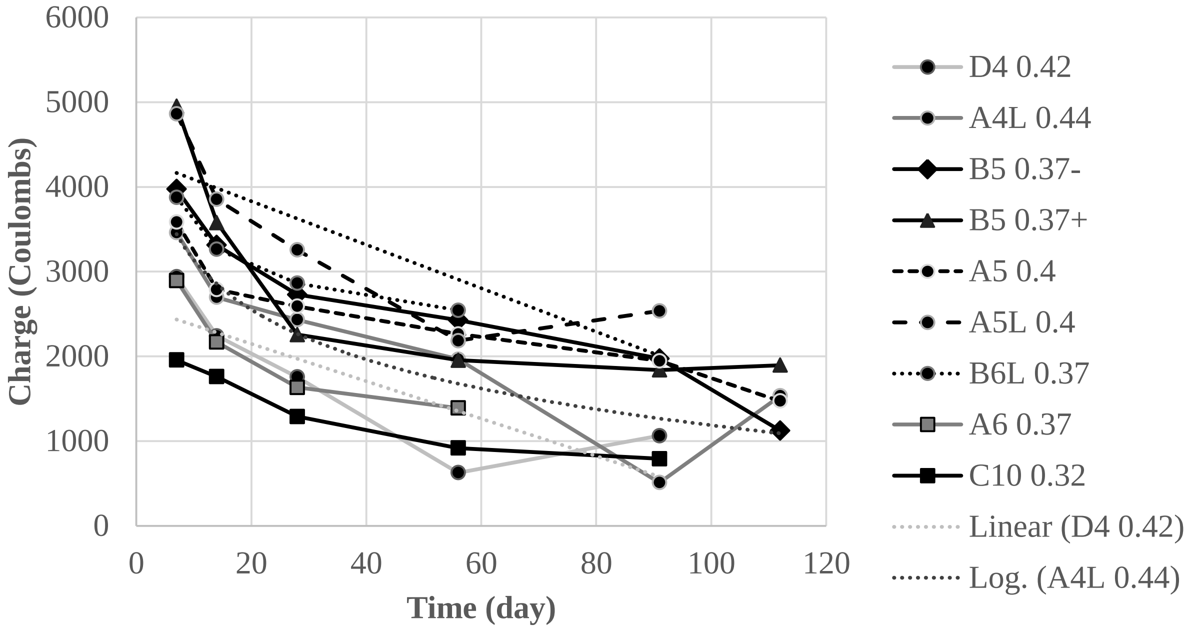


Figure 4.2 RCPT results for field mixtures

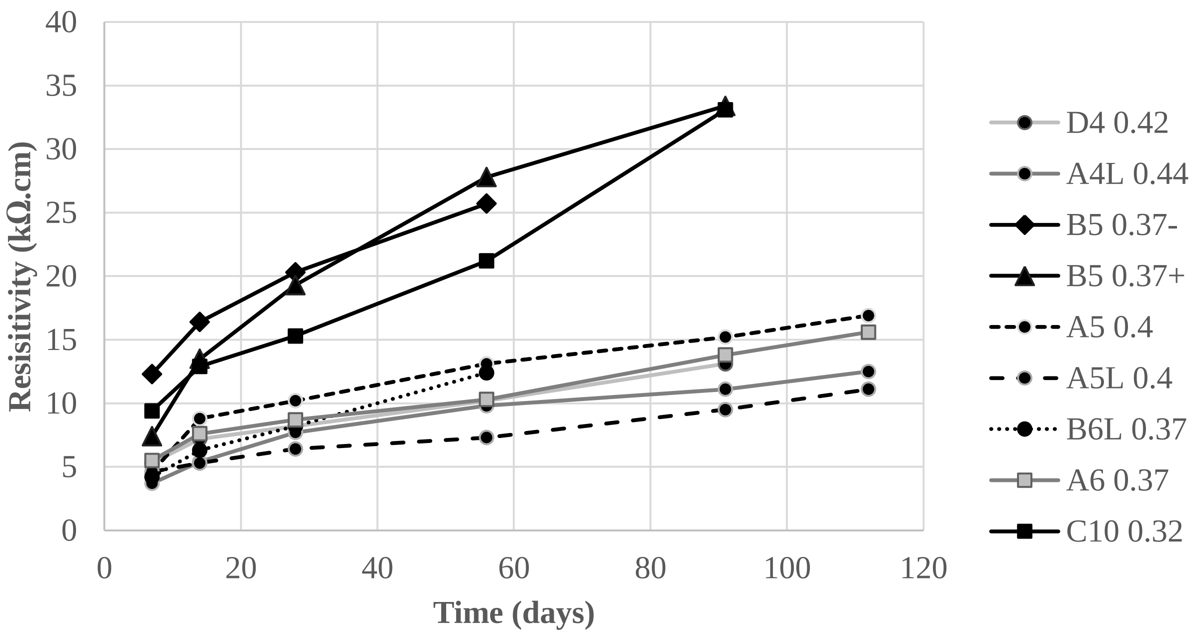


Figure 4.3 Surface resistivity results for field mixtures

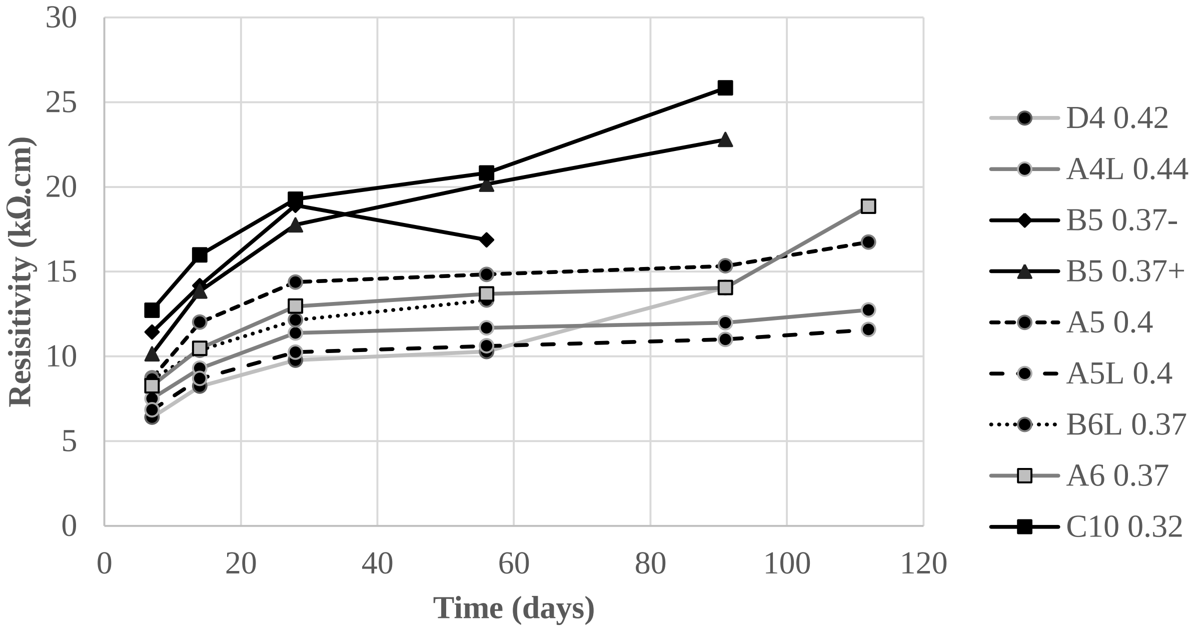


Figure 4.4 Bulk resistivity results for field mixtures

The researchers classified each mixture for chloride permeability based on the classifications presented in Section 2. For several of the field mixtures, all three tests indicated the same chloride penetrability. However, for most mixtures, there was some disagreement between the chloride penetrability classifications based on RCPT, surface resistivity, and bulk resistivity. In all cases, surface resistivity indicated either the same chloride penetrability as RCPT or one level worse than indicated by RCPT. Meanwhile, in some cases, bulk resistivity indicated better chloride penetrability than RCPT. In short, this means that, using the classifications discussed in Section 2, surface resistivity is a conservative test, while bulk resistivity is non-conservative. These results show promise for adoption of the surface resistivity test as a replacement for RCPT.

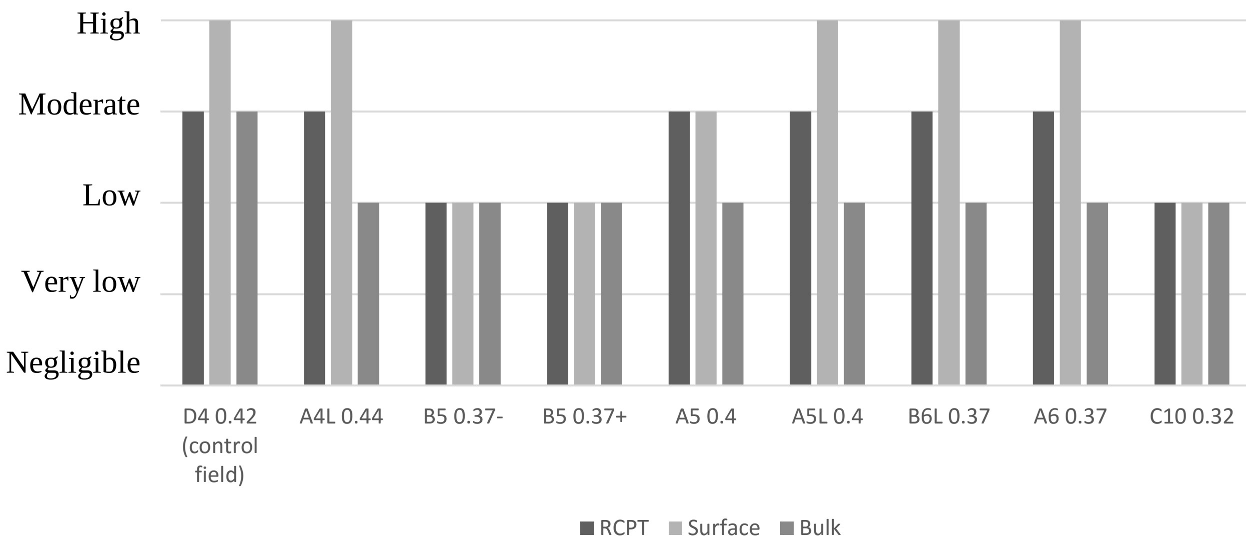
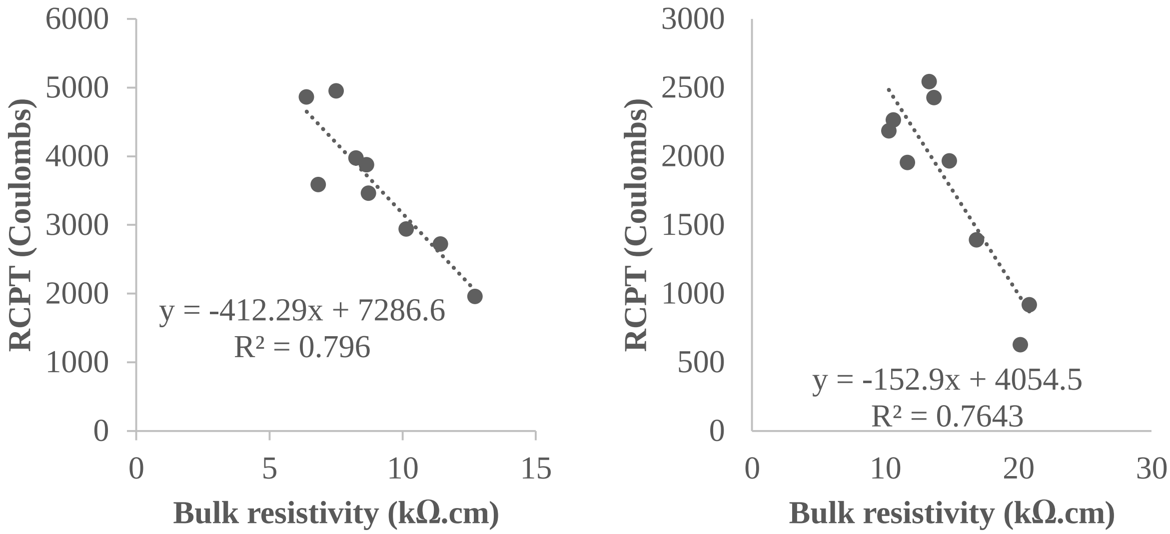


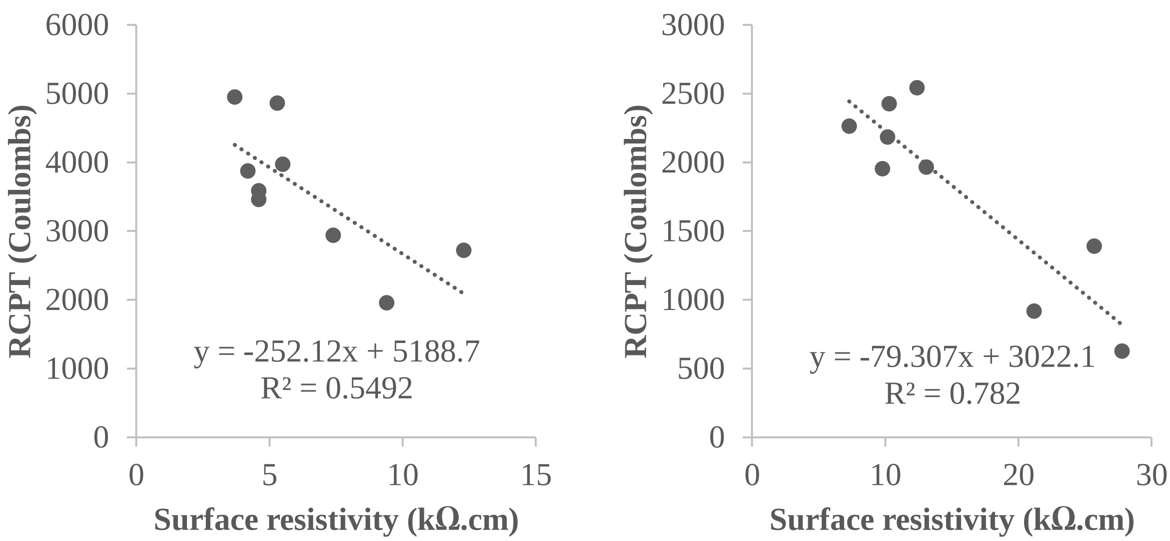
Figure 4.5 Chloride penetrability of field mixtures at 28 d

Figure 4.6–Figure 4.9 compare the various properties measured during the field study in order to determine which properties were best correlated to one another. Comparisons are made at both early age (7 d) and later age (56 d) in order to capture a more complete picture of the correlation between properties. Figure 4.6 compares RCPT and bulk resistivity, showing the expected inverse correlation. A similar relationship is observed between RCPT and surface resistivity in Figure 4.7. Figure 4.8 shows good positive correlation between surface and bulk resistivity. Finally, Figure 4.9 shows a relatively weak correlation between compressive strength and surface resistivity. The correlation is positive at early age—which is the expected trend—but negative at later age. The reason for this unexpected result is unknown to the researchers.



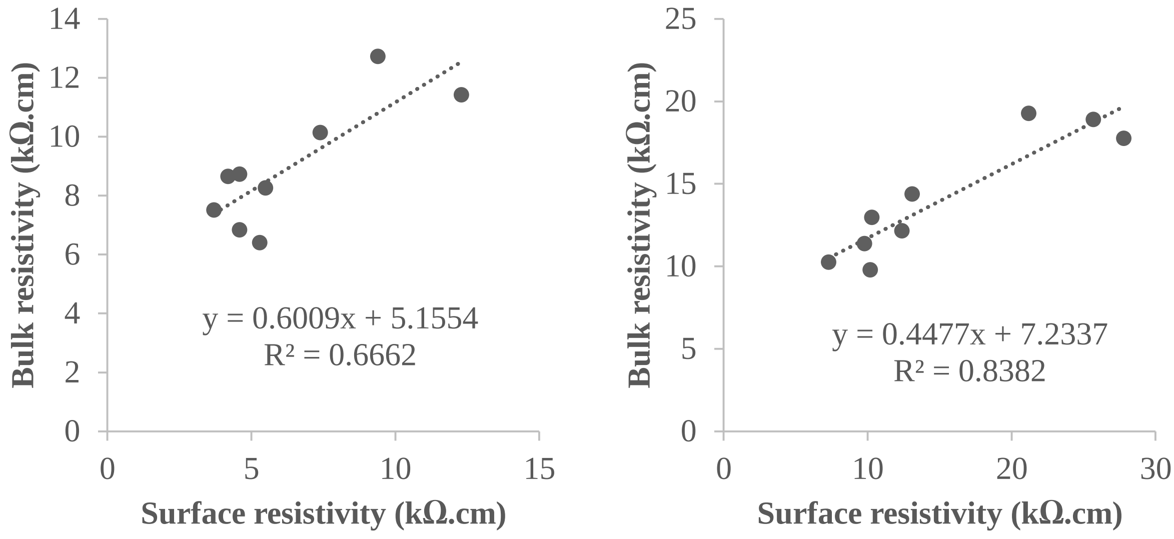
(a) (b)

Figure 4.6 RCPT vs. bulk resistivity for field mixtures at (a) 7 and (b) 56 d



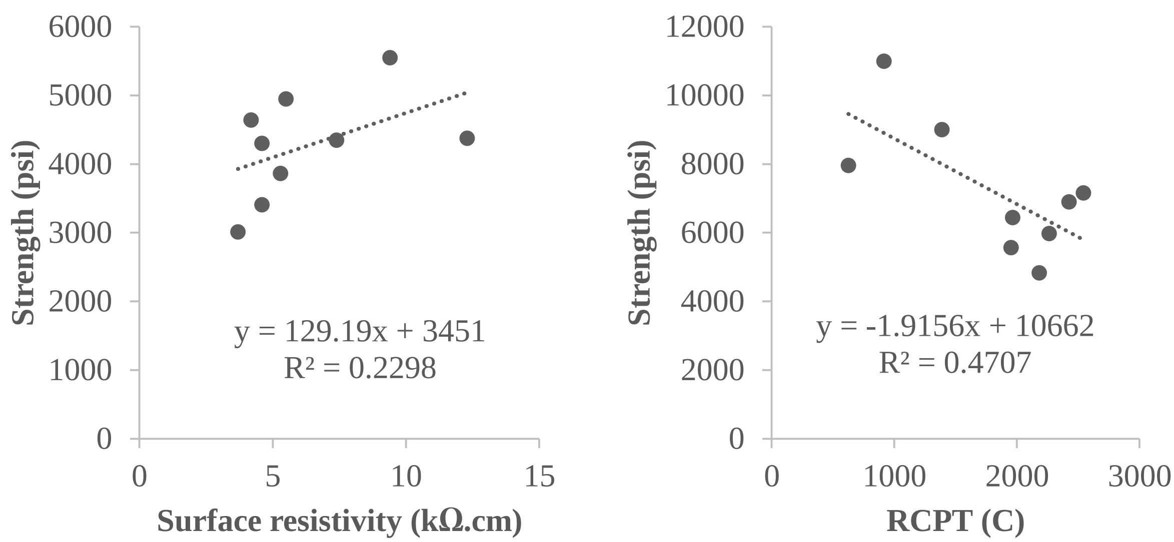
(a) (b)

Figure 4.7 RCPT vs. surface resistivity for field mixtures at (a) 7 and (b) 56 d



(a) (b)

Figure 4.8 Bulk vs. surface resistivity for field mixtures at (a) 7 and (b) 56 d



(a) (b)

Figure 4.9 Compressive strength vs. RCPT for field mixtures at (a) 7 and (b) 56 d

Bulk electrical resistivity and RCPT have a linear correlation in almost concrete ages. In addition, there is a good correlation between strength, RCPT, bulk, and surface electrical resistivity at the age of 28 days.

In order to elucidate the effects of lightweight aggregates on RCPT, surface resistivity, and bulk resistivity tests, Table 4.6 compares results for field mixtures with normal weight and lightweight aggregates. Field mixtures A5 0.4 and A5L 0.4 were identical, except that the latter was made with lightweight aggregate. Despite the mixture being otherwise identical, the mixture with normal weight aggregate performed better under all three tests than its lightweight counterpart. The inclusion of lightweight aggregates in concrete mixtures can result in reduced workability and increased variability in fresh and mechanical properties due to differences in the mixture rheology. In addition, saturated lightweight aggregates can introduce additional water into the curing concrete, thereby increasing the effected *w/cm*. These can all reduce the chloride penetrability, as observed here.

Table 4.6 Comparison of normal weight and lightweight filed mixtures at 56 d

(H = high, M = moderate, L = low)

Mixture	**Type**	**RCPT (C)**	**Bulk (kΩ.cm)**	**Surface (kΩ.cm)**
A5 0.4	Normal weight	1966 L	14.83 H	13.1 M
A5L 0.4	Lightweight	2263 M	10.61 H	7.3 H

4.3.2 Laboratory mixtures

Figure 4.10 presents the compressive strength development of eight laboratory concrete mixtures. The 28-d compressive strength of the control mixtures was approximately 6,000 psi. Internal curing, additions of lightweight aggregates, corrosion inhibitors, or slag cement improved compressive strength, while additions of heavyweight aggregates, water reducers, steel fibers, and air entrainers reduced compressive strength. Some of these effects are unexpected; for example, additions of steel fibers and heavyweight aggregates should be expected to improve compressive strength. However, the intent of this investigation is to elucidate the effects of these materials on chloride penetrability tests, so this unexpected result is not concerning. The range of 28-d compressive strengths observed in laboratory mixtures was 4,000–9,000 psi.

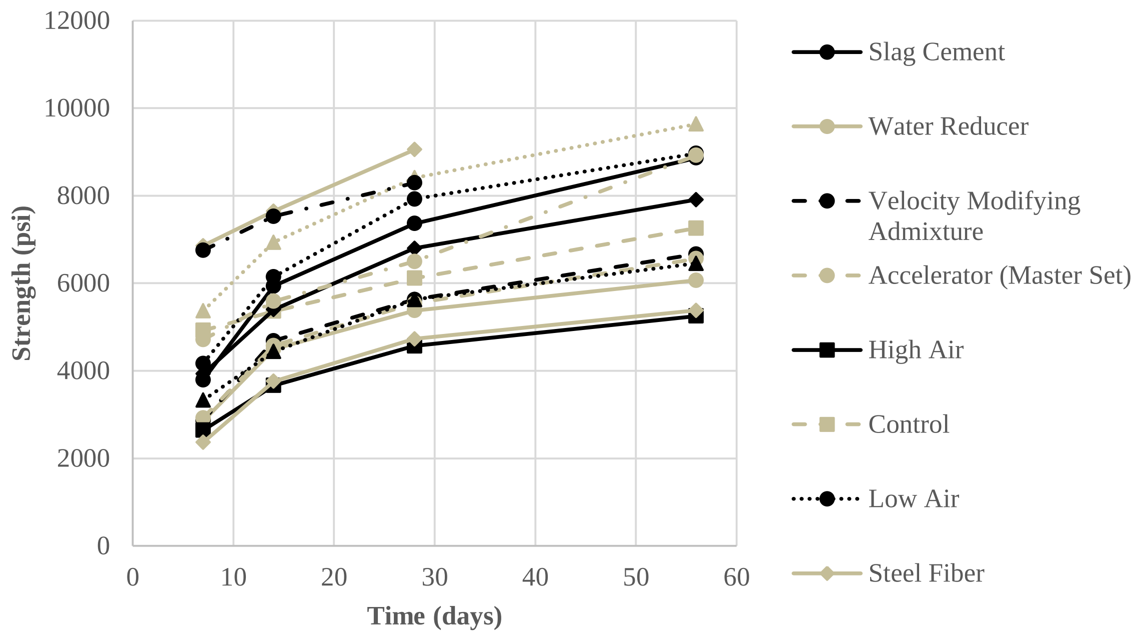


Figure 4.10 Compressive strength development of laboratory mixtures

Chloride penetrability results are presented in Figure 4.11 (RCPT), Figure 4.12 (surface resistivity), and Figure 4.13 (bulk resistivity). As in the laboratory study, the results generally followed compressive strength. Mixtures with high compressive strengths exhibited low chloride penetrability as evidenced by low charge passed under RCPT and high surface and bulk resistivity. At 28 d, the control mixture exhibited very low chloride penetrability according to the RCPT, and low chloride penetrability according to both resistivity methods. The worst performance was observed for mixtures with accelerating admixtures and slag cement. The former effect is completely expected, as accelerators are known to affect electrical indications of chloride penetrability. However, the latter effect is the opposite of the expected. Interestingly, heavyweight aggregates, including magnetite and hematite, exhibited very good performance under RCPT but very poor performance under the surface resistivity test, suggesting that the electrical conductivity of these materials tricks the resistivity tests. The best performing mixture was that with high air content.

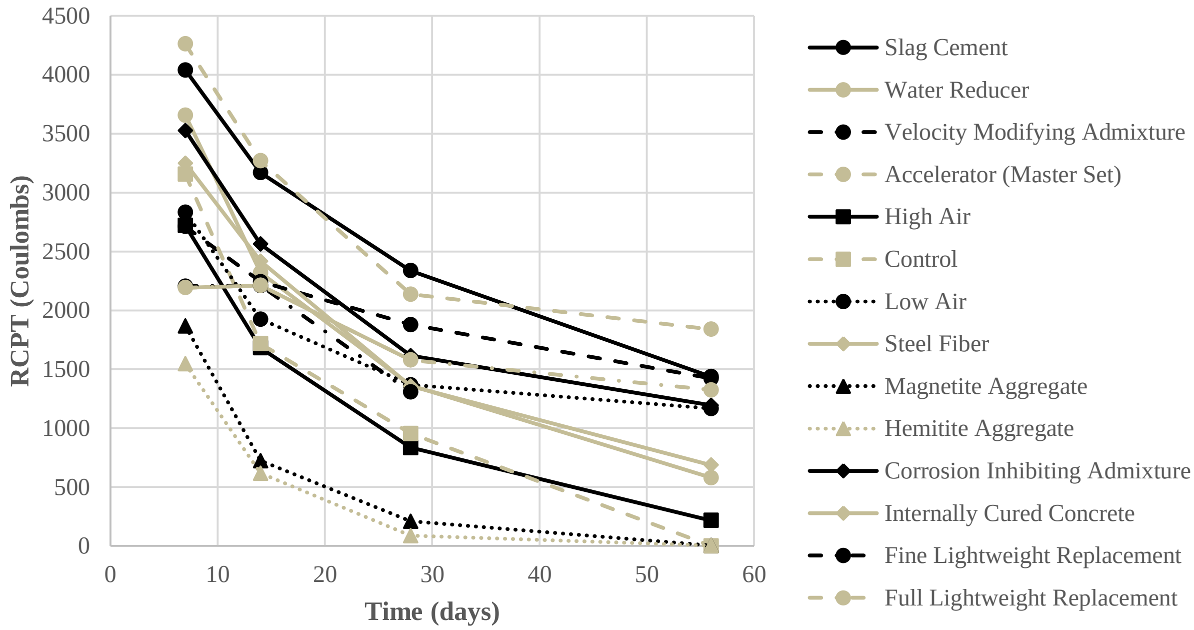


Figure 4.11 RCPT results for laboratory mixtures

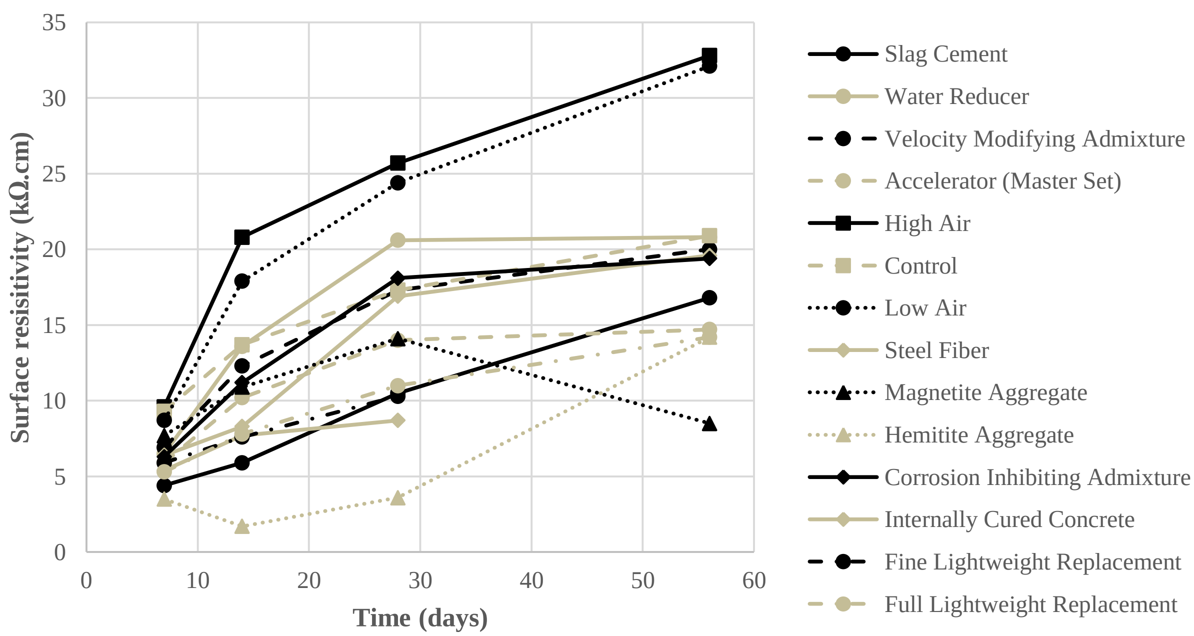


Figure 4.12 Surface resistivity results for laboratory mixtures

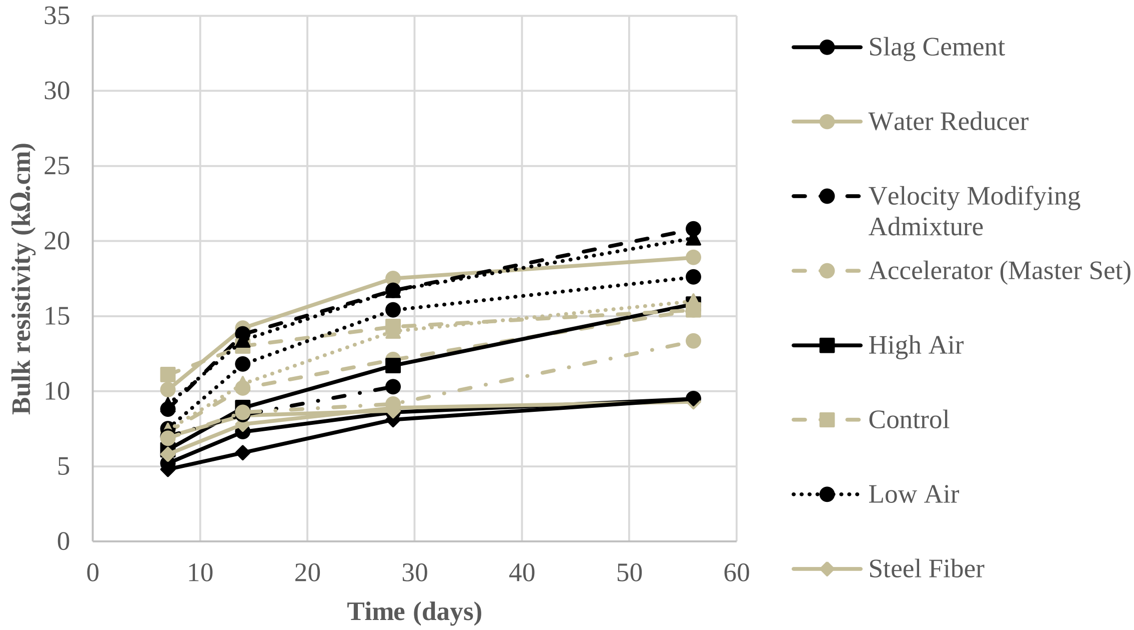


Figure 4.13 Bulk resistivity results for laboratory mixtures

Figure 4.14 compares chloride penetrability classifications for laboratory mixtures under the three tests. As before, there was generally good agreement between the classifications. Eight of the laboratory mixtures were classified the same under RCPT and surface resistivity tests. In most cases where the two classifications did not match, surface resistivity was normally only one classification conservative. In some cases, surface resistivity was highly inconsistent with RCPT, such as with magnetite aggregate or internal curing. Bulk resistivity followed RCPT and surface resistivity well in most cases. Where bulk resistivity was highly inconsistent with field mixtures, it seemed to be a better fit in the laboratory study.

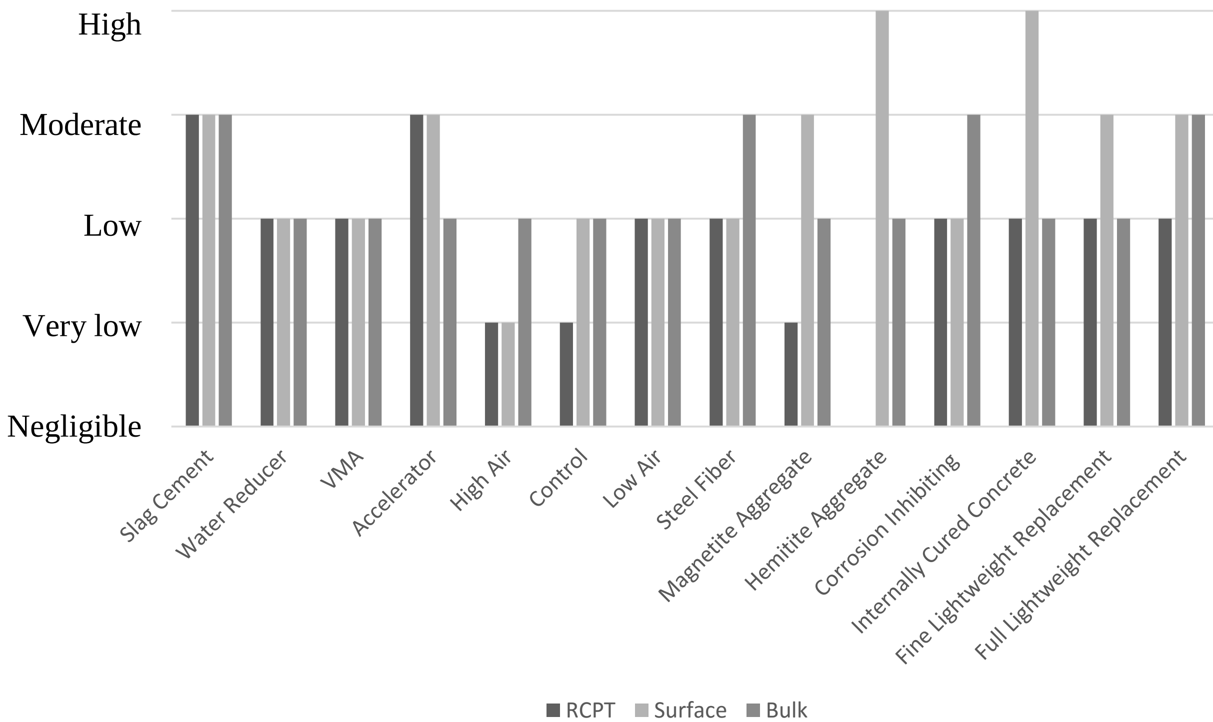


Figure 4.14 Chloride penetrability of laboratory mixtures at 28 d

Table 4.7 compares the results for the control mixture, the internally cured mixture, and those with partial and full lightweight aggregate replacement in order to elucidate the effects of lightweight aggregates on the test results. According to the RCPT, the chloride penetrability of the control was very low, and additions of lightweight aggregate (regardless of whether internal curing was used) increased the penetrability classification to low. The resistivity tests showed similar results, where inclusion of lightweight aggregate resulted in lower resistivity and therefore higher penetrability. As before, classifications based on resistivity tests were either the same as those form RCPT or slightly conservative. This comparison suggests that lightweight aggregates may affect chloride penetrability negatively, but resistivity tests are reliable at measuring penetrability in this cases.

Table 4.7 Comparison of results for normal weight and lightweight aggregates in laboratory mixtures at 28 d (H = high, M = moderate, L = low, VL = very low)

Mixture	**Type**	**RCPT (C)**	**Bulk (kΩ.cm)**	**Surface (kΩ.cm)**
Control	NW	954 VL	14.3 L	17.3 L
Internally cured	LW	1578 L	15.4 L	8.7 H
Fine lightweight replacement	LW	1306 L	10.1 L	10.3 M
Full lightweight replacement	LW	1321 L	9.1 M	11 M

4.3.3 USU mixtures

The USU investigation was performed in order to (1) help USU improve the quality of concrete on campus and (2) increase the sample size for this study. Figure 4.15 shows the compressive strength development of the six USU concrete mixtures. The control mixture exhibited a 28-d compressive strength near 3,000 psi, which was close to the design value for flatwork. Additions of metakaolin, silica fume, vitrified calcium aluminosilicate (VCAS), fly ash, and Hycrete all improved compressive strength. The best compressive strength was observed for the mixture with metakaolin, which reached almost 8,000 psi at 28 d but decreased slightly at 56 d.

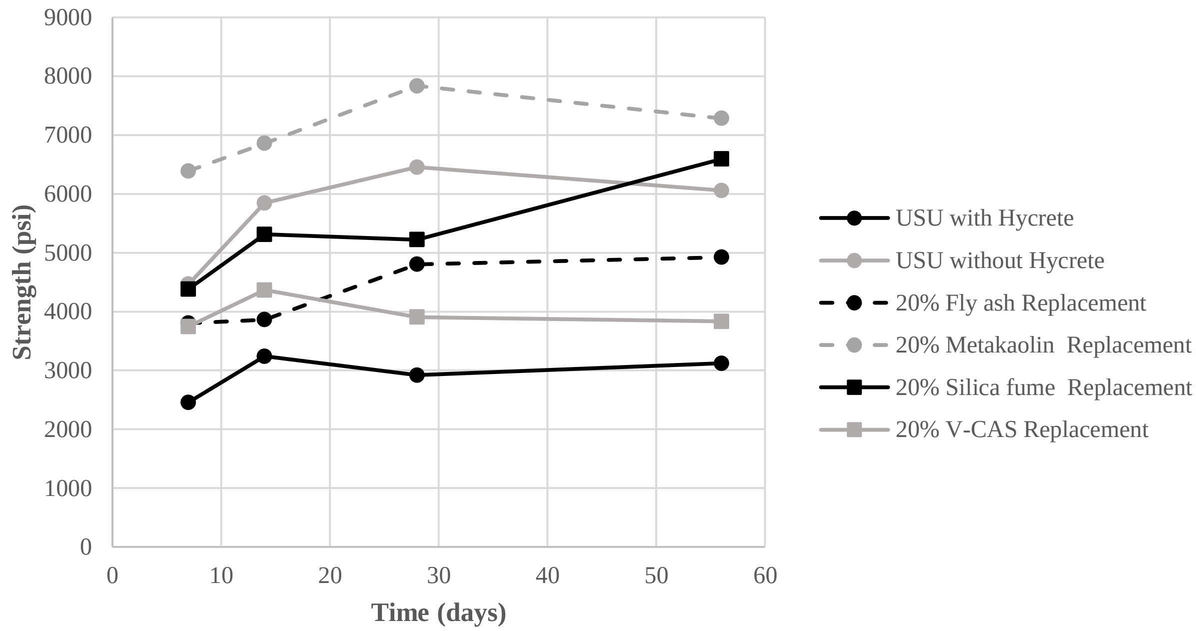


Figure 4.15 Compressive strength development of USU mixtures

Chloride penetrability results for USU mixtures are pt56 resented in Figure 4.16 (RCPT) and Figure 4.17 (surface resistivity). Under the RCPT, the control mixture results were scattered, with low penetrability at 7 d, moderate at 28 d, and negligible at 56 d. Under the surface resistivity test, the same mixture was classified as high at 7 d, moderate at 14 d, and low at 56 d. Additions of silica fume, metakaolin, fly ash, and VCAS resulted in significant improvements in chloride penetrability under both tests. RCPT suggested that additions of Hycrete resulted in worse performance, but the opposite result was observed for surface resistivity. This follows the trend of chemical admixtures affecting the test methods and contributing inconsistent results between test methods. Figure 4.18 compares chloride penetrability rankings based on RCPT and surface resistivity for USU mixtures at 28 d. As before, the classifications were in good agreement. However, in a few cases, the surface resistivity measurement suggested better performance than RCPT, meaning the surface test is non-conservative in these cases. These cases included additions of metakaolin and Hycrete, suggesting that if either of these materials are used then the correlation between the two tests should be investigated further.

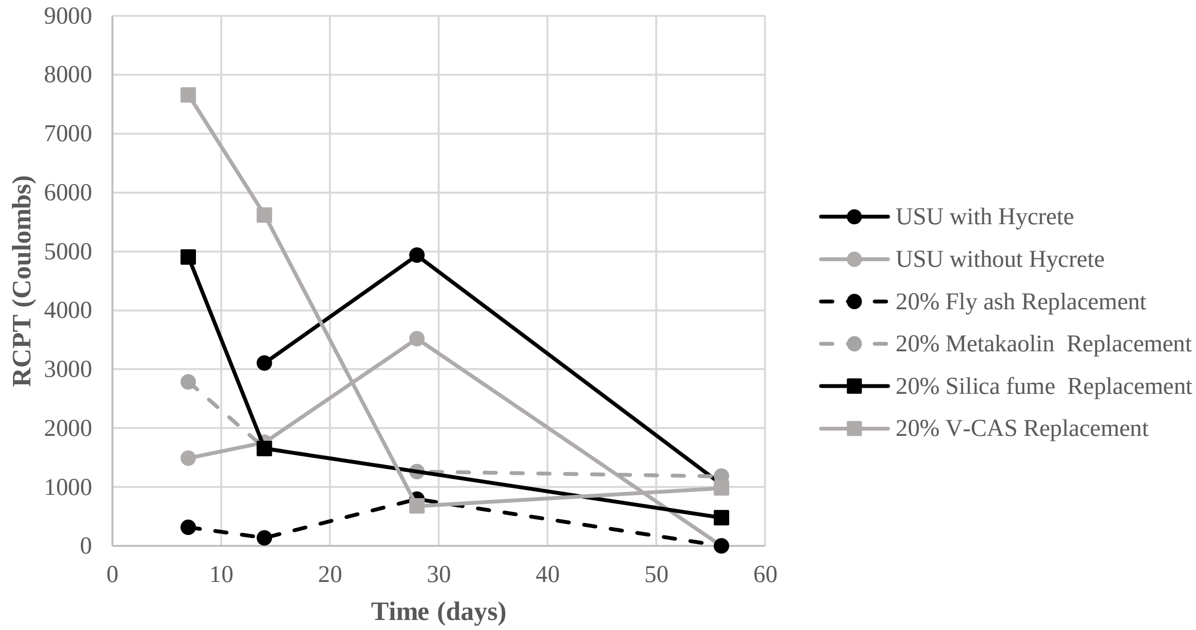


Figure 4.16 RCPT results for USU mixtures

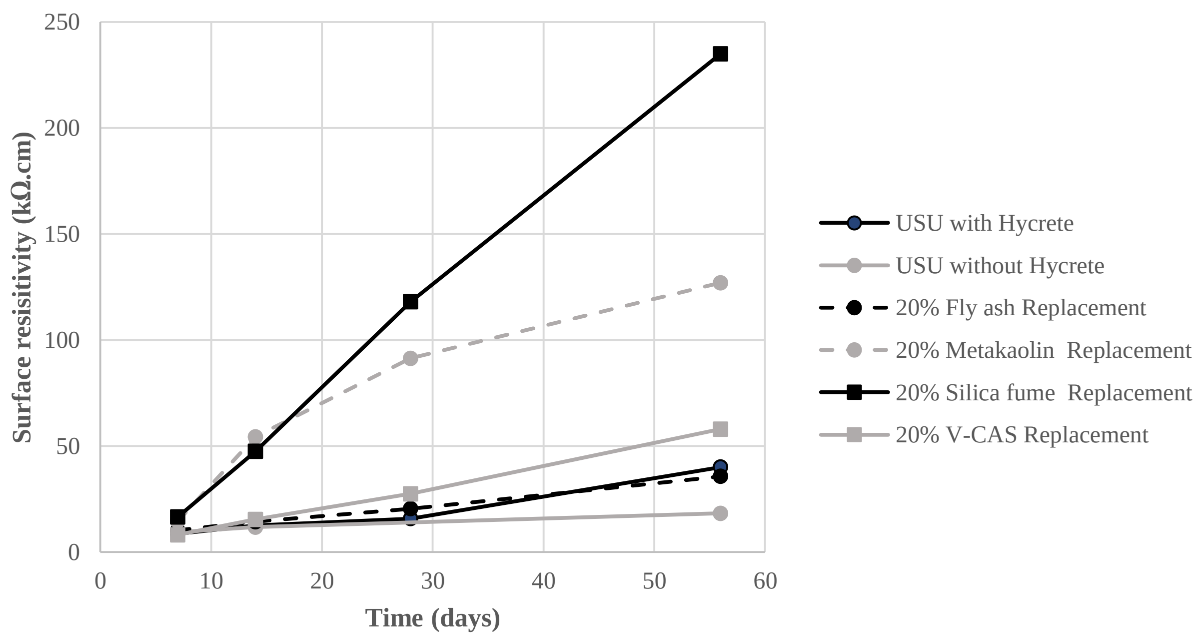


Figure 4.17 Surface resistivity results for USU mixtures

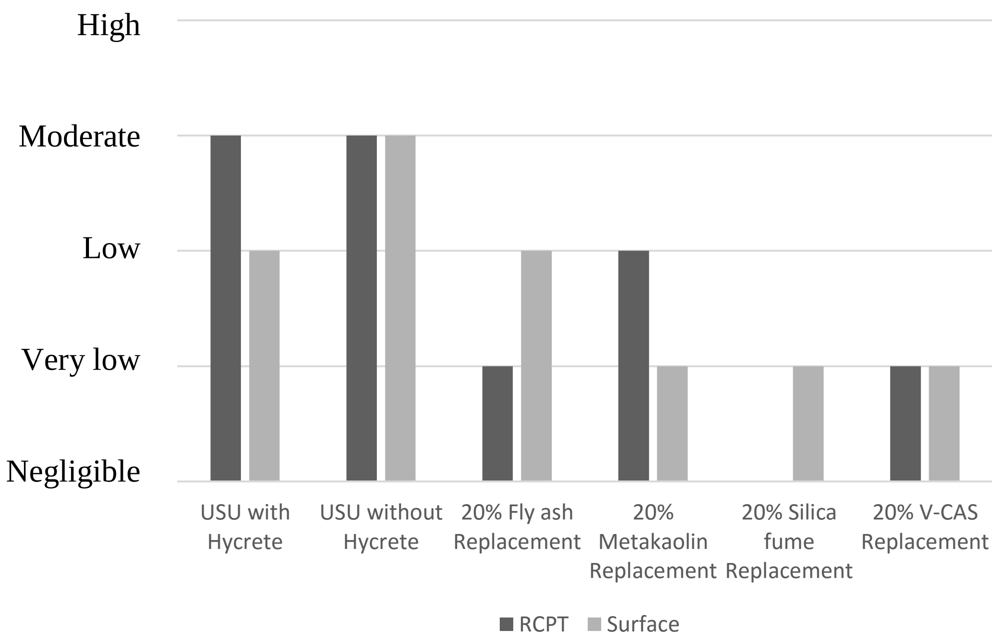


Figure 4.18 Chloride penetrability of USU mixtures at 28 d

4.3.4 RCA mixtures

In order to observe the effects of reclaimed aggregates, six mixtures were prepared with varying levels of replacement of fine, coarse, or both aggregates with similarly-graded reclaimed concrete aggregate. Figure 4.19 shows the compressive strength at 7, 14, and 28 d. As expected, the compressive strength decreased when virgin aggregates were replaced with RCA. The control compressive strength was nearly 10,000 psi at 28 d, while full replacement of both fine and coarse aggregates with RCA reduced that value by about 30%. Figure 4.20 shows surface resistivity measurements for the same six RCA mixtures. As expected, the surface resistivity was highest for the mixture with 100% virgin aggregates. Inclusion of RCA is known to reduce concrete quality (as evidenced by reduced compressive strength), thereby increasing the chloride penetrability as seen here.

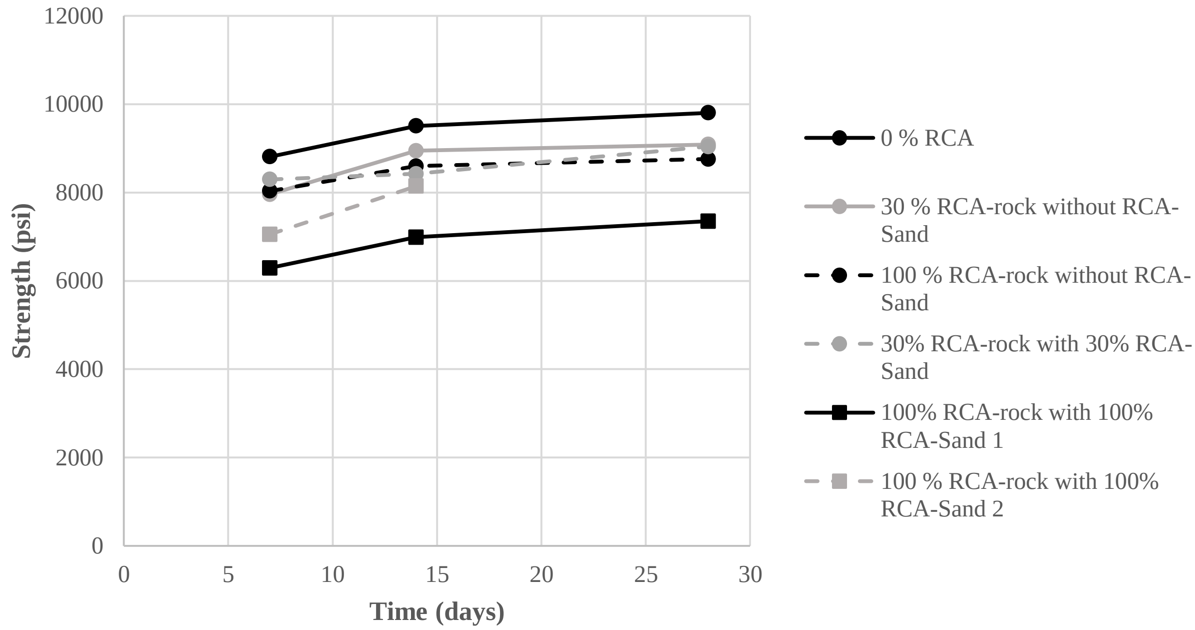


Figure 4.19 Compressive strength development of RCA mixtures

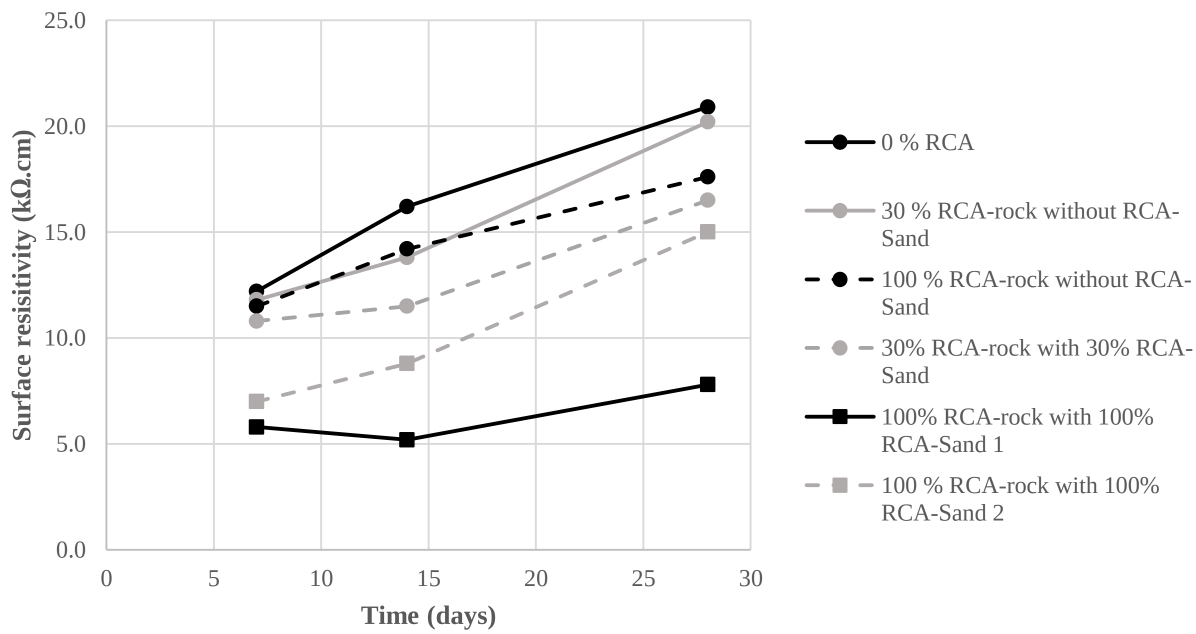
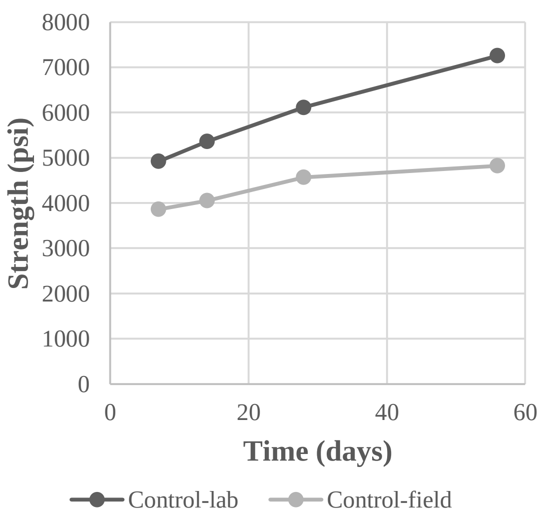


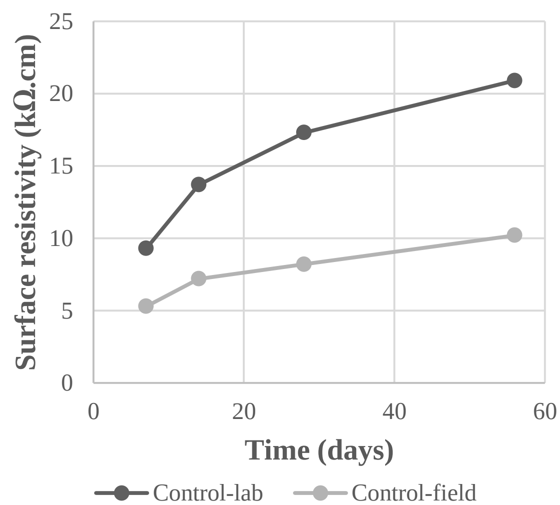
Figure 4.20 Surface resistivity results for RCA mixtures

4.3.5 Comparison of field and laboratory results

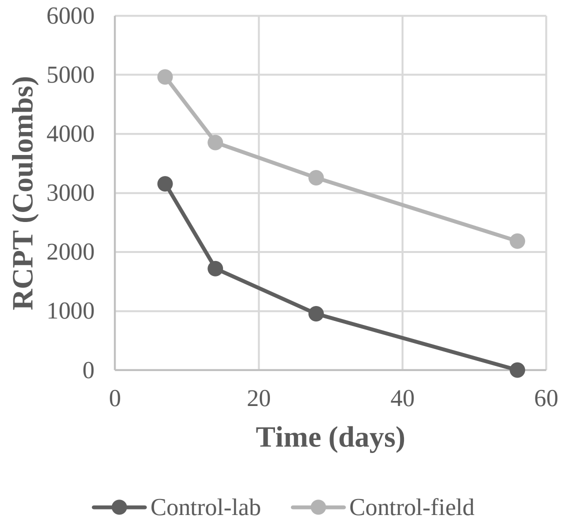
In order to compare results from field and laboratory studies, the researchers duplicated field mixture D4 0.42 in the laboratory. Results for compressive strength, RCPT, and resistivity are shown in Figure 4.21. The field mixture exhibited worse performance on all counts: the compressive strength was lower than that of the laboratory duplicate, and the chloride penetrability was worse (higher charge passed during RCPT and lower bulk and surface resistivity). This investigation shows similar results to the Oklahoma State University research (Hartell 2015). There are several likely reasons for this result. There is inevitably much more control over the mixture in the laboratory; controls over temperature, humidity, batch weights, mixture homogeneity, and other factors contribute to improved concrete quality. However, empirical evidence also suggests that batch plant operators, drivers, and contractors may add additional water to the concrete, which may go unreported on the batch ticket. A lower quality concrete will inevitably result. This result suggests that specifiers should specify a better penetrability performance than desired in order to account for worse performance in the field than in the laboratory.



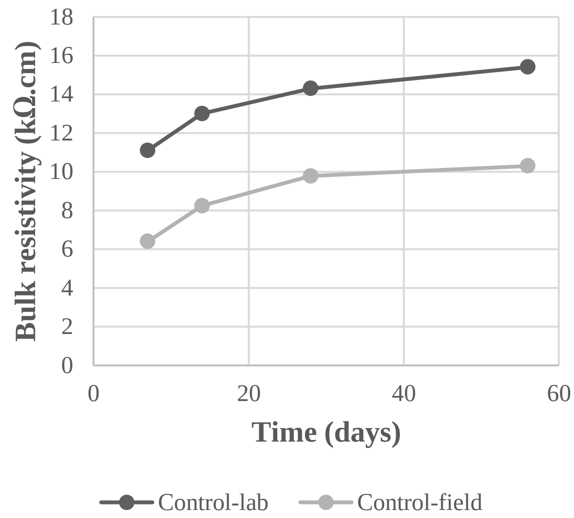
(a) Compressive strength



(b) Surface resistivity



(c) RCPT



(d) Bulk resistivity

Figure 4.21 Comparison of field and laboratory results

4.3.6 Comparison of penetrability classifications

Figure 4.22 presents a direct comparison of test results for field mixtures. The plot shows the numerical difference between penetrability classifications based on surface resistivity and either RCPT or bulk resistivity. A negative number shows that the test classified the mixture one class lower (better) than the surface resistivity. For example, the control field mixture was classified one class better under both RCPT and bulk resistivity than surface resistivity, and the plot therefore shows a value of -1 for both tests. This shows that, for field mixtures, the surface resistivity test was closer to the RCPT test than the bulk resistivity test. Practitioners require a test that is exact or conservative. The non-conservative nature of most of the bulk resistivity classifications shown here suggest that the bulk resistivity test is not as useful. However, the reader should note that the researchers have presented a few cases in this report where the surface resistivity test is also non-conservative.

Figure 4.23 shows the same comparison for laboratory mixtures at 28 d. Again, the correlation between RCPT and surface resistivity was in most cases very good. However, several cases emerged where the surface resistivity test was very far off from the RCPT. In these cases, the surface resistivity classification was conservative, which is desired. The bulk resistivity test was also well correlated to the RCPT, but several observations were non-conservative, and several were more than one classification apart.

Finally, Figure 4.24 shows the same comparison for USU concrete mixtures at 28 d. Similar results are observed, where the RCPT and surface resistivity were well correlated, and most of the surface resistivity classifications were either identical to those from RCPT or were one class conservative. Additions of metakaolin and Hycrete both resulted in surface resistivity classifications that were non-conservative, but only differed from RCPT classifications by one class.

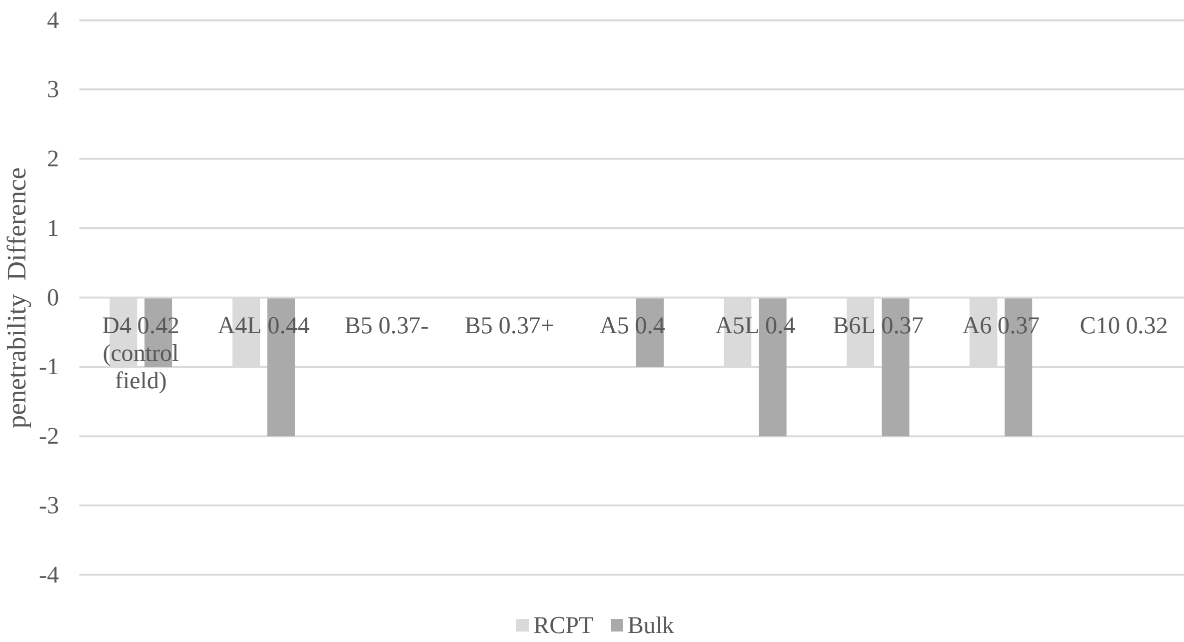


Figure 4.22 Difference between chloride penetrability based on surface resistivity and RCPT or bulk resistivity for field mixtures at 28 d

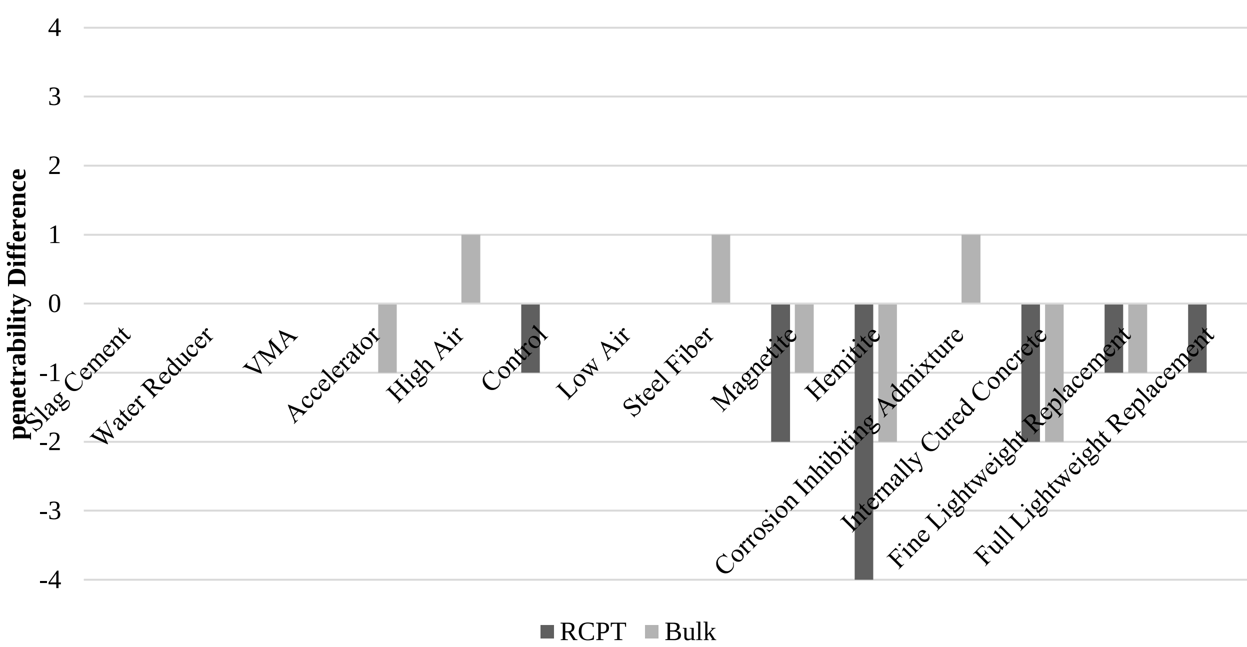


Figure 4.23 Difference between chloride penetrability based on surface resistivity and RCPT or bulk resistivity for laboratory mixtures at 28 d

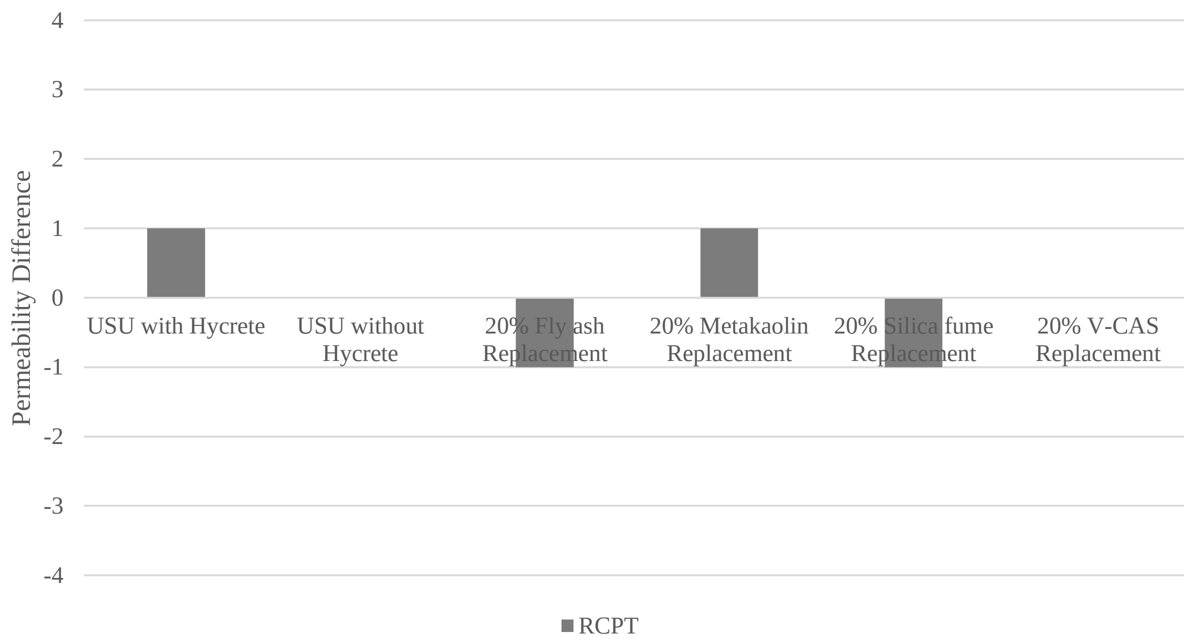


Figure 4.24 Difference between chloride penetrability based on surface resistivity and RCPT or bulk resistivity for USU mixtures at 28 d

4.3.7 Ranking penetrability tests

Following the use of RCPT, surface resistivity, and bulk resistivity methods for evaluations of dozens of concrete mixtures at several ages, the researchers ranked the methods in terms of ease of operation, test duration, preparation time, chance of error, and apparatus cost.

Table 4.8 shows the results of this comparison. The surface resistivity test was the easiest to perform; the operator only needed to load the specimen into the fixture and press a button. Meanwhile, bulk resistivity and RCPT measurements require the operator to assemble a complicated fixture and connect several cables. The surface resistivity measurement also required the least time commitment, for both specimen preparation and testing. The combined time for surface resistivity was under 3 min; the total time commitment for the RCPT was about 30 h. Surface resistivity presented the least chance for error due to the ease of performing the test. Bulk resistivity and RCPT measurements are error prone due to the tendency for improper assembly of the measurement cells. Finally, the surface resistivity device was the cheapest of the three devices tested here.

Table 4.8 Ranking of chloride penetrability test methods

Ease	**Test duration**	**Preparation time**	**Chance of error**	**Apparatus cost ($)**
Surface	Surface (15 s)	Surface (2 min)	Surface	Surface (4012)
Bulk	Bulk (60 s)	Bulk (30 min)	Bulk	Bulk (5830)
RCPT	RCPT (6 h)	RCPT (24 h)	RCPT	RCPT (8404)

4.3.8 Comparison with results from other studies

The researchers compared the results of this investigation with those of two similar investigations performed in Florida (Kessler et al. 2008) and Virginia (Ozyildirim 2011). Kessler at al (2008) compared surface resistivity and RCPT results for 529 concretes at 28 d, including mixtures with normal weight and lightweight aggregates. Ozyildirim (2011) used concretes from six states with lightweight aggregates and *w/cm* between 0.35 and 0.43. Figure 4.25 compares the results of both studies to the results for lightweight aggregates mixtures evaluated in the present study. Figure 4.26 compares all results from the present study to those reported in the Florida and Virginia studies. The Virginia study has more scatter than the Utah study. In the Utah Study, the aggregate used to make the concrete were from the state of Utah alone, whereas the Virginia study used several sources. This comparison indicates that the results presented in this study show good agreement with the comprehensive Florida study (only the trend line is shown to improve readability), and considerably lower resistivity than the Virginia.

In general, the Florida study and the Utah Study show a similar correlation between Surface and RCPT. The Virginia study cannot be fully compared to these two studies since it studies only lightweight aggregates. Moreover, the Florida and Utah studies have less aggregate origin diversities than Virginia. Based on this plot, the concretes in the respective programs show similar trends regarding surface resistivity and RCPT indicating that the transformation of resistivity values to penetrability (i.e., low, very low etc.) are appropriate. It should be noted that Figure 4.26 includes a few points from the present study that are very far away from the others; these include heavyweight aggregates that result in spurious readings for resistivity tests.

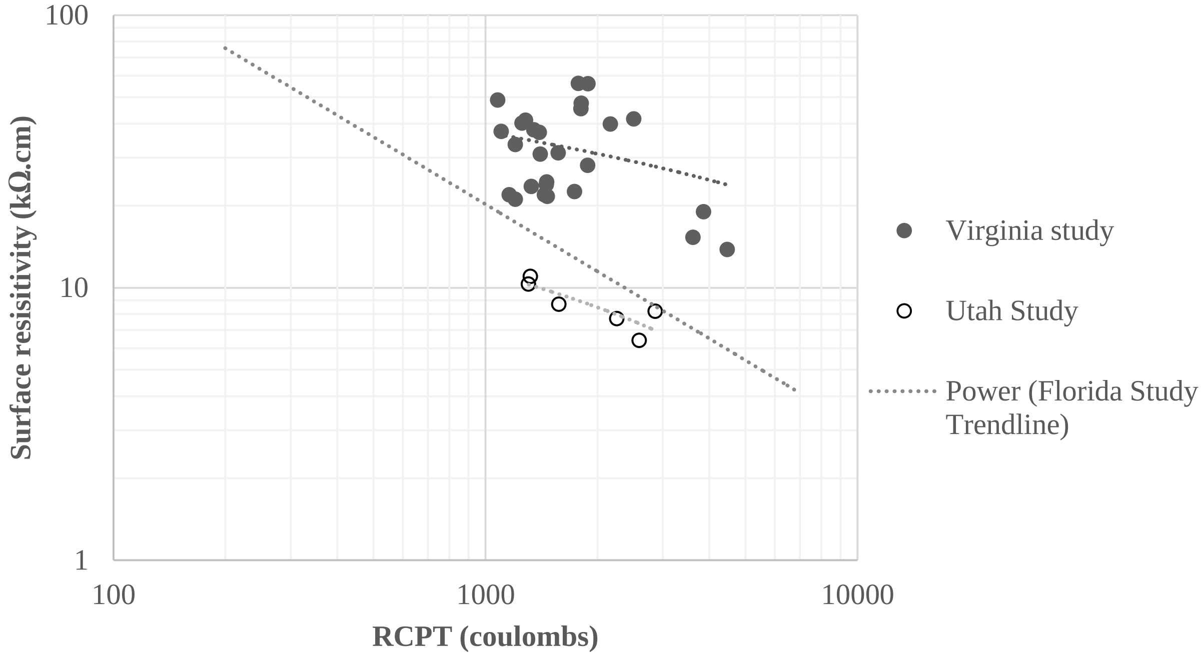


Figure 4.25 Comparison of lightweight results with other studies

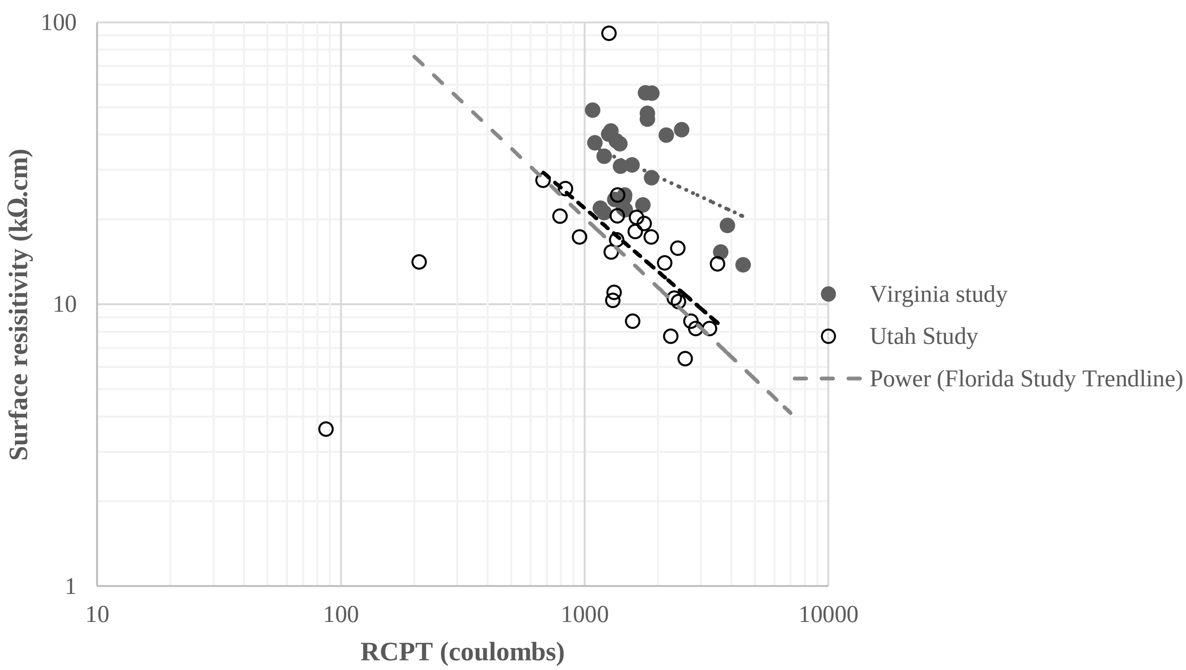


Figure 4.26 Comparison of all results with other studies

4.4 Ongoing testing

The test results are presented in the context that the RCPT provides a true measurement of chloride penetrability. However, it is known that all electrical test methods are prone to errors when the pore solution chemistry of concrete changes or when conductive materials are included. Thus, for a more complete analysis, there is a need to compare the results presented here to those from diffusion-based tests, which do provide a true measurement of chloride penetrability. These measurements are in progress as part of a continuation of the study presented here.

5.0 CONCLUSIONS

This report presents results from an investigation into the use of electrical resistivity based testing as a replacement to the RCPT. The goal was to determine the viability of using the surface or bulk resistivity tests to specify bridge deck concrete with some UDOT specified level of penetrability. Testing commenced on field mixtures provided by Utah precasters and ready-mix companies as well as a series of laboratory mixtures. The field mixture investigation revealed that most of the Utah concretes for bridge decks from various producers provided similar penetrability and mixture constituents in general. The laboratory mixtures selected a control mixture from the field mixtures and varied the admixtures and contents. The results indicated that surface and bulk resistivity provide, in general, conservative estimations of RCPT penetrability for field and laboratory mixtures. Secondary testing of some USU specified mixtures and RCA mixtures was presented that was performed as part of parallel, but unpublished studies. The results indicated that RCA aggregate concrete may contain chloride within the aggregate that will negatively affect the apparent penetrability, but is unlikely to have affected the actual penetrability. From the USU mixtures, a waterproofing agent, Hycrete, and large amounts of admixtures were investigated that show dramatic changes in penetrability. It was found that Hycrete increased the penetrability according to RCPT and lowered penetrability according to surface resistivity readings. The other admixtures decreased all measured permeabilities significantly. The relationship between the surface, UDOTs preferred future test, and the RCPT test results and mixtures investigated herein, are similar to those from a large Florida study and provide less penetrability (per surface resistivity and RCPT) than those investigated in a Virginia study. Surface electrical resistivity testing is easier, faster and cheaper concrete durability test compare to bulk electrical resistivity testing and RCPT.

The results presented in this report support the following conclusions:

- The inter-laboratory investigation between the UDOT lab and the USU lab indicated that there was no significant difference between the readings on the different machines.
- Based on the results from the field mixtures,

- Surface and bulk resistivity provide a conservative estimate of RCPT penetrability for the Utah field mixtures investigated.
- The field mixtures resulted in a range from low penetrability to high penetrability for the tests considered.
- The maximum different between RCPT, bulk and surface resistivity penetrability classifications was only one level.
- There is a linear trend between bulk and surface resistivity

- Based on the results from the laboratory study
    - The control mixture for the laboratory study, which was a duplicate of a field mixture, had decreased penetrability by two full classifications (i.e., field classification, moderate, lab classification, very low for RCPT)
    - The addition of nearly every admixture increased penetrability, even those that did not alter the cement matrix or pore water, like steel fibers.
    - The replacement of fly ash in the control mixture with slag resulted in an increase in penetrability by two classifications for, RCPT, bulk and surface resistivity.
    - All chemical admixtures resulted in an increase in penetrability, at the levels tested, of one classification, when compared to the control mixture.
    - Adding conductive materials, like heavyweight aggregate and steel fibers can result in an apparent increase in penetrability, although the cement matrix and true penetrability are the same or similar.
- Based on the results of the recycled concrete aggregate study
    - Resistivity testing and RCPT testing indicated higher penetrability for RCA concretes when compared to the control.
        - This difference is likely due to the presence of chloride ions in the RCA paste in the aggregates, although this was not tested.
- Based on the USU concrete study
    - The waterproofing admixture Hycrete causes higher penetrability when compared to the control for surface resistivity and RCPT.

- Large volumes of mineral admixtures silica fume and Metakaolin can dramatically decrease penetrability.

The following recommendations are made for implementation of surface resistivity as a performance based test for Utah bridge decks:

- Specifying an electrical resistivity, when expecting a RCPT resistivity, will conservatively result in similar or less permeable concrete bridge decks.
- If concrete mixtures and tests submitted to UDOT for pre-approval are made in controlled laboratory conditions, expect up to two penetrability classifications higher than what will occur in the field.
- Producers can expect an increase in penetrability when adding the chemical and mineral admixtures to their current approved mixtures.
- For future performance based specifications for UDOT bridge decks, if a given penetrability is desired, one classification level below that should be specified to account for the unconservative effect on resistivity caused by laboratory mixing conditions and the conservative difference between the surface resistivity testing and RCPT classifications.

Future work should focus on correlating the results presented in this report to 90-day salt ponding testing or a modified ponding test, which may provide a more accurate estimation of concrete penetrability.

Table 5.1 Recommended chloride penetrability classifications

Chloride Penetrability	**Surface Resistivity (kΩ.cm)**	**Bulk Resistivity (kΩ.cm)**	**RCPT (C)**
High	<10	<5	>4000
Moderate	10-15	5-10	2000-4000
Low	15-25	10-20	1000-2000
Very low	25-200	20-200	100-1000
Negligible	>200	>200	<100

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APPENDIX A: DETAILED FIELD MIXTURE DESIGNS AND RAW DATA

Table A.1 D4 0.42 properties and test results

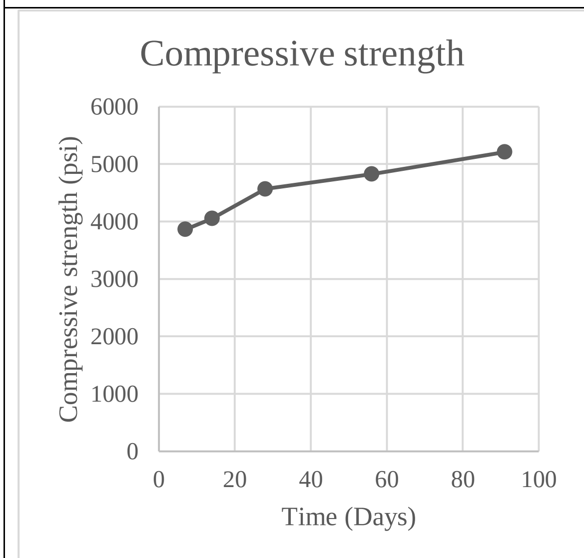
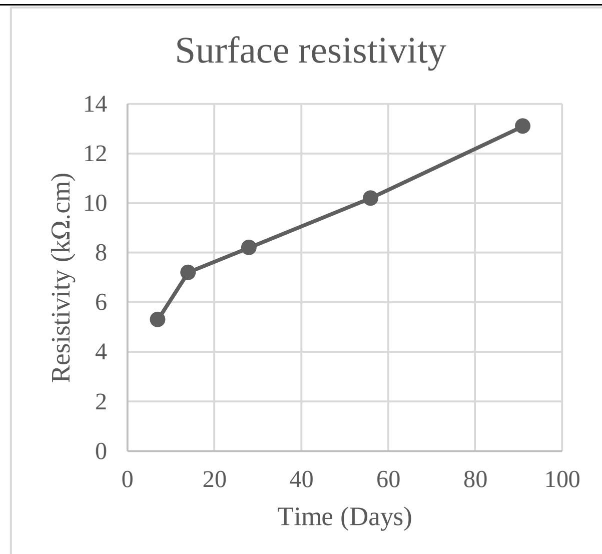
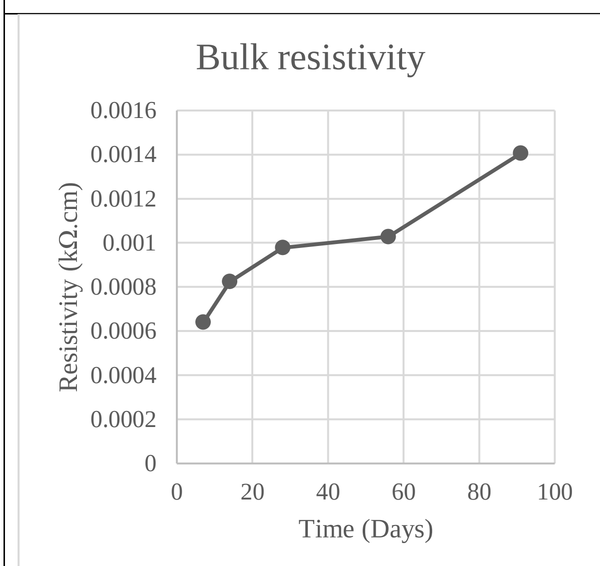
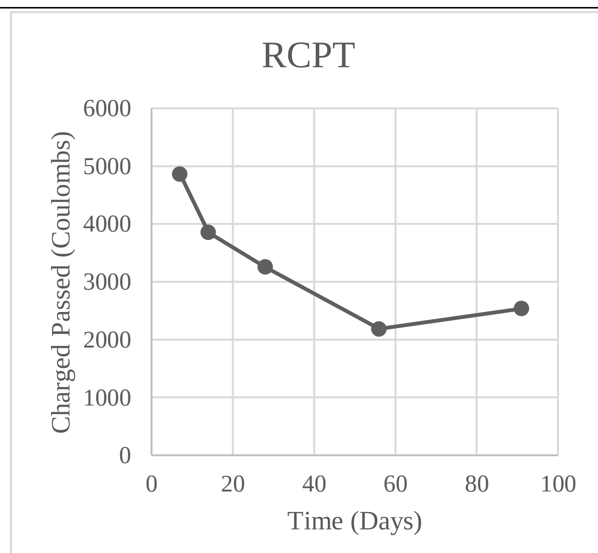
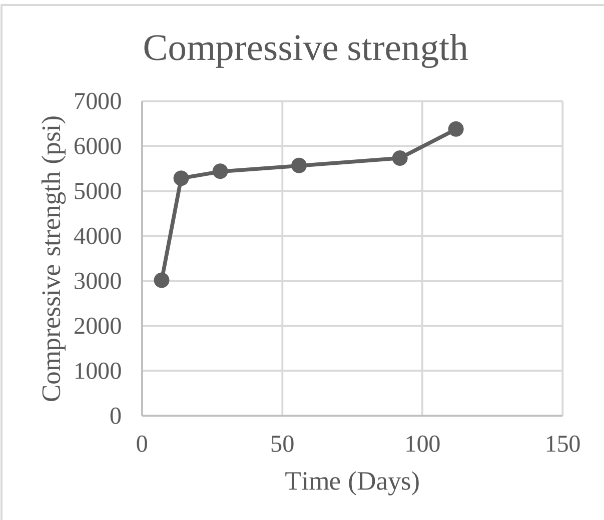
Mix Design Name	D4 0.42
Design Strenght	4000 psi
W/CM	0.42
Air	5-7.5%
Slump	3-6 in
Unit weight	141.84
	
	

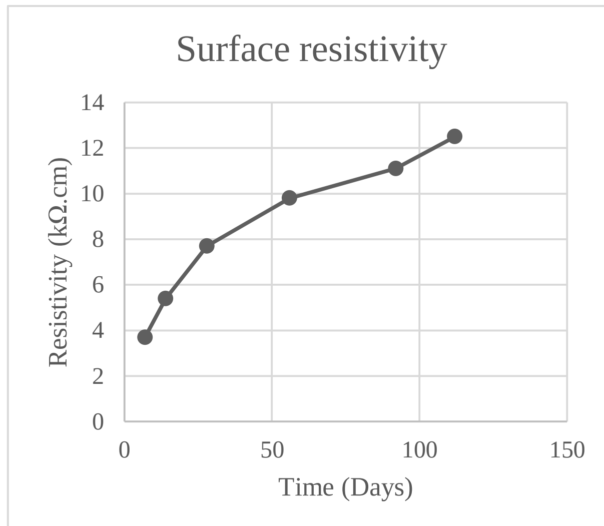
Table A.2 D4 0.42 mix design

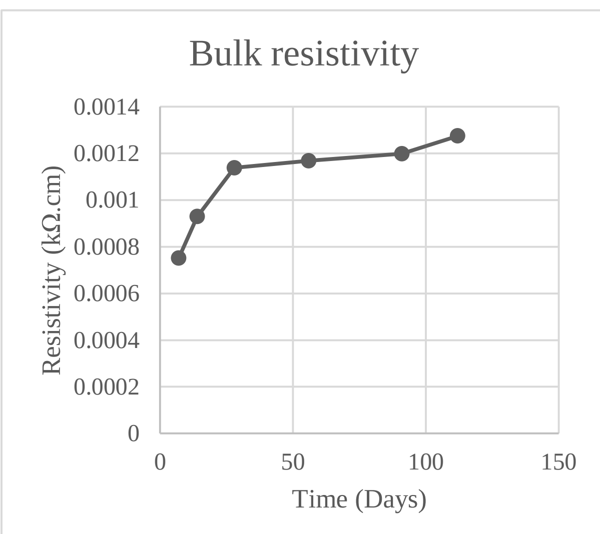
Material Type	Description		Design Quantity	Specific Gravity	Volume (ft3)
Cement	Portland type II/V (Holcim)		489 lb	3.15	2.488
Fly Ash	Fly Ash - F		122 lb	2.35	0.832
Coarse Aggregate	3/4” Rock		1643 lb	2.656	9.913
Fine Aggregate	Sand		1320 lb	2.646	7.995
Water	Potable water (City Water)		254 lb	1.00	4.071
Admixture	Water reducer (4 fl oz/100lb CM)		1.593	1	--
		Air Content	6.00 %	--	1.701
		Yield	3829.7 lb	--	27.00

Table A.3 A4L 0.44 properties and test results

Mix Design Name	A4L 0.44
Design Strenght	4000 psi
W/CM	0.44
Air	5-7.5%
Slump	3-6 in
Unit weight	117.6







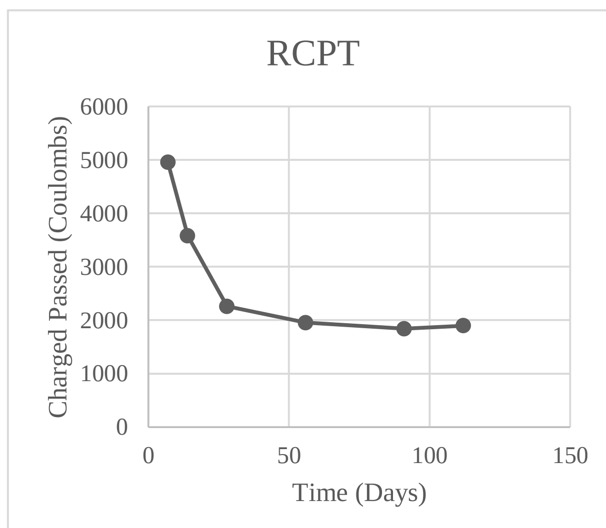
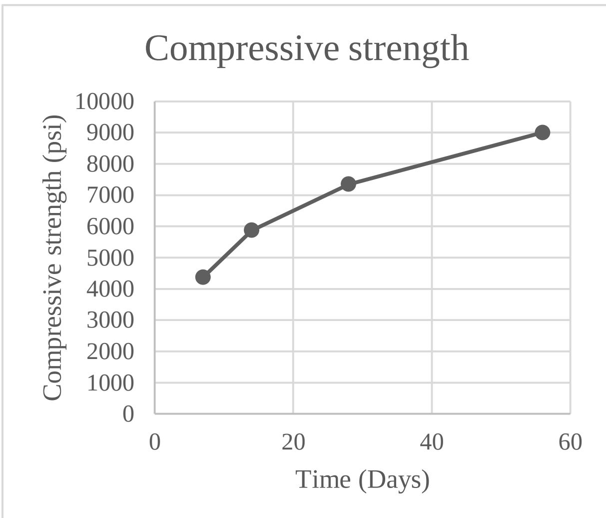


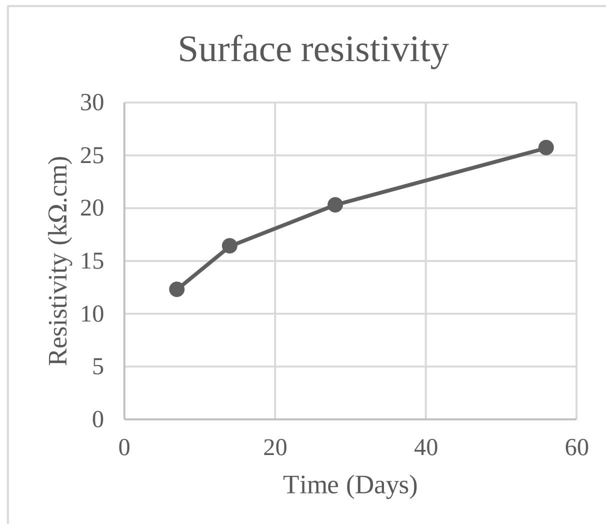
Table A.4 A4L 0.44 mix design

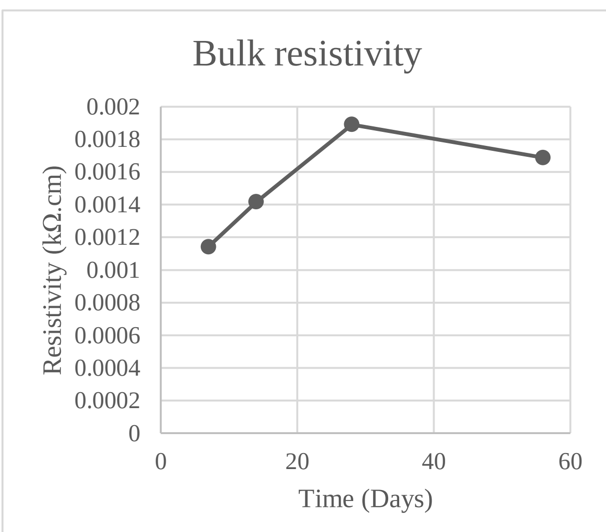
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	LIGHT WEIGHT COARSE	1092 lb	1.77	9.89
Fine Aggregate	SAND - WASHED CONCRETE	1069 lb	2.60	6.59
Water	POTABLE WATER	37.2 gal	1.00	4.97
Admixture	AIR ENTERING ADMIXTURE - ASTM C260	9 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, D	7 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, F	14 lq oz	--	--
	Air Content	6.30 %	--	1.70
	Yield	3176 lb	--	27.00

Table A.5 B5 0.37- properties and test results

Mix Design Name	B5 0.37-
Design Strenght	5000 psi
W/CM	0.368
Air	5-7.5 %
Slump	4-8.5 in







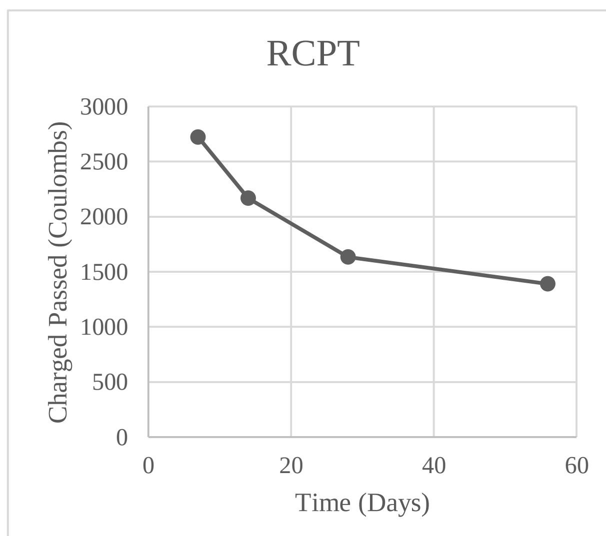
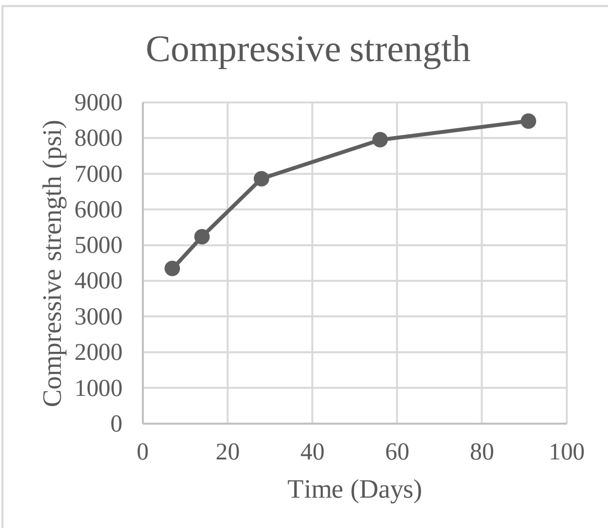


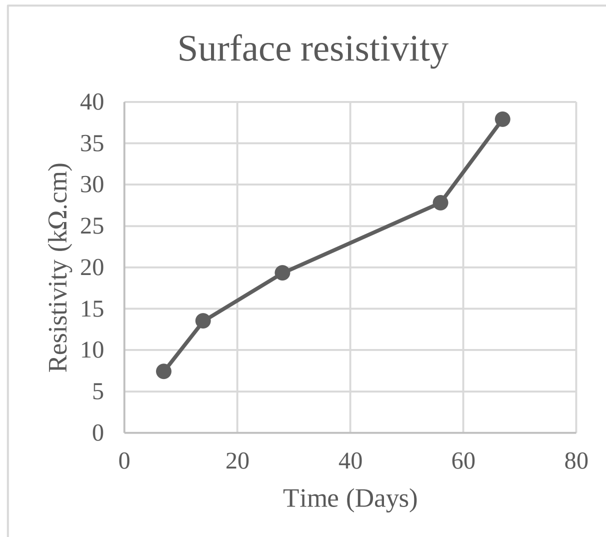
Table A.6 B5 0.37- mix design

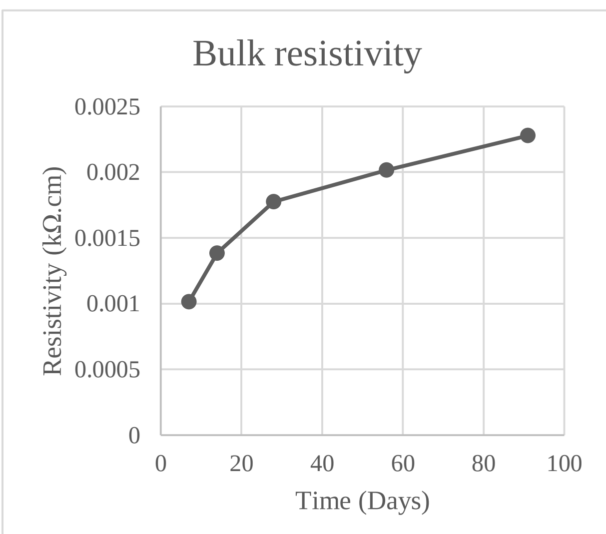
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)	639 lb	3.15	3.25
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)	160 lb	2.60	0.99
Coarse Aggregate	KSG67 - Astm C-33 #67	1550 lb	2.49	9.98
Fine Aggregate	KSGFA - ASTM C-33 Concrete Sand	1030 lb	2.55	6.47
Water	Water WAT01 - Well Water (City Water supply)	292 lb	1.00	4.68
Admixture	Water reducer - Sika Plastiment retarder (Sika Corp ADMIX)	19.18 floz	1.2	--
Admixture	Accelerating Admixture - Sika NC accelerant (Sika Corp ADMIX)	127.84 floz	1.4	--
Admixture	Sika2100 - Sika Viscocrete HRWR (Sika Corp ADMIX)	47.94 floz	1.1	0.05
Admixture	Sika air (Sika Corp ADMIX)	3.60 floz (US)	1	--
	Air Content	6.50 %	--	1.77
	Yield	3688 lb	--	27.19

Table A.7 B5 0.37+ properties and test results

Mix Design Name	B5 0.37+
Design Strenght	5000 psi
W/CM	0.372
Air	6%
Slump	4-9 in







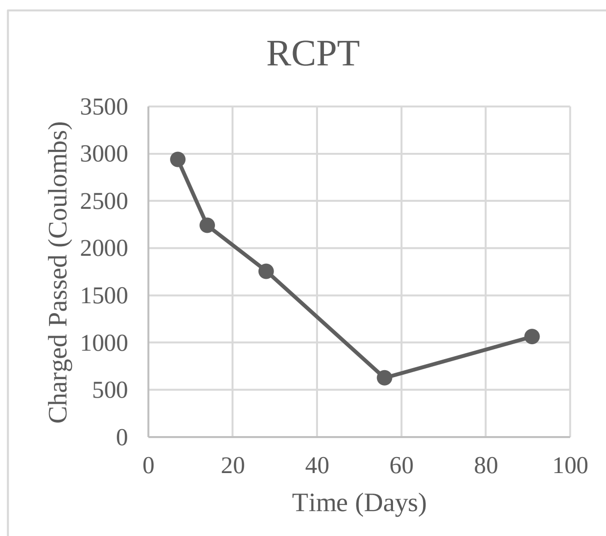
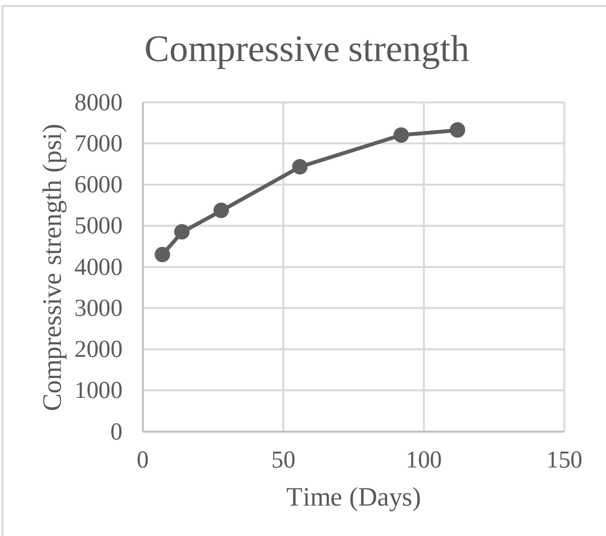


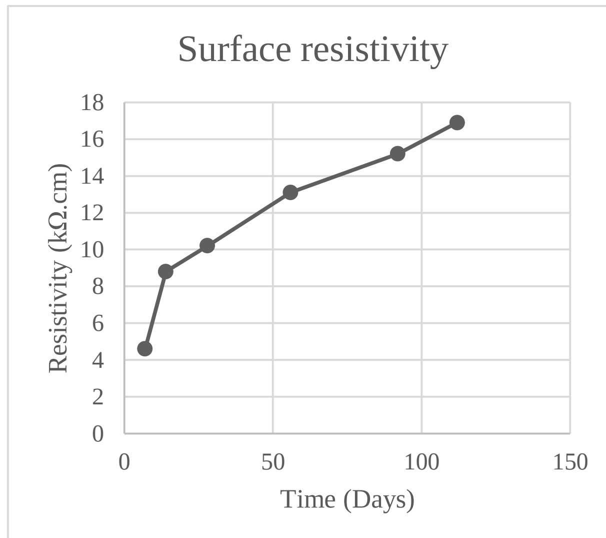
Table A.8 B5 0.37+ mix design

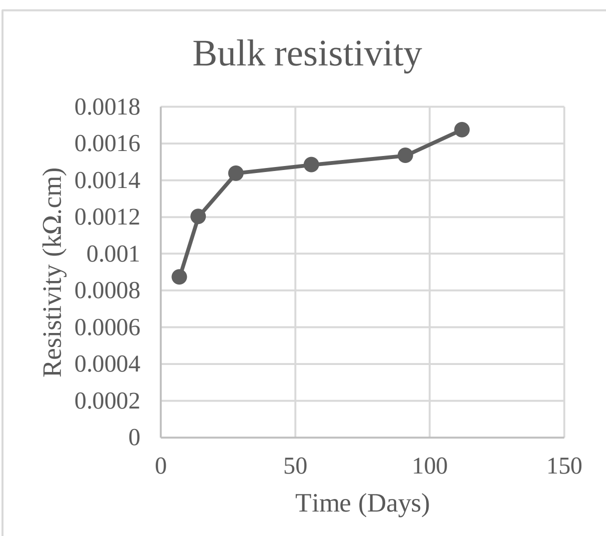
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)	564 lb	3.15	2.87
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)	141 lb	2.60	0.87
Coarse Aggregate	VSG67VRM - Astm C-33 #67 (Valley Sand and Gravel)	1615 lb	2.49	10.39
Fine Aggregate	KSGFA - ASTM C-33 Concrete Sand (Valley Sand and gravel)	1145 lb	2.55	7.20
Water	Water WAT01 - Well Water (City Water supply)	260 lb	1.00	4.17
Admixture	Sika Plastiment retarder (Sika Corp ADMIX)	14.10 floz	1.2	--
Admixture	Sika NC accelerant (Sika Corp ADMIX)	112.80 floz	1.4	--
Admixture	Sika2100 - Sika Viscocrete HRWR (Sika Corp ADMIX)	42.30 floz	1.1	0.04
Admixture	Sika air (Sika Corp ADMIX)	3.17 floz (US)	1	--
	Air Content	6.00 %	--	1.63
	Yield	3740 lb	--	27.17

Table A.9 A5 0.4 properties and test results

Mix Design Name	A5 0.4
Design Strenght	5000 psi
W/CM	0.4
Air	5-7.5%
Slump	3-5 in
Unit weight	137.8







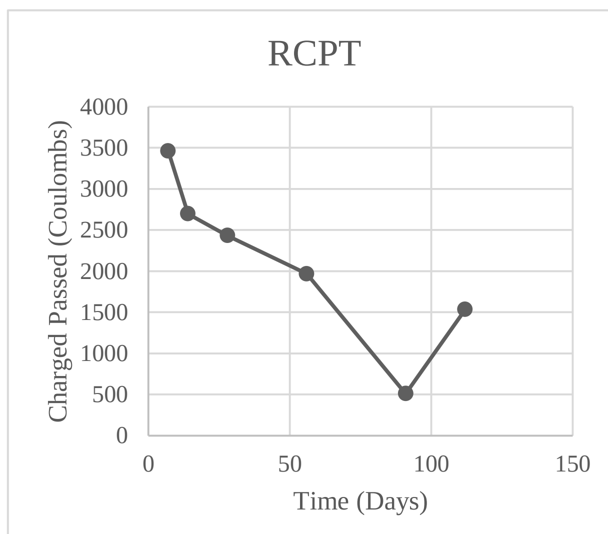
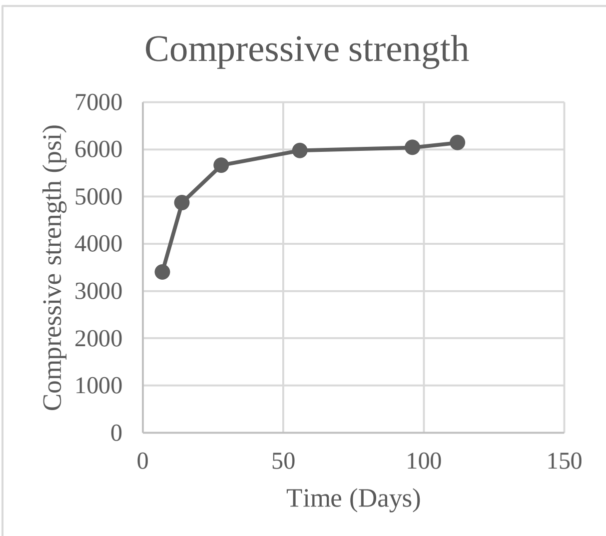


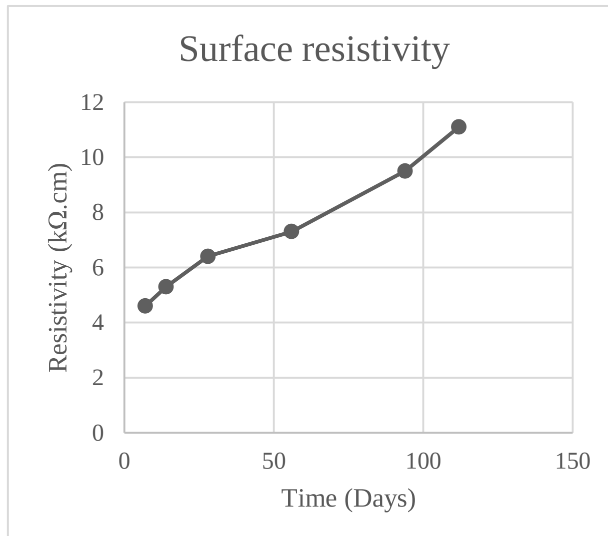
Table A.10 A5 0.4 mix design

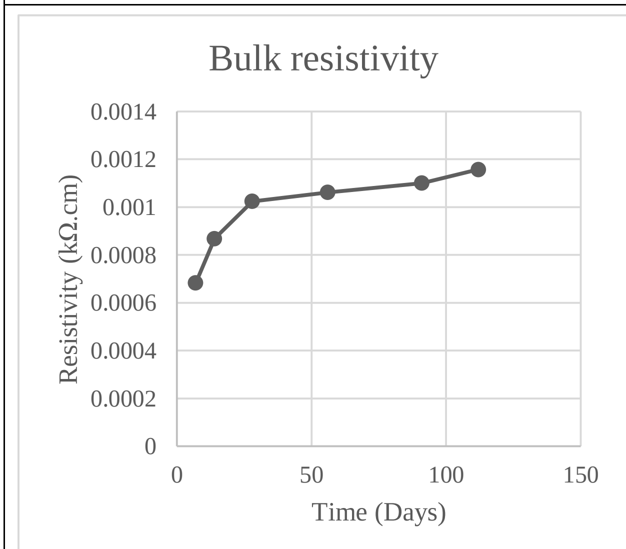
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1689 lb	2.58	10.49
Fine Aggregate	SAND - WASHED CONCRETE	1044 lb	2.60	6.43
Water	POTABLE WATER	33.8 gal	1.00	4.52
Admixture	AIR ENTERING ADMIXTURE - ASTM C260	19 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, D	21 lq oz	--	--
	Air Content	6.30 %	--	1.70
	Yield	3720 lb	--	27.00

Table A.11 A5L 0.4 properties and test results

Mix Design Name	A5L 0.4
Design Strenght	5000 psi
W/CM	0.4
Air	4.5-7.5%
Slump	3-5 in
Unit weight	133.1







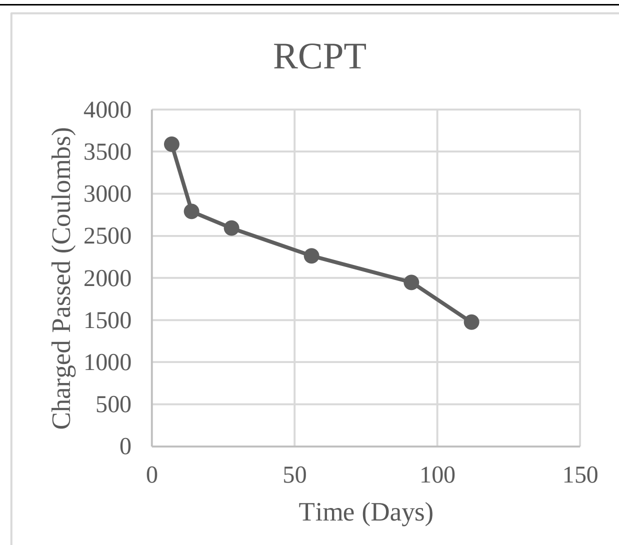
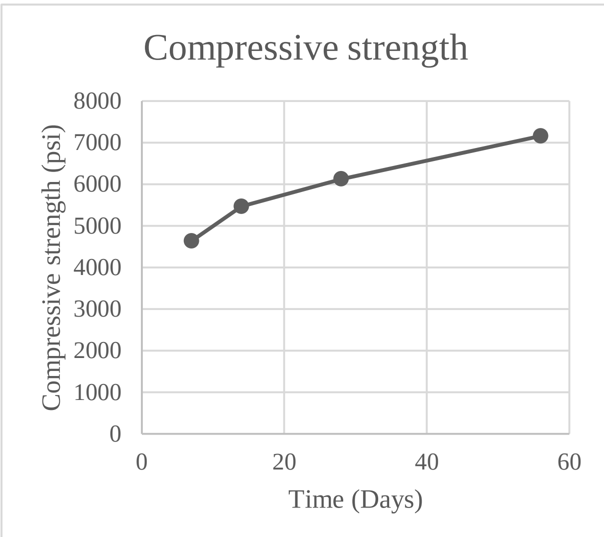


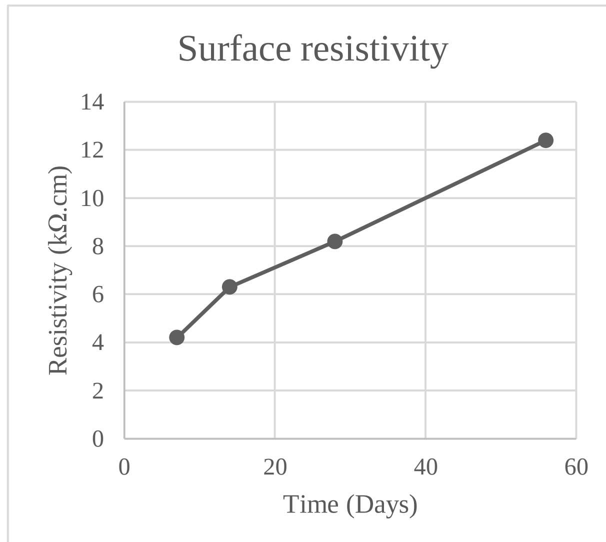
Table A.12 A5L 0.4 mix design

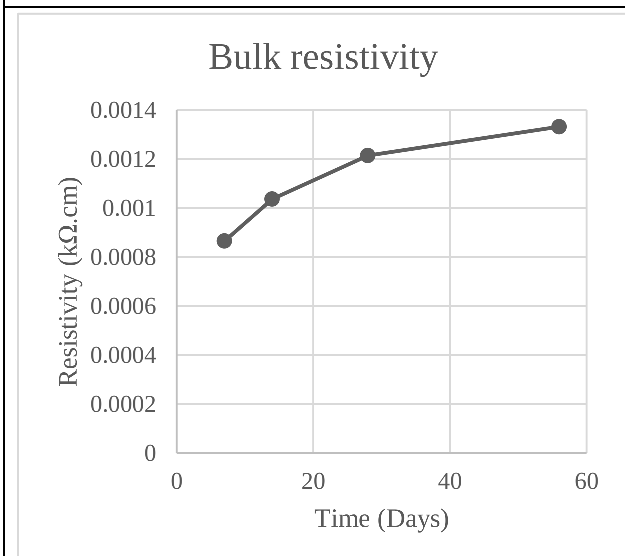
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1676 lb	2.58	10.41
Fine Aggregate	LIGHT WEIGHT FINES	353 lb	1.84	3.07
Fine Aggregate	SAND - WASHED CONCRETE	581 lb	2.60	3.58
Water	POTABLE WATER	33.4 gal	1.00	4.46
Admixture	AIR ENTERING ADMIXTURE - ASTM C260	10 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, D	20 lq oz	--	--
	Air Content	6.00 %	--	1.62
	Yield	3593 lb	--	27.00

Table A.13 B6L 0.37 properties and test results

Mix Design Name	B6L 0.37
Design Strenght	6000 psi
W/CM	0.368
Air	5-7.5%
Slump	4-9 in







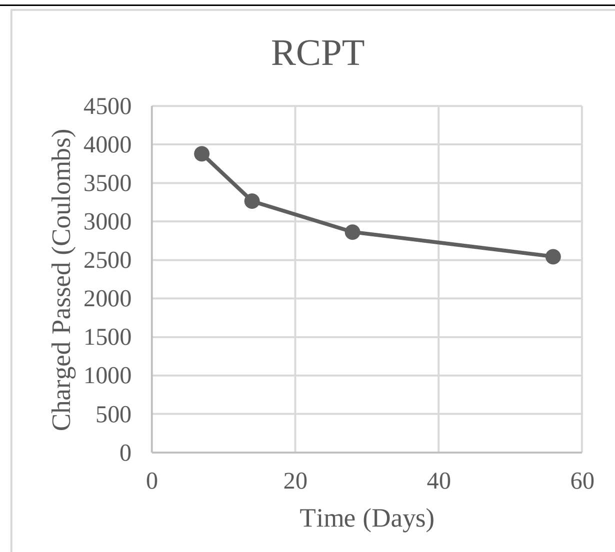
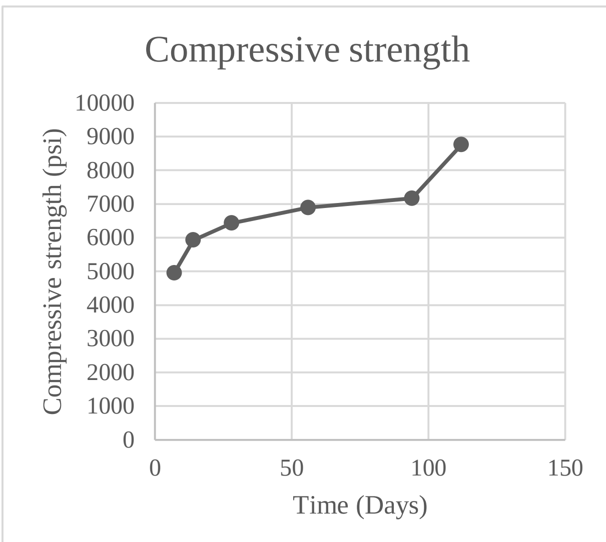


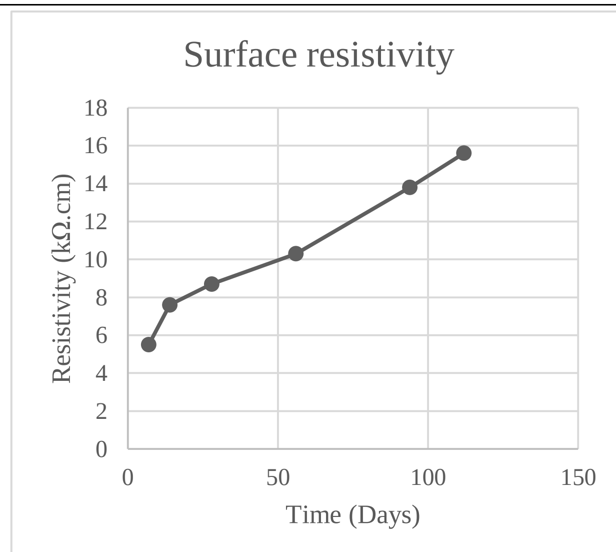
Table A.14 B6L 0.37 mix design

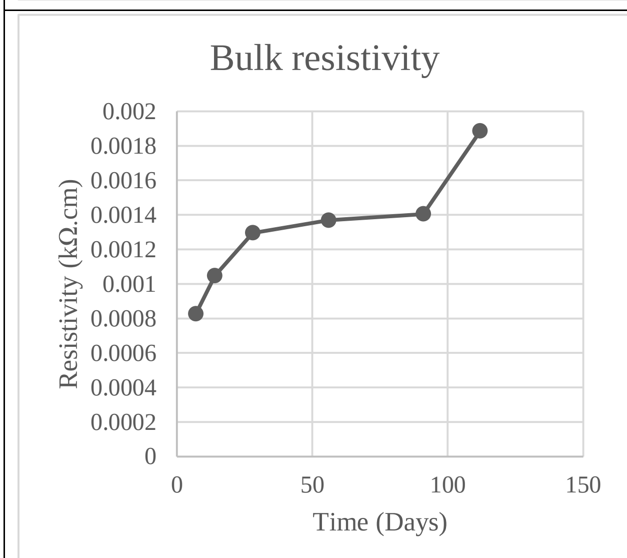
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)	640 lb	3.15	3.26
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)	160 lb	2.60	0.99
Coarse Aggregate	UTECA - UTELITE c-330 #67 (UTELITE AGGREGATES)	1155 lb	2.49	10.34
Fine Aggregate	KSGFA - ASTM C-33 Concrete Sand	971 lb	2.55	6.10
Water	Water WAT01 - Well Water (City Water supply)	292 lb	1.00	4.68
Admixture	Sika Plastiment retarder (Sika Corp ADMIX)	16 floz	1.2	--
Admixture	Sika NC accelerant (Sika Corp ADMIX)	128 floz	1.4	--
Admixture	Sika2100 - Sika Viscocrete HRWR (Sika Corp ADMIX)	52 floz	1.1	0.05
Admixture	Sika air (Sika Corp ADMIX)	3.60 floz (US)	1	--
	Air Content	6.50 %	--	1.77
	Yield	3235 lb	--	27.19

Table A.15 A6 0.37 properties and test results

Mix Design Name	A6 0.37
Design Strenght	6000 psi
W/CM	0.37
Air	5-7.5%
Slump	4-9 in
Unit weight	138.1







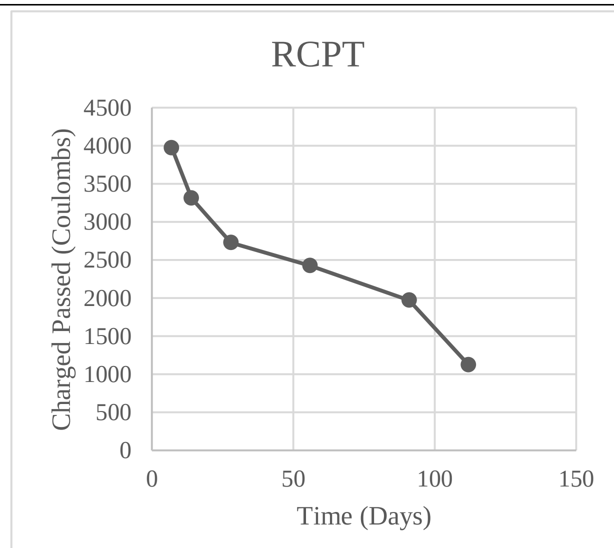
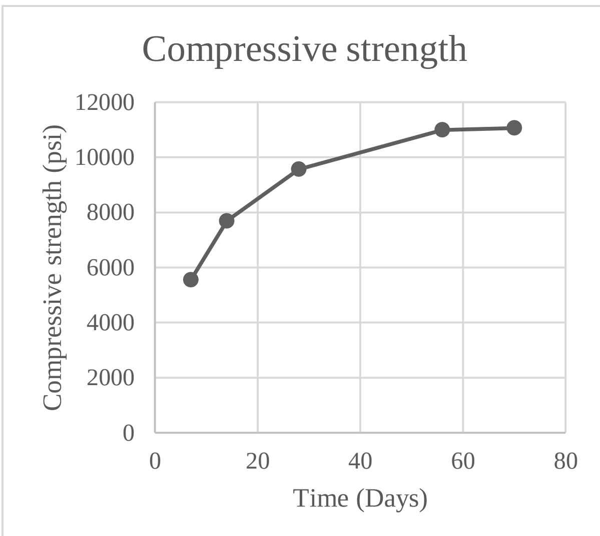


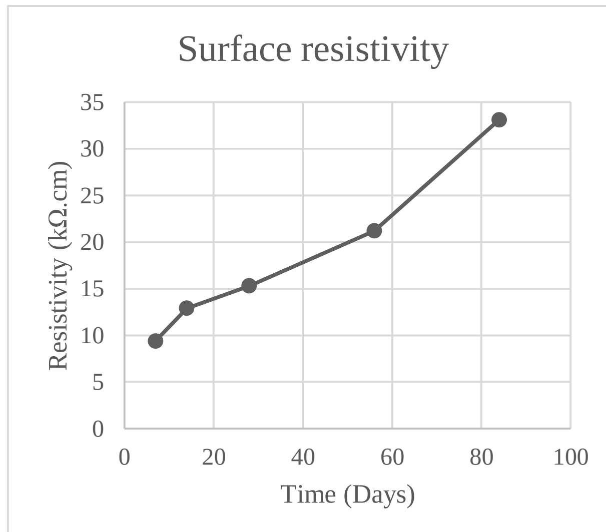
Table A.16 A6 0.37 mix design

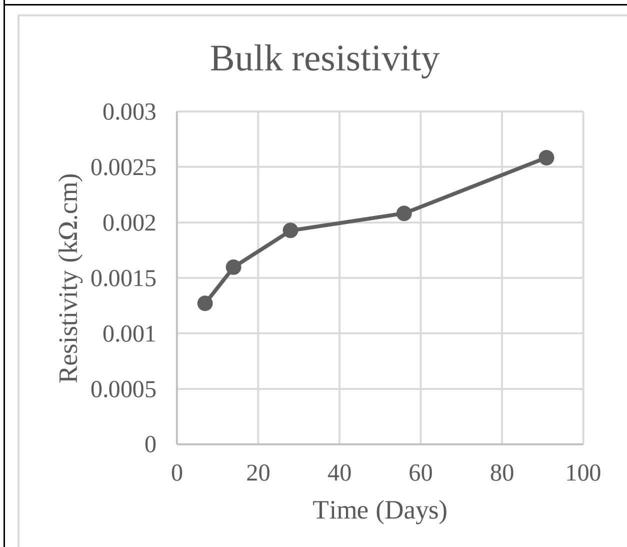
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	602 lb	3.15	3.06
Fly Ash	TYPE F FLY ASH, ASTM C 618	150 lb	2.30	1.05
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1613 lb	2.58	10.02
Fine Aggregate	SAND - WASHED CONCRETE	1084 lb	2.60	6.68
Water	POTABLE WATER	33.6 gal	1.00	4.49
Admixture	AIR ENTERING ADMIXTURE - ASTM C260	19 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, D	15 lq oz	--	--
Admixture	WATER REDUCER - ASTM C494 TYPE A, F	90 lq oz	--	--
	Air Content	6.30 %	--	1.70
	Yield	3729 lb	--	27.00

Table A.17 C10 0.32 properties and test results

Mix Design Name	C10 0.32
Design Strenght	10000 psi
W/CM	0.32
Air	5-7.5%
Slump	22
Unit weight	138.25







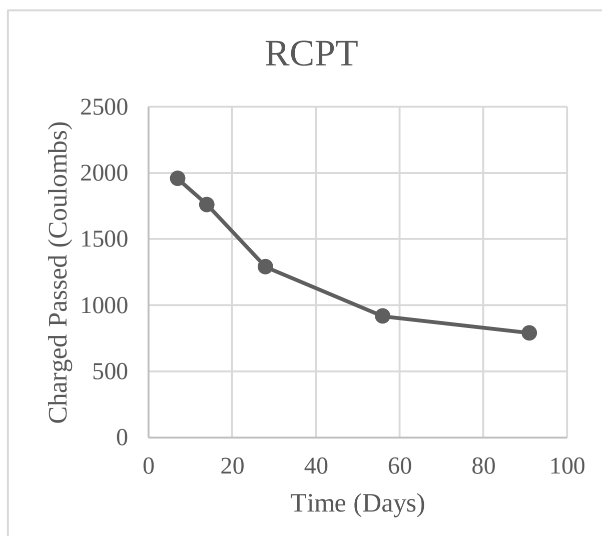


Table A.18 C10 0.32 mix design

Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Holcim gray Type III	700 lb	3.15	3.561
Fly Ash	Fly Ash - F	175 lb	2.36	1.188
Aggregate	Sand	1055 lb	2.591	6.526
Aggregate	Coarse	1014 lb	2.582	6.292
Aggregate	Medium	499 lb	2.582	3.099
Water	Water	280 lb	1.00	4.488
Admixture	Water reducer (16 oz/100wt)	140 fl oz	--	--
Admixture	Air entering (0.55 oz/100wt)	5 fl oz	--	--
Admixture	Hydration controlling admixture (0.6 oz/100wt)	5 fl oz	--	--
Admixture	Viscosity modifying admixture (0.8 oz/100wt)	7 fl oz	--	--
	Air Content	6.25 %	--	1.69
	Yield	3733 lb	--	27.00