CAIT-UTC-NC35

Evaluating Electrical Resistivity as a Performance based Test for Utah Bridge Deck Concrete

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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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Chapter 1: Introduction

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.

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.

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.

Outline of the Report

In the following report, the background, data collection and data evaluation with results, and discussion of the investigation will be presented. The final chapter will reiterate the conclusions and recommendations for future research.

Chapter 2: Background

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.

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).

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

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 1.1. The test setup is shown in Figure 2.2 and cells used in the RCP test are shown in Figure 2.2.

Table 1.1 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

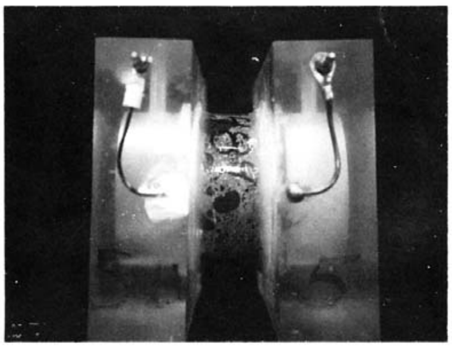


Figure 1.2 Specimen ready for test (ASTM C1202 2012)

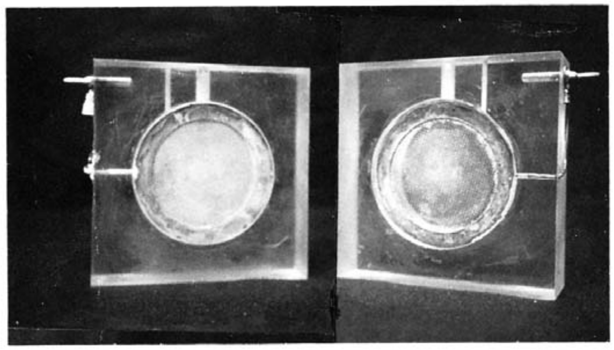


Figure 2.2 Applied Voltage Cell-Face View (ASTM C1202 2012)

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 2.3, 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 2.5 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 2.4.

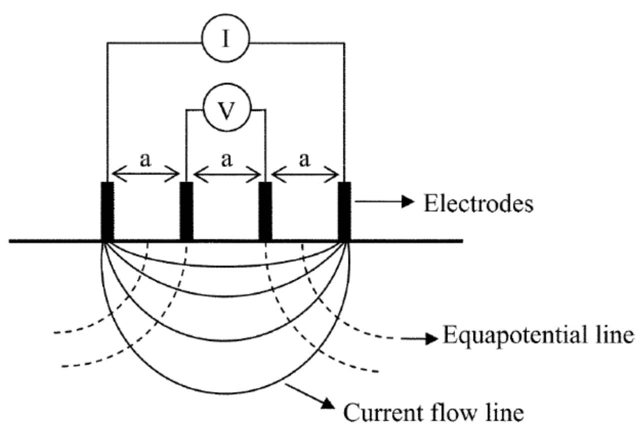


Figure 2.3 Schematic representation of surface resistivity test (Sengul and Gjørv 2008)

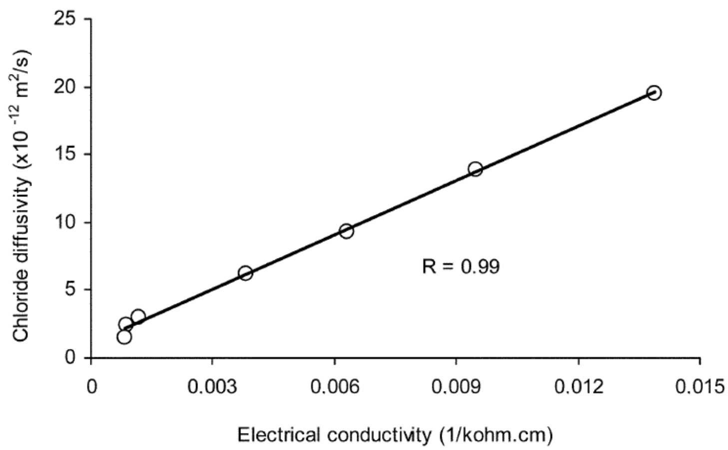


Figure 2.4 Relationship between chloride diffusivity and electrical conductivity for concrete tested using the four-electrode method (Sengul and Gjørv 2008)

Figure 2.5 Giatec Scientific Inc. instrument for measuring surface resistivity

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

Steel bars should not be in the affected depth of applied current flow (see Figure 2.3), otherwise the measured resistivity will be significantly lower in comparison to the real resistivity of concrete (Millard and Gowers 1991).

As a specimen becomes semi-infinite, probe spacing must be chosen carefully in order to give accurate and consistent results.

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.

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 difficulties are challenges for in situ measurements of resistivity properties, but are not a problem when measuring standard cylinder specimens. Probe spacing in Giatec Surf™ that was used in this research was 4 cm.

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 2.6 and Figure 2.7. Concrete electrical resistivity can be calculated using Equation 2.

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

Where:

A = cross-sectional area of cylinder

L = length of the specimen

Z = impedance that occurs due to the resistance of concrete

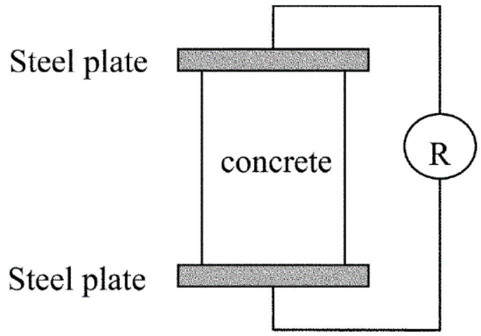


Figure 2.6 Bulk resistivity method (Sengul and Gjørv 2008)

Figure 2.7 Giatec Scientific Inc. instrument for measuring Bulk resistivity

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 2.8. This relationship is similar to that of surface resistivity.

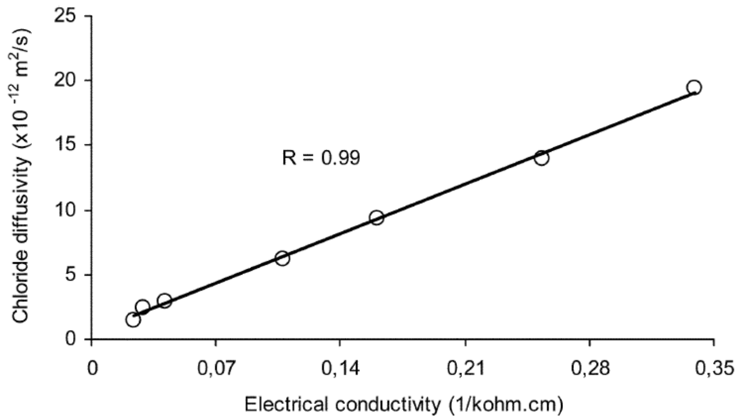


Figure 2.8 Relationship between chloride diffusivity and electrical conductivity for concrete tested using the two-electrode method (Sengul and Gjørv 2008)

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).

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).

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 2.9.

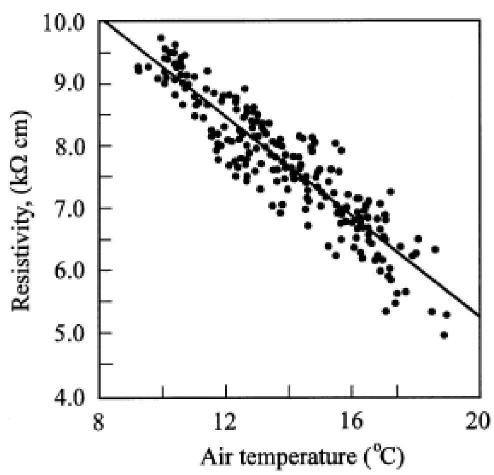


Figure 2.9 Relationship between measured resistivity and air temperature (Gowers and Millard 1999)

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 2.10 clearly shows that using different cement could lead to different resistivity.

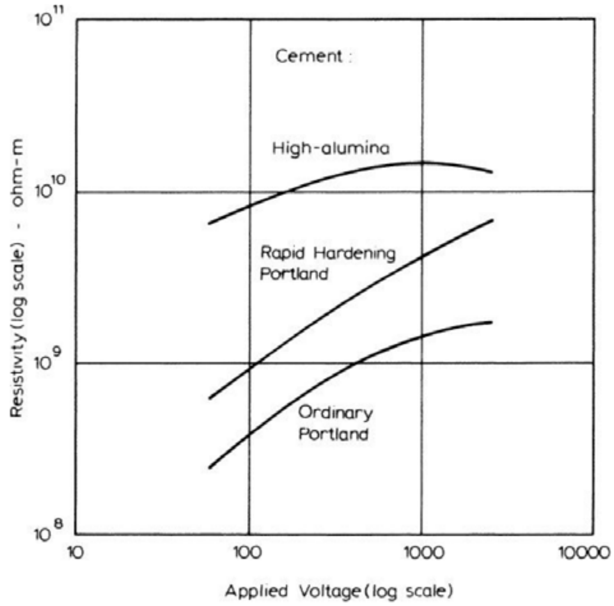


Figure 2.10 Relation between resistivity and applied voltage of different cement concretes with W/CM= 0.49 (Neville 1995)

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:

a) Since water is a conductive material, a higher W/CM ratio causes a decrease of resistivity (Neville 1995).

b) 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 2.11.

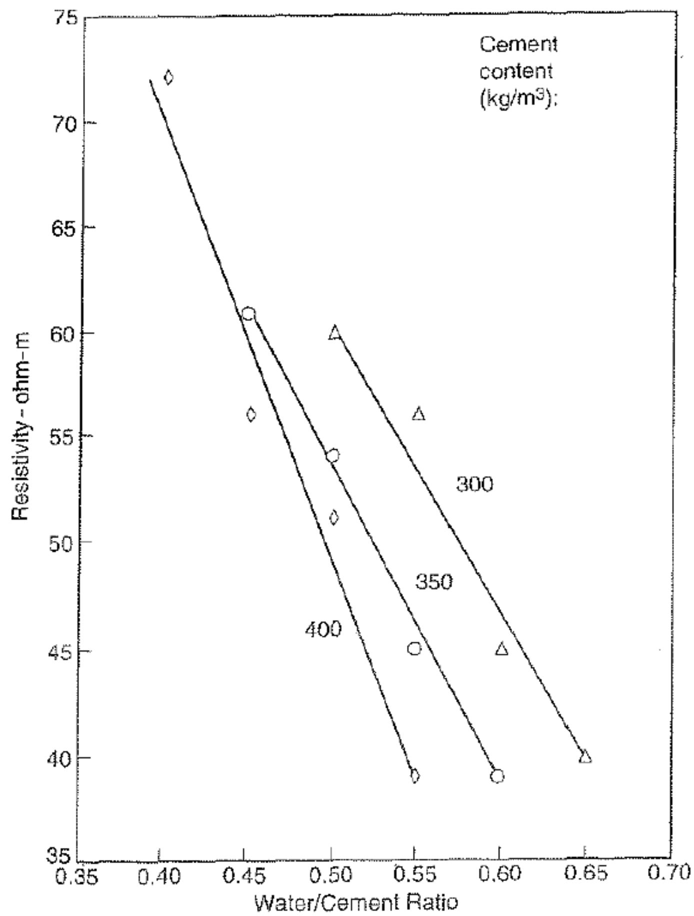


Figure 2.11 Relation between electrical resistivity and W/CM ratio at 28 days with different cement contents (Neville 1995)

Conclusion

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:
  - For example: fly ash, silica fume, iron blast-furnace slag, Metakaolin
- Chemical Admixtures:
  - For example: water-reducing admixtures, retarding admixtures, accelerating admixtures, superplasticizers, corrosion-inhibiting admixtures
- Aggregate type and size:
  - Normal weight aggregates: sand & gravel, crushed stone
  - Lightweight aggregates: expanded shale, clay, slate, or perlite
  - Heavy weight aggregates: dense rocks such as barytes, magnetite, and other heavy metallic ores
- Paste fraction
- Water to cement ratios (W/CM)
- Curing methods: immersion, accelerated
- Surface wetting: probe surface contact
- Temperature of sample
- Degree of saturation

Chapter 3: Data Collection

Overview

The procedure for collecting data will be explained in this chapter. All tests done during this research project will be explained, and all concrete mix designs will be presented. In addition, the inter-laboratory investigation between the UDOT lab and the USU lab will be explained.

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

Mixing instructions

Below are the steps to that was made 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)

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

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 2.1 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.

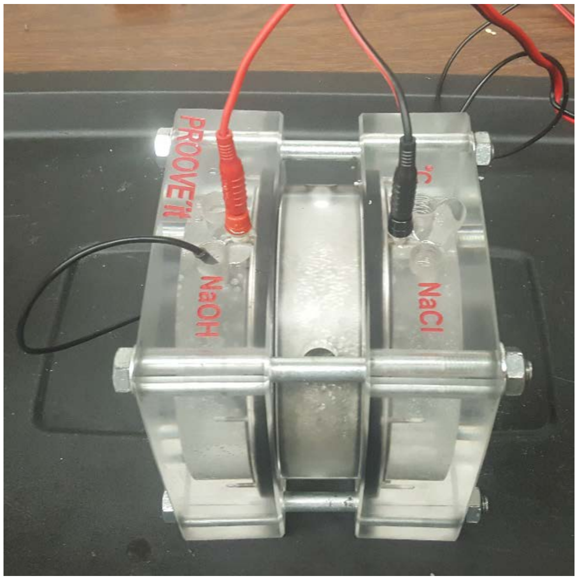


Figure 3.2 RCP test cell while measuring the current and temperature

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

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 . 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.

Figure 3.3 Surface electrical resistivity sample holder

Table shows the relation of chloride penetrability classification and surface electrical resistivity at 23°C.

Table 3.2 Relation between surface resistivity and chloride penetrability at 23°C (Kessler et al. 2005)

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

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, which is the inverse of electrical resistivity, was then calculated and presented in Figure and Figure for field and lab phase respectively.

$$\sigma = \frac{K \times I_1 \times L}{(V \times D^2)}$$ *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 shows the relation of chloride penetrability classification and Bulk electrical resistivity (Thomas 2016, Thomas 2018).

Table 3.3 Relation between Bulk resistivity and chloride penetrability (Thomas 2016)

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

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 , the concrete had a slump of 2.5 inches.

Figure 3.4 slump test

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 and Figure respectively.

Figure 3.5 pressure method apparatus

Figure 3.6 volumetric method apparatus

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).

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):

$$P_c = \frac{n_1^2}{n^2} \times 100 \qquad \textit{Equation 4}$$

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):

$$DF = \frac{PN}{M} \qquad \textit{Equation 5}$$

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 Within-laboratory durability Factor Precision for Averages of Two or More Beams in procedure A. Figure shows the freeze and thaw machine.

Table 3.4 Within-laboratory durability Factor Precision for Averages of Two or More Beams in 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 and thaw machine

Figure 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.

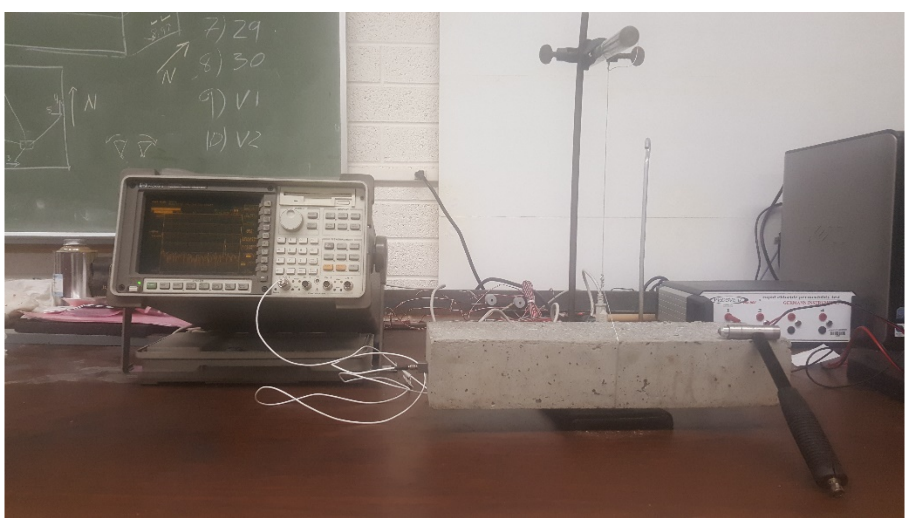


Figure 3.8 Appratus for messuring the relative dynamic modulus of elasticity

Mix designs

In the field phase, eleven different mixes were cast in the laboratory environment. Mix design properties are shown in Table. A more detailed table for each field mix design gathered in this phase can be found in Appendix A: Detailed Field Mix Designs. 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 secondary 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 make 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.

Field mix designs

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 entrainment	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/100 wt	0.6 oz/100wt

Table 3.5 Mix design specifications in field phase

Lab mix design

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 3.6 Mix design specifications in lab phase

USU mix designs

3.7 shows the USU mix designs.

Table 3.7 USU mix designs

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

RCA mix designs

Table shows the mix designs that contain recycled concrete aggregate as either coarse or fine aggregate.

Table 3.8 Mix design specifications for RCA

Mix Design	Age (day)								
	7			14			28		
	Surface		Strength	Surface		Strength	Surface		Strength
	kΩ.cm	Penetrability Level	psi	kΩ.cm	Penetrability Level	psi	kΩ.cm	Penetrability Level	psi
0 % RCA	12.2	Moderate	8811	16.2	Low	9506	20.9	Low	9802
30 % RCA-rock without RCA-Sand	11.8	Moderate	7960	13.8	Moderate	8946	20.2	Low	9087
100 % RCA-rock without RCA-Sand	11.5	Moderate	8035	14.2	Moderate	8598	17.6	Low	8756
30 % RCA-rock with RCA-Sand	10.8	Moderate	8297	11.5	Moderate	8423	16.5	Low	9038
100 % RCA-rock with RCA-Sand	5.8	High	6291	5.2	High	6988	7.8	High	7350
100 % RCA-rock without RCA-Sand	7.0	High	7053	8.8	High	8142	15.0	Low	--

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 . 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 investigation with USU and UDOT surface electrical resistivity machine

Conclusion

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.

Chapter 4: Data Evaluation

Overview

This investigation is categorized in field and lab phases. Also, this chapter discusses use of Recycled Concrete Aggregate (RCA) and Utah State University's (USU) base concrete mix. In addition to the main focus of this research project. Moreover, data, and results will be presented in this chapter.

As stated in the Background, many variables can influence the electrical resistivity and RCPT tests. If all variables and permutations were to be fully investigated, thousands of concrete mixtures would be required. Therefore, the research team has requested Utah concrete suppliers to give samples of their typical concrete to be in the field phase. Ideally, this would give the research program an adequate picture of the current state of practice within Utah.

In the lab phase, one of the field mixes was chosen as the control mix and duplicated in the lab in order to see the differences in the controlled and field environment. In addition, changes were made to the lab control mix to see the effect of different materials on the resistivity and durability of concrete.

Recycled concrete aggregates in place of normal aggregates were tested to see their effects on various concrete properties as part of a different investigation. Penetrability measurements (RCPT and surface resistivity) were made and since they were related to this project, the results are included. In addition, the USU base mix for on-campus concrete sidewalks was included since USU sidewalks suffer from similar deterioration bridge decks. This was also a separate investigation, but the penetrability results are presented here.

The raw data in each phase will be presented in the experimental results section. Comparison of data will be presented in the discussion section. In addition, the data was plotted and all the findings will be presented in the discussion section. Moreover, some guidance will be provided to the Utah Department of Transportation and concrete suppliers all around Utah.

Experimental results

Field raw data

Table and Table show the raw data for four different ages of concrete in the field phase.

Table 4.1 Field raw data for 7 and 14 day testing

Mix Design	Age (day)											
	7						14					
	RCPT		Surface		Bulk	Strength	RCPT		Surface		Bulk	Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi
D4 0.42	4963	High	5.3	High	6.4	3862	3852	Moderate	7.2	High	8.2	4053
A4L 0.44	4952	High	3.7	High	7.5	3009	3579	Moderate	5.4	High	9.3	5283
B5 0.37-	2722	Moderate	12.3	Moderate	11.4	4372	2168	Moderate	16.4	Low	14.2	5874
B5 0.37+	2938	Moderate	7.4	High	10.1	4345	2241	Moderate	13.5	Moderate	13.8	5234
A5 0.4	3461	Moderate	4.6	High	8.7	4301	2697	Moderate	8.8	High	12.0	4850
A5L 0.4	3586	Moderate	4.6	High	6.8	3403	2788	Moderate	5.3	High	8.7	4873
B6L 0.37	3877	Moderate	4.2	High	8.6	4637	3264	Moderate	6.3	High	10.4	5468
A6 0.37	3973	Moderate	5.5	High	8.3	4948	3312	Moderate	7.6	High	10.5	5926
C10 0.32	1956	Low	9.4	High	12.7	5547	1759	Low	12.9	Moderate	16.0	7689

Table 4.2 Field raw data for 28 and 56 day testing

Mix Design	Age (day)											
	28						56					
	RCPT		Surface		Bulk	Strength	RCPT		Surface		Bulk	Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi
D4 0.42	3255	Moderate	8.2	High	9.8	4567	2183.9	Moderate	10.2	Moderate	10.3	4825
A4L 0.44	2257	Moderate	7.7	High	11.4	5437	1954	Low	9.8	High	11.7	5562
B5 0.37-	1634	Low	20.3	Low	18.9	7348	1389.81	Low	25.7	Very low	16.9	9000
B5 0.37+	1756	Low	19.3	Low	17.8	6859	626.85	Very low	27.8	Very low	20.2	7950
A5 0.4	2432	Moderate	10.2	Moderate	14.4	5369	1966	Low	13.1	Moderate	14.8	6434
A5L 0.4	2591	Moderate	6.4	High	10.2	5663	2263	Moderate	7.3	High	10.6	5974
B6L 0.37	2863	Moderate	8.2	High	12.1	6125	2543.62	Moderate	12.4	Moderate	13.3	7157
A6 0.37	2729	Moderate	8.7	High	13.0	6430	2426	Moderate	10.3	Moderate	13.7	6890
C10 0.32	1289	Low	15.3	Low	19.3	9562	917.07	Very low	21.2	Low	20.8	10993

Lab raw data

Table and Table show the raw data for four different ages of concrete in the lab phase.

Table 4.3 Field raw data for 7 and 14 day testing

Mix Design	Age (day)											
	7						14					
	RCPT		Surface		Bulk	Strength	RCPT		Surface		Bulk	Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi
Slag Cement	4039	High	4.4	High	5.2	3791	3168	Moderate	5.9	High	7.3	5935
Water Reducer	3656	Moderate	6.5	High	10.1	2856	2319	Moderate	13.6	Moderate	14.2	4495
Velocity Modifying Admixture	2711	Moderate	6.9	High	8.8	2869	2243	Moderate	12.3	Moderate	13.8	4684
Accelerator (Master Set)	4261	High	5.9	High	7.3	2923	3268	Moderate	10.2	Moderate	10.2	4577
High Air	2719	Moderate	9.6	High	6.1	2641	1681	Low	20.8	Low	8.9	3664
Control-lab	3154	Moderate	9.3	High	11.1	4923	1717	Low	13.7	Moderate	13	5360
Low Air	2833	Moderate	8.7	High	7.5	4167	1925	Low	17.9	Low	11.8	6147
Steel Fiber	3248	Moderate	6.4	High	5.8	2365	2417	Moderate	8.3	High	7.8	3761
Magnetite Aggregate	1867	Low	7.7	High	9.1	3331	723	Very low	10.9	Moderate	13.4	4441
Hematite Aggregate	1546	Low	3.5	High	7.4	5368	617	Very low	1.7	High	10.5	6937
Corrosion Inhibiting Admixture	3526	Moderate	6.3	High	4.8	3928	2562	Moderate	11.2	Moderate	5.9	5398

Table 4.4 Field raw data for 28 and 56 day testing

Mix Design	Age (day)											
	28						56					
	RCPT		Surface		Bulk	Strength	RCPT		Surface		Bulk	Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	kΩ.cm	psi
Slag cement	2336	Moderate	10.5	Moderate	8.6	7366	1437	Low	16.8	Low	9.5	8863
Water reducer	1362	Low	20.6	Low	17.5	5375	579.8	Very low	20.8	Low	18.9	6067
VMA	1879	Low	17.3	Low	16.7	5628	1422	Low	20	Low	20.8	6667
Masterset	2136	Moderate	14	Moderate	12.1	5541	1839	Low	14.7	Moderate	15.4	6561
High air	835	Very low	25.7	Very low	11.7	4568	216	Very low	32.8	Very low	15.8	5253
Control-lab	954	Very low	17.3	Low	14.3	6113	0.14	Negligible	20.9	Low	15.4	7258
Low air	1368	Low	24.4	Low	15.4	7925	1166	Low	32.1	Very low	17.6	8965
Steel fiber	1357	Low	16.9	Low	8.9	4729	686	Very low	19.6	Low	9.3	5381
Magnetite	210	Very low	14.1	Moderate	16.7	5627	4	Negligible	8.5	High	20.2	6453
Hematite	87	Negligible	3.6	High	14	8411	3.95	Negligible	14.2	Moderate	16.0	9637
Corrosion	1615	Low	18.1	Low	8.1	6797	1193	Low	19.4	Low	9.5	7909

Inter-laboratory Investigation

Six samples were transported from the USU curing room to the UDOT fog room. All the samples were under water the whole time of transportation. The samples were in the UDOT fog room for five days in order to reach temperature and moisture equilibrium. The results of this investigation are tabulated in Table .

Table 4.5 Inter-laboratory investigation results for seven different cylinders

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

As is shown, there are negligible differences between the results in these two machines. It is worth mentioning that the UDOT machine was purchased earlier and has an older version of the software installed.

USU raw data

Table and

Table show the different test results for USU concrete mix investigation.

Table 4.6 USU raw test results for 7 and 14 day

Mix Design	Age (day)									
	7					14				
	RCPT		Surface		Strength	RCPT		Surface		Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	psi
USU with Hycrete	--	--	8.6	High	2459	3104	Moderate	12.6	Moderate	3241
USU without Hycrete	1491	Low	9.4	High	4466	1759	Low	11.8	Moderate	5845
20% Fly ash Replacement	315	Very low	10.3	Moderate	3802	138	Very low	14.4	Moderate	3863
20% Metakaolin Replacement	2784	Moderate	14.7	Moderate	6387	1661	Low	54.4	Very low	6858
20% Silica fume Replacement	4902	High	16.6	Low	4383	1653	Low	47.5	Very low	5312
20% V-CAS Replacement	7655	High	8.2	High	3746	5615	High	15.4	Low	4367

Table 4.7 USU raw test results for 28 and 56 day

Mix Design	Age (day)									
	28					56				
	RCPT		Surface		Strength	RCPT		Surface		Strength
	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	psi	Charged Passed (Coulombs)	Penetrability Level	kΩ.cm	Penetrability Level	psi
USU with Hycrete	4934	High	15.8	Low	2921	1043.35	Low	40.1	Very low	3121
USU without Hycrete	3517	Moderate	0	High	6453	0.18	Negligible	18.3	Low	6056
20% Fly ash Replacement	793	Very low	20.5	Low	4803	0.22	Negligible	35.7	Very low	4922
20% Metakaolin Replacement	1261	Low	91.4	Very low	7835	1184.36	Low	127	Very low	7281
20% Silica fume Replacement	--	Negligible	118	Very low	5222	480.23	Very low	235	Negligible	6591
20% V-CAS Replacement	677	Very low	27.5	Very low	3907	981.11	Very low	58	Very low	3832

RCA raw data

Table shows the results for mixes that contain recycled concrete aggregate as either coarse or fine aggregate.

Mix Design	Age (day)								
	7			14			28		
	Surface		Strength	Surface		Strength	Surface		Strength
	kΩ.cm	Penetrability Level	psi	kΩ.cm	Penetrability Level	psi	kΩ.cm	Penetrability Level	psi
0 % RCA	12.2	Moderate	8811	16.2	Low	9506	20.9	Low	9802
30 % RCA-rock without RCA-Sand	11.8	Moderate	7960	13.8	Moderate	8946	20.2	Low	9087
100 % RCA-rock without RCA-Sand	11.5	Moderate	8035	14.2	Moderate	8598	17.6	Low	8756
30 % RCA-rock with RCA-Sand	10.8	Moderate	8297	11.5	Moderate	8423	16.5	Low	9038
100 % RCA-rock with RCA-Sand 1	5.8	High	6291	5.2	High	6988	7.8	High	7350
100 % RCA-rock without RCA-Sand 2	7.0	High	7053	8.8	High	8142	15.0	Low	--

Table 4.8 RCA raw data for different ages

Discussion

Field phase

The average compressive strength of three caped 4 by 8-inch concrete cylinders is shown graphically in Figure for all different field mixes. As shown in Figure , the concrete gained its compressive strength mostly within the first 28 days. Factors that affect compressive strength are W/CM ratio, type of curing, presence of SCMs, and concrete age. As shown in Figure , a higher W/CM ratio means there is more water and more porosity in concrete, which results in a lower compressive strength. In the field phase, the rate of strength gain in C10 0.32 is the highest since it was heated under a blanket for 3 days after casting. Other cylinders were either cured immersed or cured in the temperature control room with about 75 percent moisture. Moreover, all the field mixes exceeded their design strength.

Figure shows the amount of charge that passed a 2-inch slice of concrete during 6 hours. The 2-inch slice of concrete was taken from the middle of each 4 by 8-inch concrete specimen. Any factors that can influence the mobility of ions through cement paste porosity can influence the RCPT coulombs. W/CM is an important one of those factors. The quantity of charge that passed decreased when W/CM was lower. As concrete ages, its porosity decreases, therefore, the amount of charge that can pass through a 2-inch slice of concrete during a 6-hour RCP test will decrease. The rate of this decrease in charge passed levels out as concrete ages. The research team faced errors in D4 0.42 and A5L 0.4 at age 56 days and A4L 0.44 at age 91 days. The possible reason behind these errors is leakage during the test, which has been corrected. This data should be disregarded and is only presented for transparency. If leakage occurs, the amount of pressure applied to each face of concrete decreases. Consequently, the amount of charge that can pass will decrease. Also, the applied voltage (60 volts) will be applied to a smaller area of the concrete cross section.

Surface electrical resistivity was measured by the Wenner method (four probe). One concrete cylinder from each concrete mix design was selected for this test. In all field mix designs, surface electrical resistivity increased with concrete age. However, the rate of this increase decayed, especially after 28 days. As shown in Figure , increase in surface resistivity can be modeled by a linear trend. Each of the points in the graph represent the resistivity of one centimeter of concrete.

The research team encountered some errors in the process of testing surface electrical resistivity of cylinders. The error was related to apparent high resistivity in some sensors. This error was solved by wetting the surface of the cylinder and using conductive gel on top of the sensors. A Giatec Surf apparatus, which was used in these tests, uses four channels of four probe arrays. These arrays are located 90 degrees from each other. Concrete mixes that have a lower W/CM ratio have more electrical resistivity. Concrete with lower W/CM ratios have less pore connectivity, which lead to higher resistivity.

The concentration of ions in pore solution increases with concrete aging, since calcium and alkali ions dissolute with age (Nokken et al. 2006). This causes lower electrical resistivity or higher electrical conductivity. As shown in Figure , bulk electrical resistivity does not change significantly 28 days after casting. Since concrete porosity is profoundly affected by W/CM ratio, concrete with a lower W/CM ratio has a higher bulk resistivity.

Figure 12 shows the penetrability level for field mixes at 28 days. In this figure, Penetrability level 4 is High, 3 is moderate, 2 is low, 1 is very low and 0 is negligible. As is apparent, all the different durability tests are within a one-category tolerance of each other, in most cases, the resistivity tests are one category above (more penetrability) than the RCPT. This indicates that the use of the resistivity methods to enforce a minimum penetrability for UDOT bridge decks will provide a conservative penetrability.

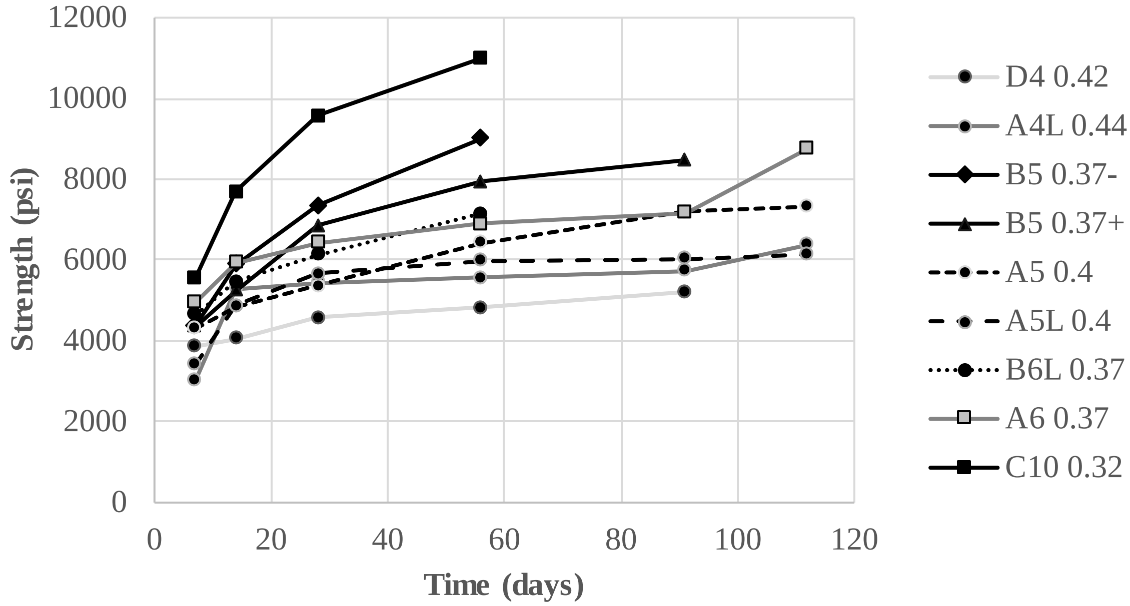


Figure 4.1 Field compressive strength

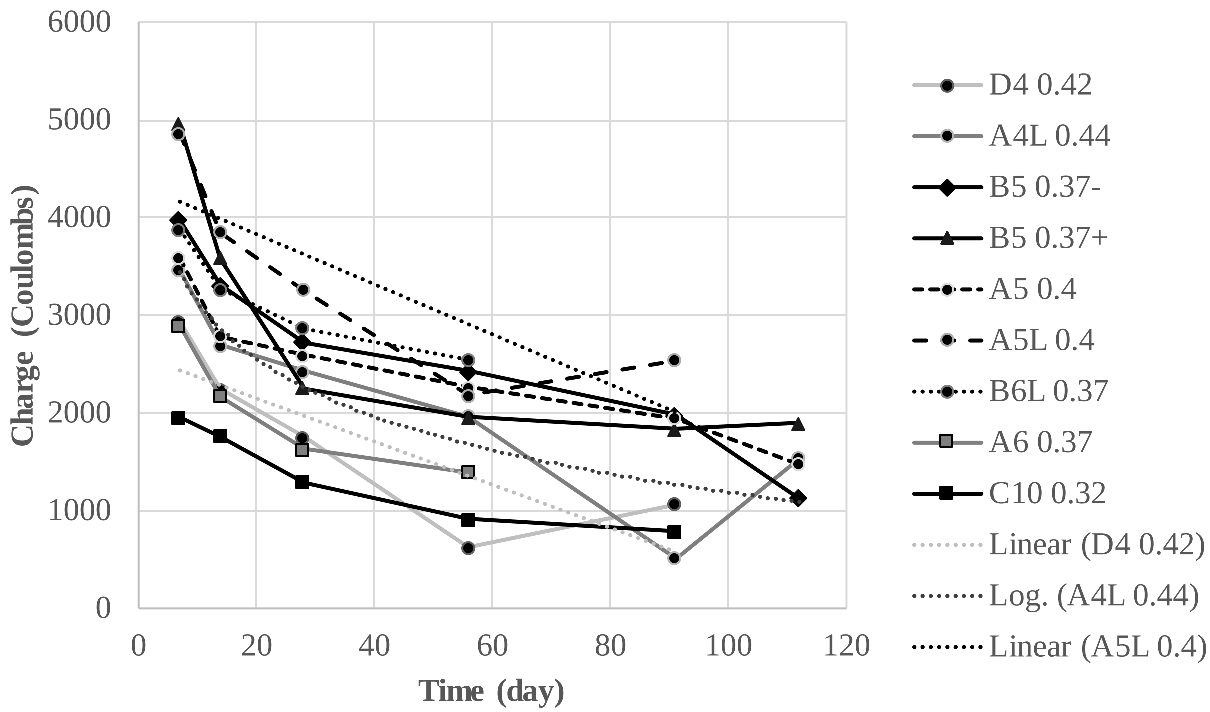


Figure 4.2 Field RCPT results

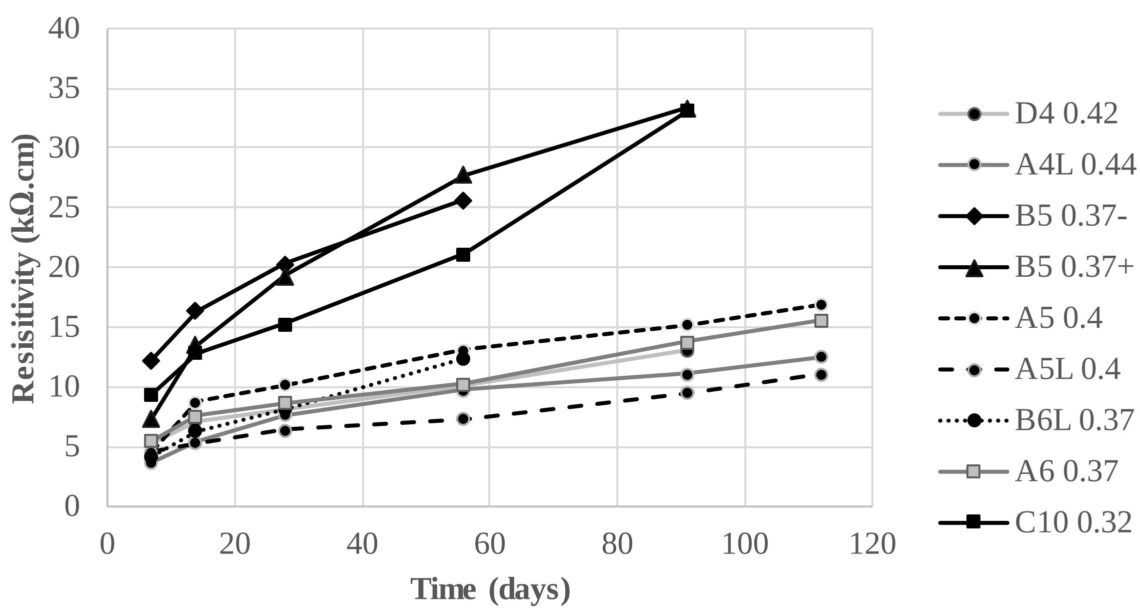


Figure 4.3 Field Surface resistivity results

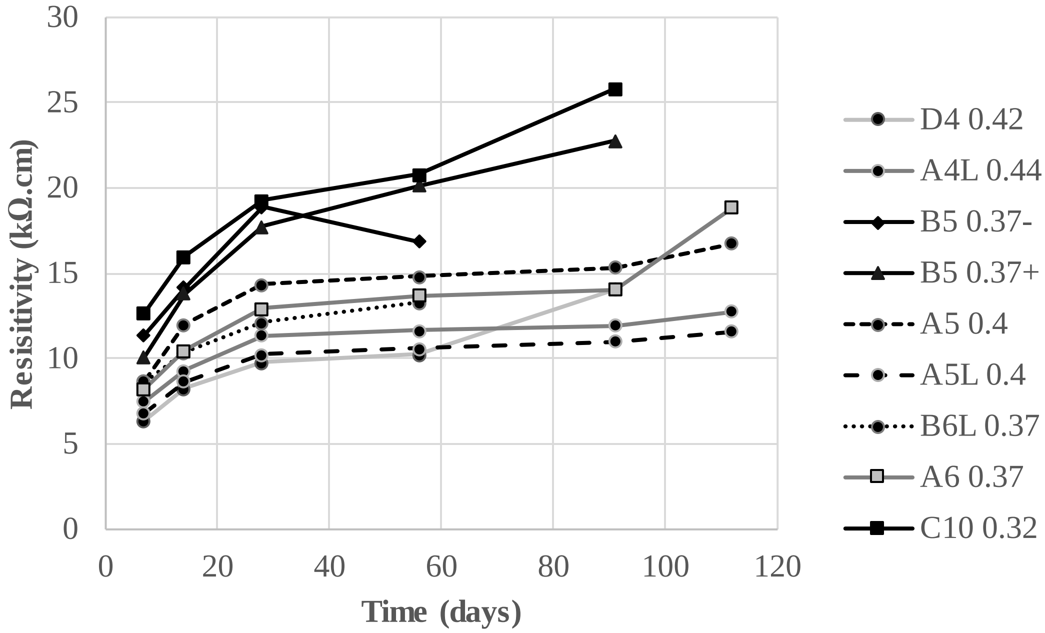


Figure 4.4 Field Bulk resistivity results

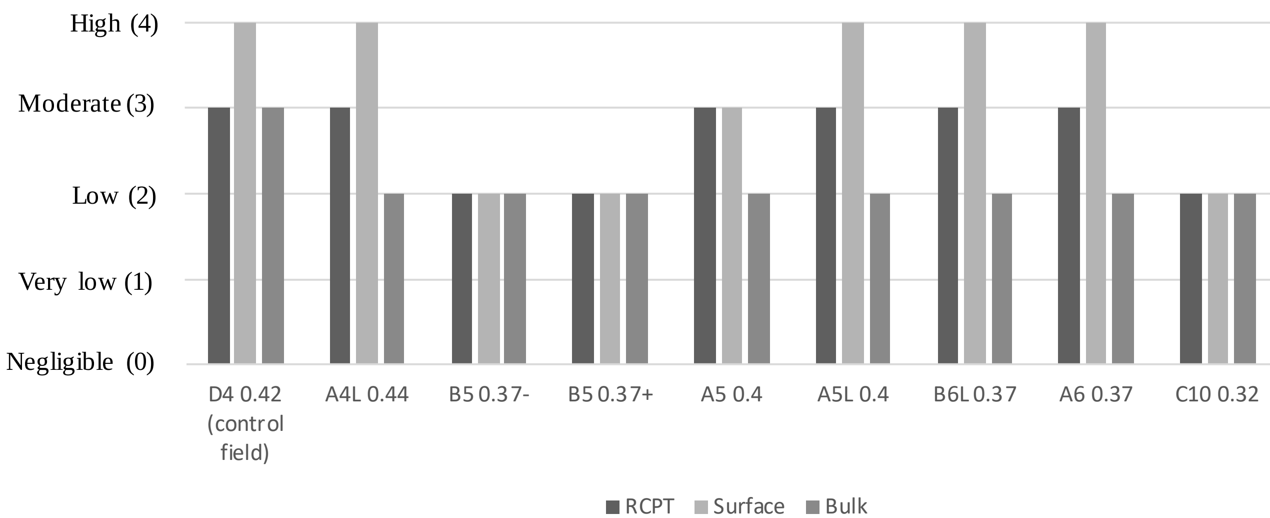


Figure 12 Field penetrability level in 28 day

Field lightweight mix vs. field normal weight mix

Three lightweight mixes were cast in this phase. In this section, the results of a normal mix are compared to a similar light weight mix design. The mixes selected were both cast by the same company with similar water to cement ratios and similar design strengths. The results of these mixes are presented in Table .

Table 4.9 Field normal weight mix vs. field lightweight mix results at 56 day test

Mix design	Type	RCPT 56 (coulomb)	Classification	Bulk 56 (kΩ.cm)	Classification	Surface 56 (kΩ.cm)	Classification
A5 0.4	NW	1966	Low	14.83	High	13.1	High
A5L 0.4	LW	2263	Moderate	10.61	High	7.3	Moderate

Although these two mixes have similar water to cement ratios, were cast by the same company, and have the same design strength, they are not exactly the same. Based on Table , all the tests showed that using normal weight aggregate produces more durable concrete, per the electrical tests. Lightweight aggregates tend to be difficult to prepare and mix, due to the more complex pre-saturation requirements, which anecdotally has resulted in higher variability of fresh and hardened properties, when compared to normal weight aggregate concrete. For this reason, a concrete supplier's proficiency at making lightweight aggregate may profoundly change these results, but more testing would be necessary to validate this assertion.

Field statistical analysis of data

A Pearson product-moment correlation was applied to all data gained from all the tests in the field phase to see any linear correlation between the data. The Pearson correlation gives a value between negative one and positive one, where positive one means total positive correlation, zero means no correlation, and negative one means total negative correlation.

Different variables were plotted against one another to show their correlation. Also, the correlation between two variables changed during the concrete curing time. Therefore, age 7 days and 56 days were chosen to show the relation between variables in early and mature ages of concrete, respectively. These plots can be seen in Figure .

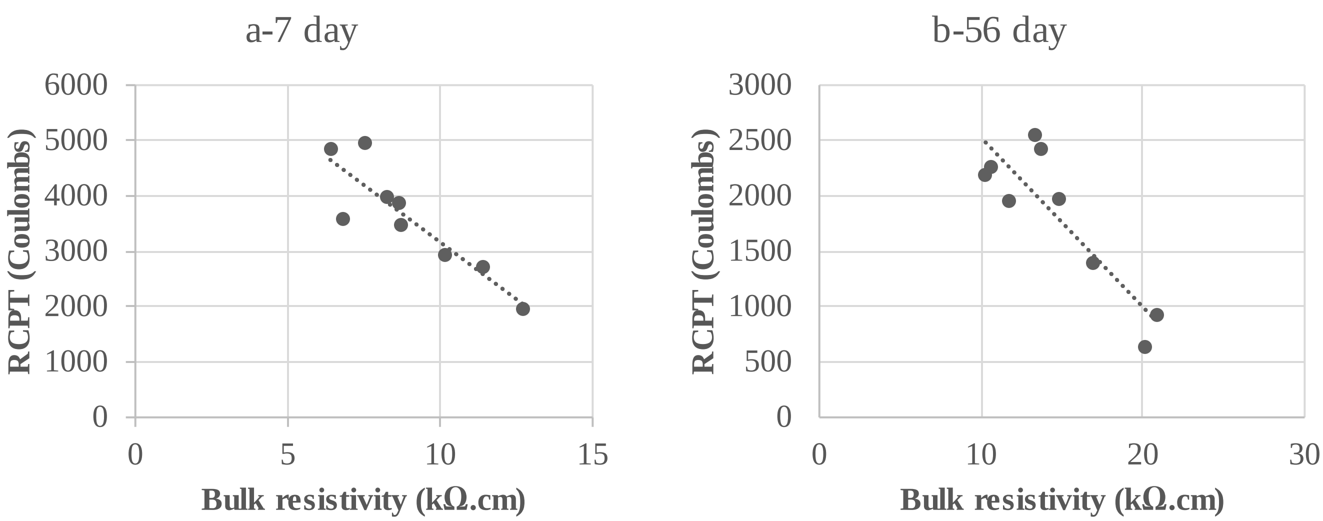


Figure 4.6 (a) RCPT vs. Bulk at 7 day, (b) RCPT vs. Bulk at 56 day

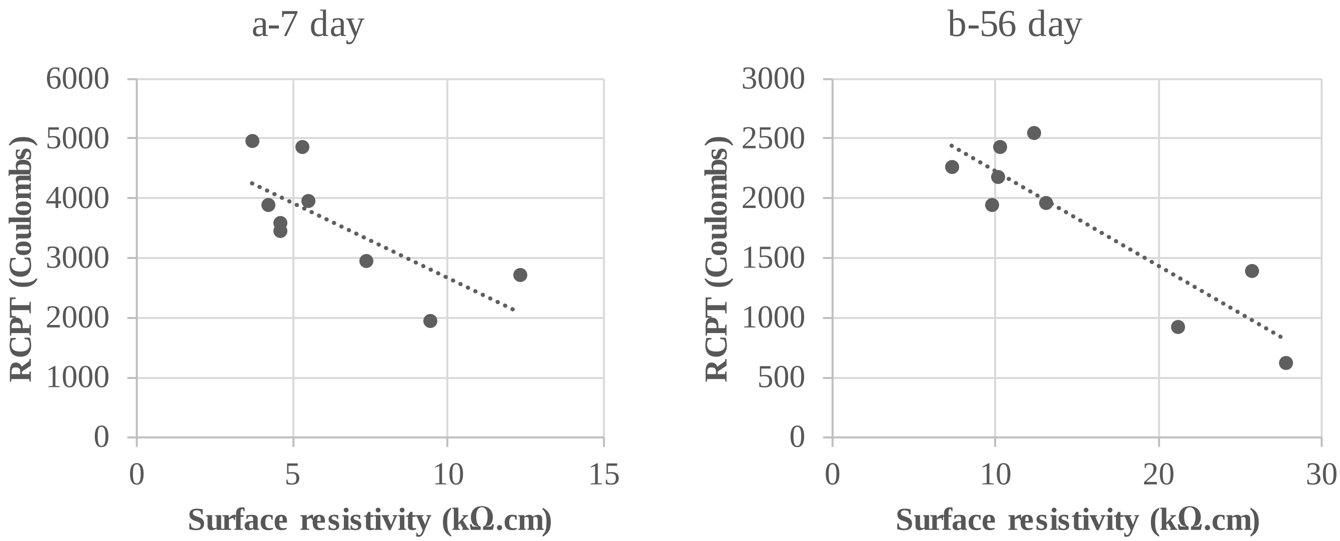


Figure 4.7 (a) RCPT vs. Surface at 7 day, (b) RCPT vs. Surface at 56 day

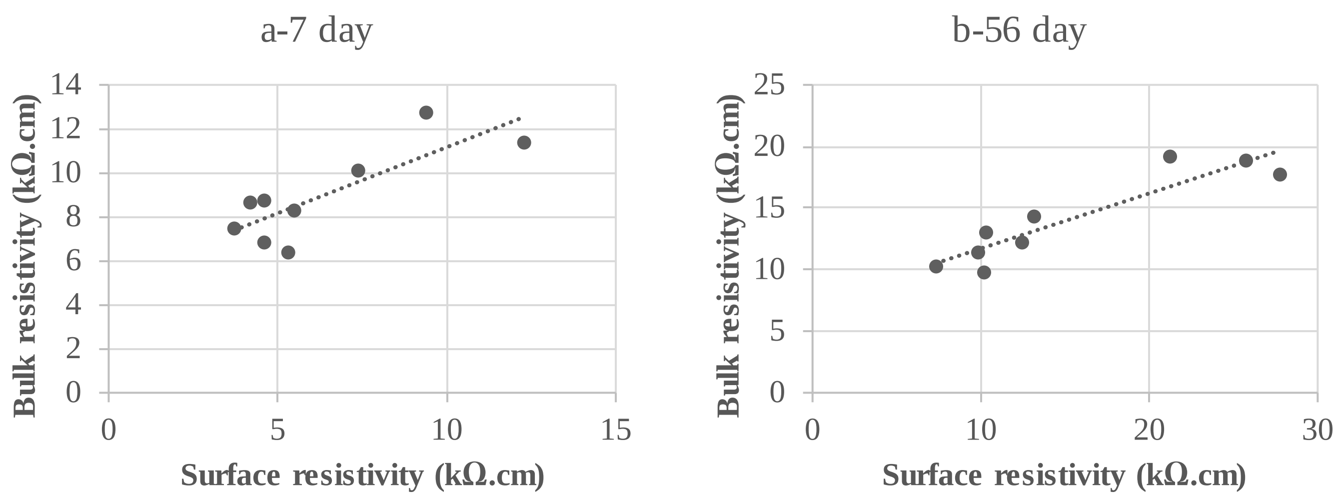
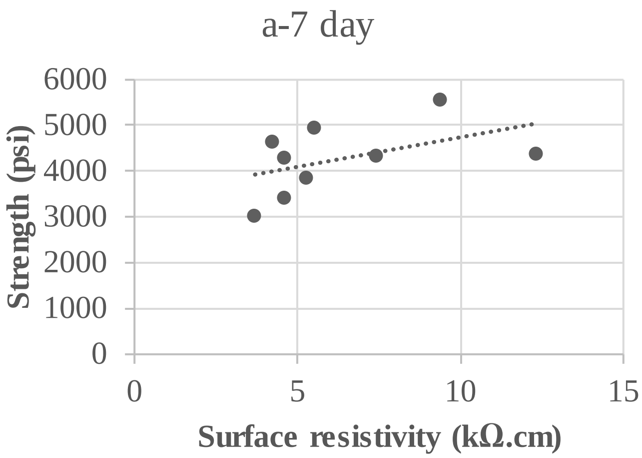


Figure 4.8 (a) Bulk vs. Surface at 7 day, (b) Bulk vs. Surface at 56 day



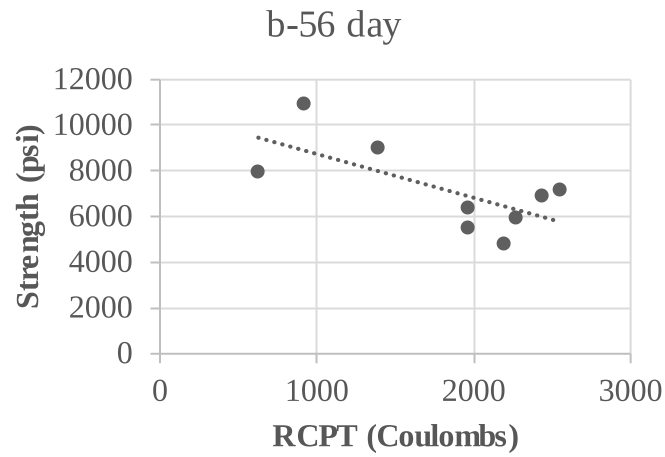


Figure 4.9 (a) Strength vs. Surface at 7 day, (b) Strength vs. RCPT at 56 day

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.

Lab phase

Even though Magnetite and Hematite mixes are not comparable to other mixes since their mix designs are different, they show low penetrability. Magnetite and Hematite aggregates tricked the surface electrical resistivity. Since the origin of these aggregates is Iron (metal), the surface electrical resistivity shows a lower resistivity and cannot be trusted. As shown in Figure , Hematite and Magnetite mixes show lower resistivity. On the other hand, RCPT in Figure shows a lower penetrability. Comparing high air content concrete (9% air) with low air content concrete (3% air) shows that higher air content concretes have a lower penetrability.

Figure shows the penetrability level for lab mixes at 28 days. In this figure, Penetrability level 4 is High, 3 is moderate, 2 is low, 1 is very low, and 0 is negligible.

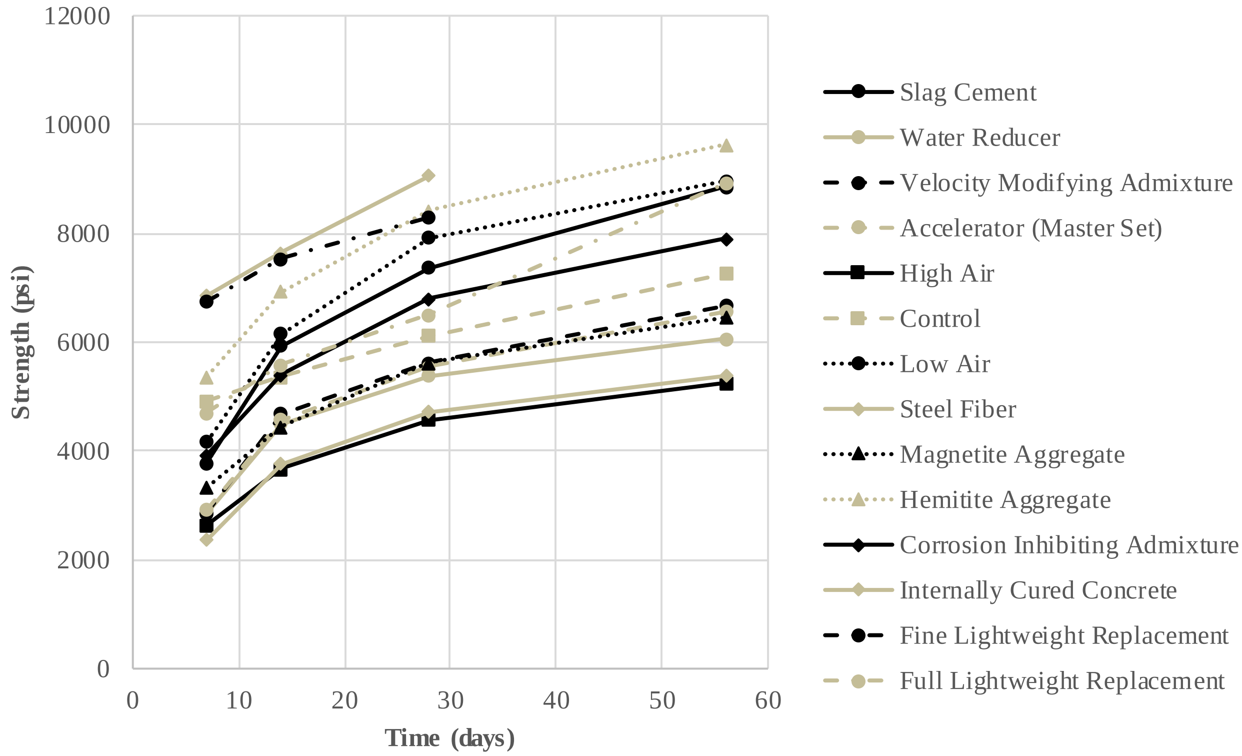


Figure 4.10 Lab compressive strength

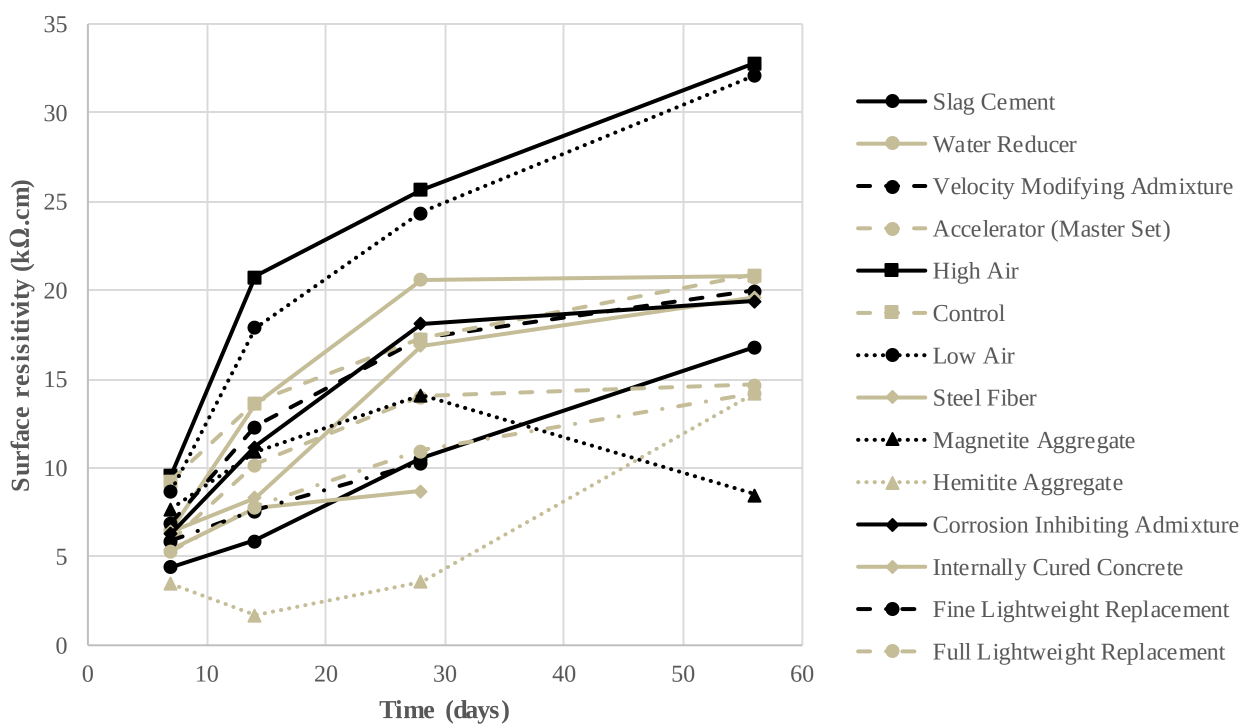


Figure 4.11 Lab surface resistivity results

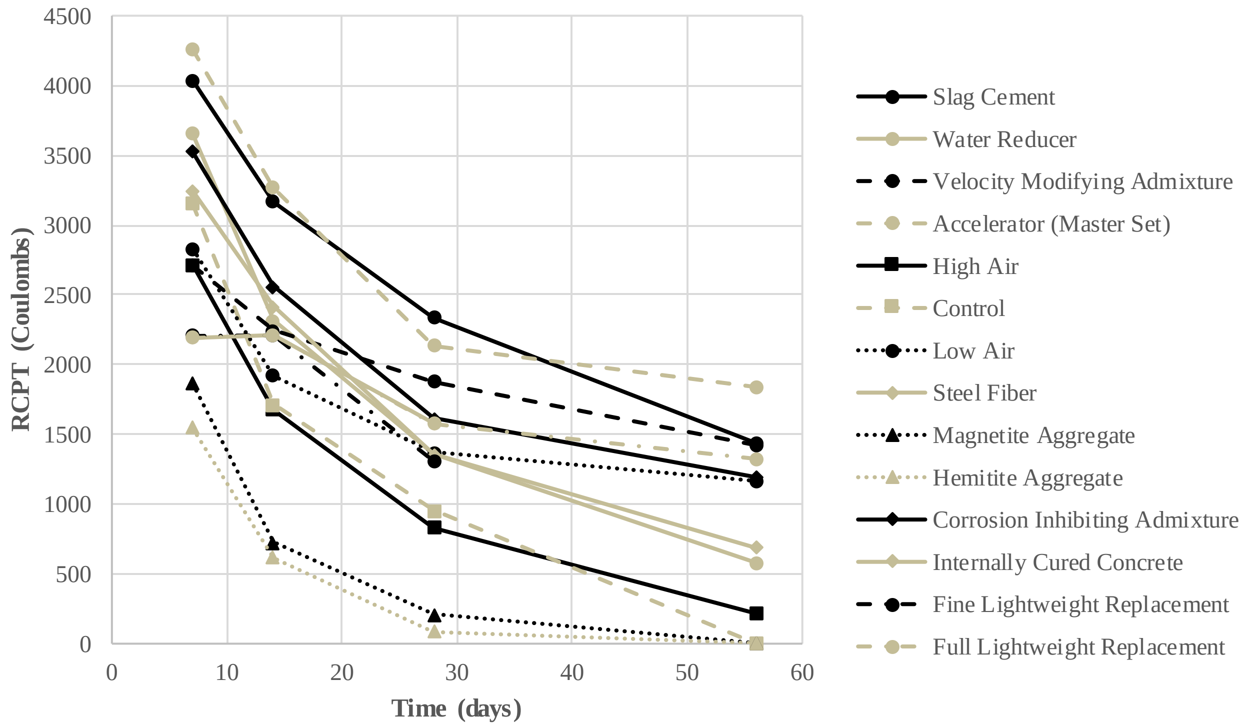


Figure 4.12 Lab RCPT results

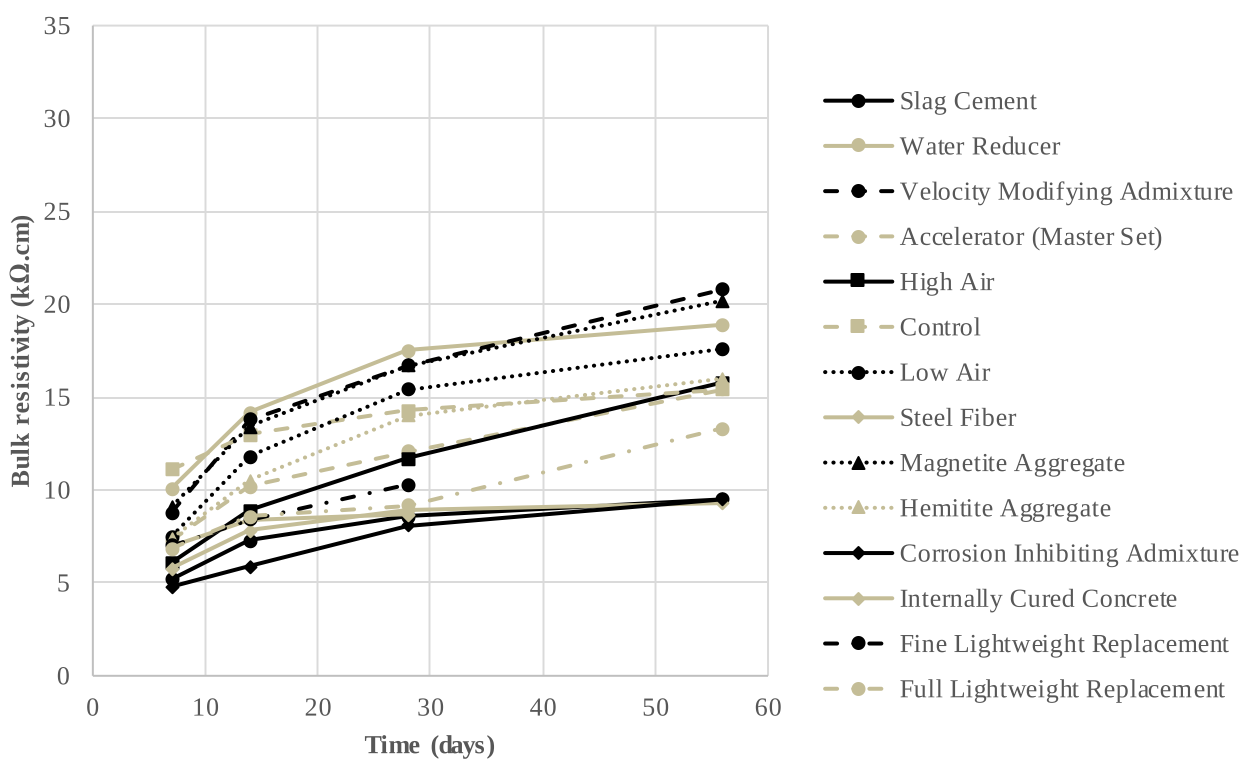


Figure 4.13 Lab Bulk resistivity results

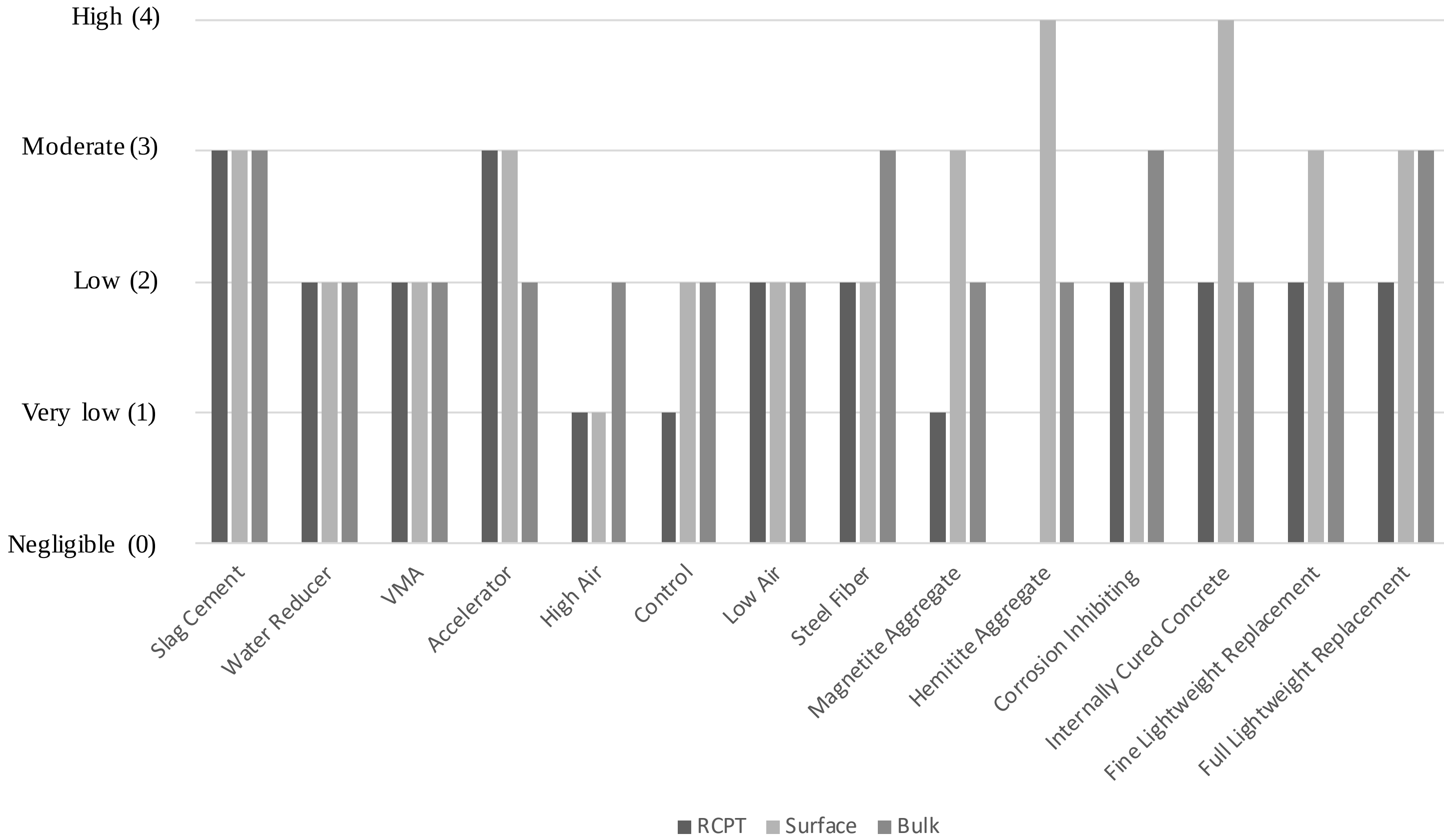


Figure 4.14 Lab penetrability level in 28 day

Lab lightweight mix vs. lab normal weight mix

Three lightweight mixes were cast in the lab phase. Lab control mix has a W/CM ratio of 0.42. On the other hand, the three lightweight mixes have a 0.3 W/CM ratio. All the lightweight aggregates were saturated for at least 3 days before the mixing and in Saturated Surface Dry (SSD) condition when mixed with cement.

As it is shown in Table , the normal weight mix has a better penetrability classification than all the lightweight mixes. This conclusion was also concluded in the field section too. It can also be concluded that more lightweight aggregate in the mix will lead to the more penetrability in the concrete. It is also worth mentioning that the proficiency of a concrete supplier in making lightweight concrete can change these results.

Table 4.10 Lab normal weight mix vs. lab lightweight mix results at 28 day test

Mix design	Type	RCPT 28 (coulomb)	Classification	Bulk 28 (kΩ.cm)	Classification	Surface 28 (kΩ.cm)	Classification
Control lab	NW	954	Very low	14.3	Low	17.3	Low
Internally Cured	LW	1577.99	Low	15.4	Low	8.7	High
Fine Lightweight Replacement	LW	1306.22	Low	10.1	Low	10.3	Moderate
Full Lightweight Replacement	LW	1320.7	Low	9.1	Moderate	11	Moderate

USU investigation

In the USU investigation, both removing Hycrete and adding secondary cementitious materials to the USU mix (control mix) improved the strength of the concrete. The supplementary cementitious materials that were used in this research are fly ash type F, Slag cement, Metakaolin, Silica fume, and V-CAS. Twenty percent replacement by volume was selected for each secondary cementitious material that replaced the Portland cement. Mixes with Metakaolin and Silica fume had the highest strength while Hycrete and V-CAS had the lowest.

Metakaolin, fly ash, V-CAS, and silica fume prevented the easy flow of ions from cathode to anode so that the results show a lower penetrability while using these secondary cementitious materials as a replacement of Portland cement. Silica fume and Metakaolin boosted surface concrete electrical resistivity. This is the result of changing the pore structure and the small size of these materials.

Figure shows the penetrability level for USU mixes at 28 days. In this figure, Penetrability level 4 is High, 3 is moderate, 2 is low, 1 is very low, and 0 is negligible. As can be seen, all the different durability tests typically achieve one category tolerance, with the exception of the

Hycrete mixture which where the RCPT exhibited two categories higher penetrability than both resistivity tests.

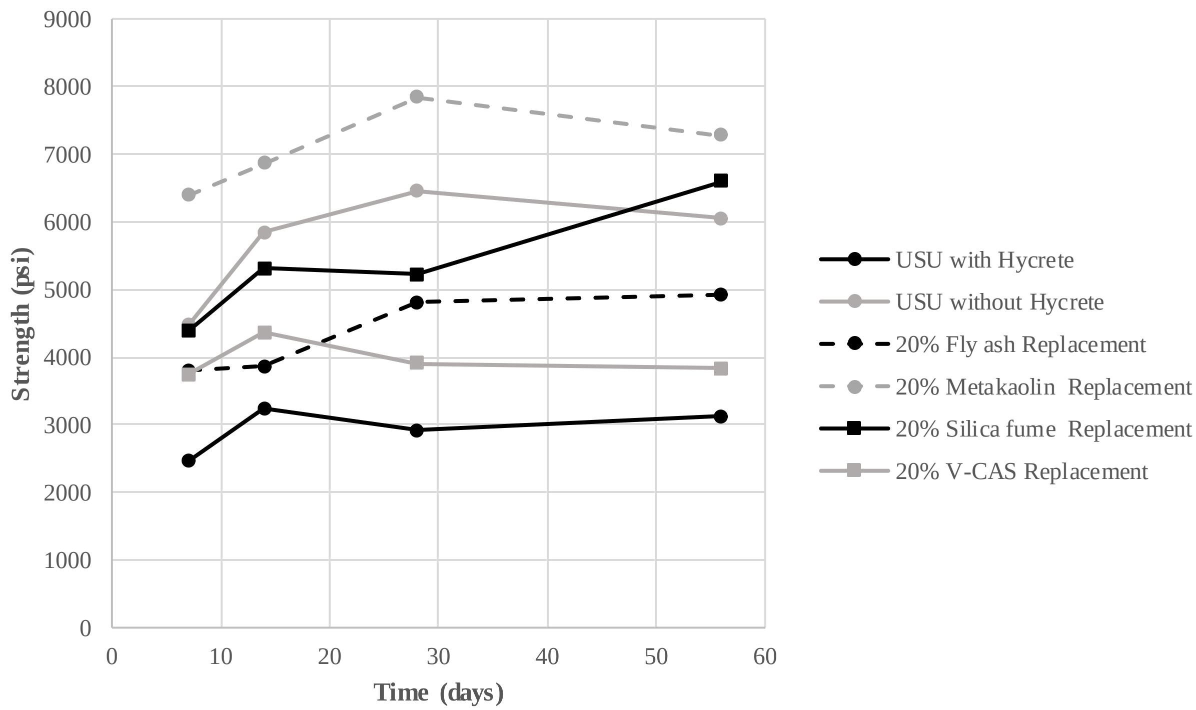


Figure 4.15 USU compressive strength

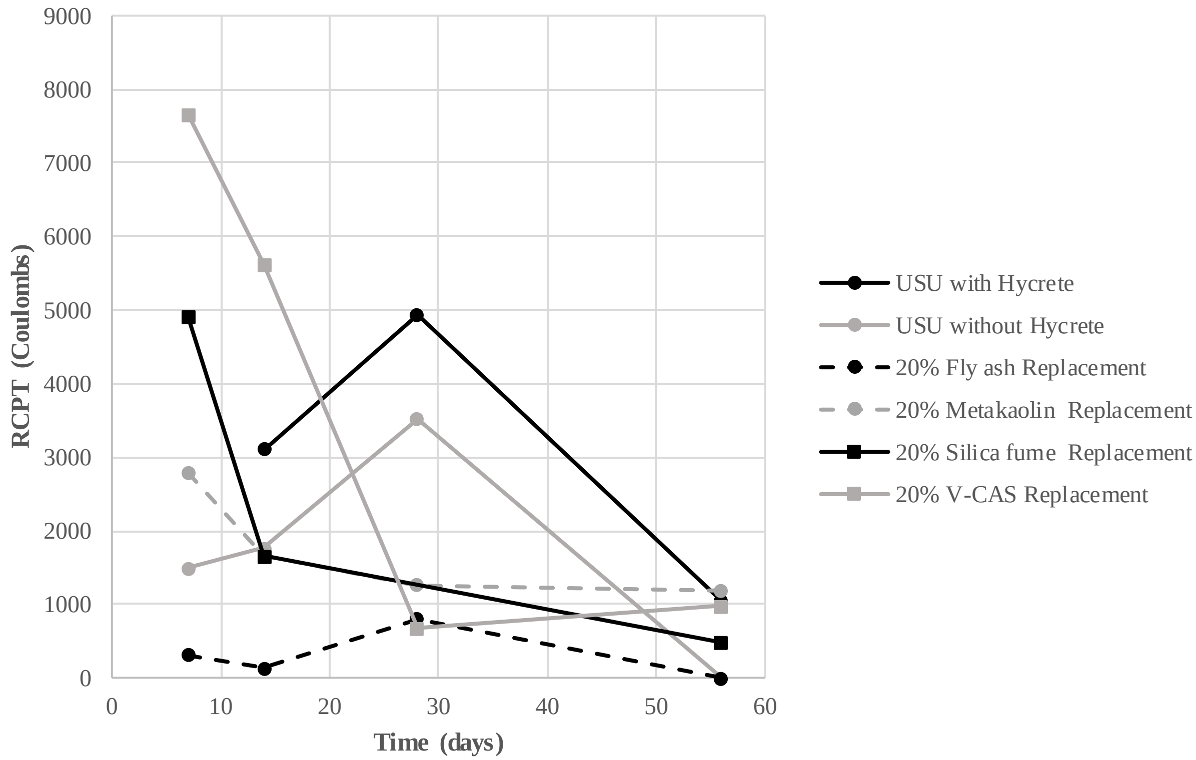


Figure 4.16 USU RCPT results

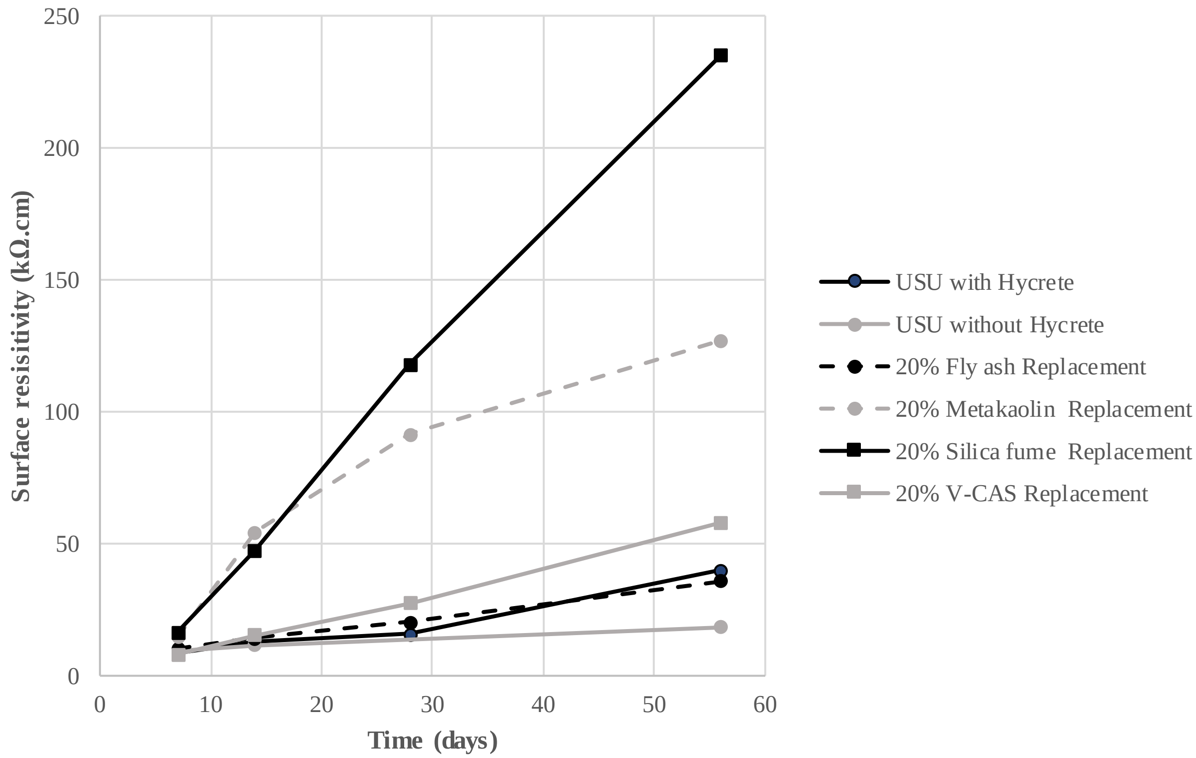


Figure 4.17 USU surface resistivity results

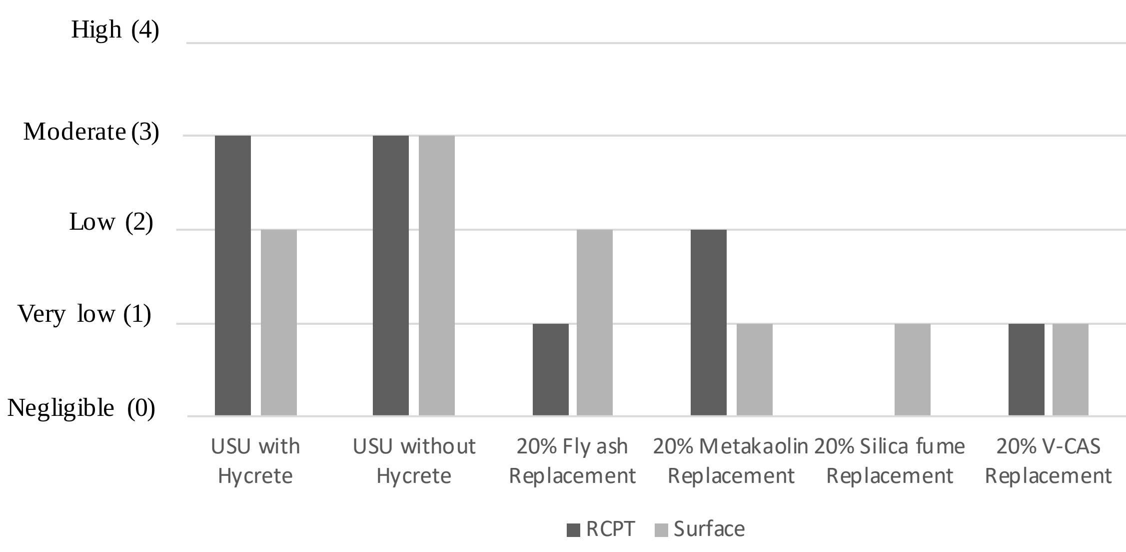


Figure 4.18 USU penetrability level in 28 day

Recycled Concrete Aggregate (RCA)

The decrease in strength when using recycled concrete aggregate in low portions (30 percent) was up to 10 percent. However, replacing all the aggregates with RCA will decrease the strength considerably, up to 25 percent.

Concrete with no recycled concrete aggregate showed better resistivity than concrete composed of 30 percent or 100 percent recycled aggregate. However, replacing a small portion of regular aggregate with RCA resulted in a small decrease in resistivity. These results could increase the use of RCA in future concrete mix designs. The research team believes these aggregates were exposed to chloride in their previous environment, which could be the reason behind the lower resistivity readings when using RCA. Chloride testing was not performed on the RCA because of its expense and was not part of the scope of this investigation.

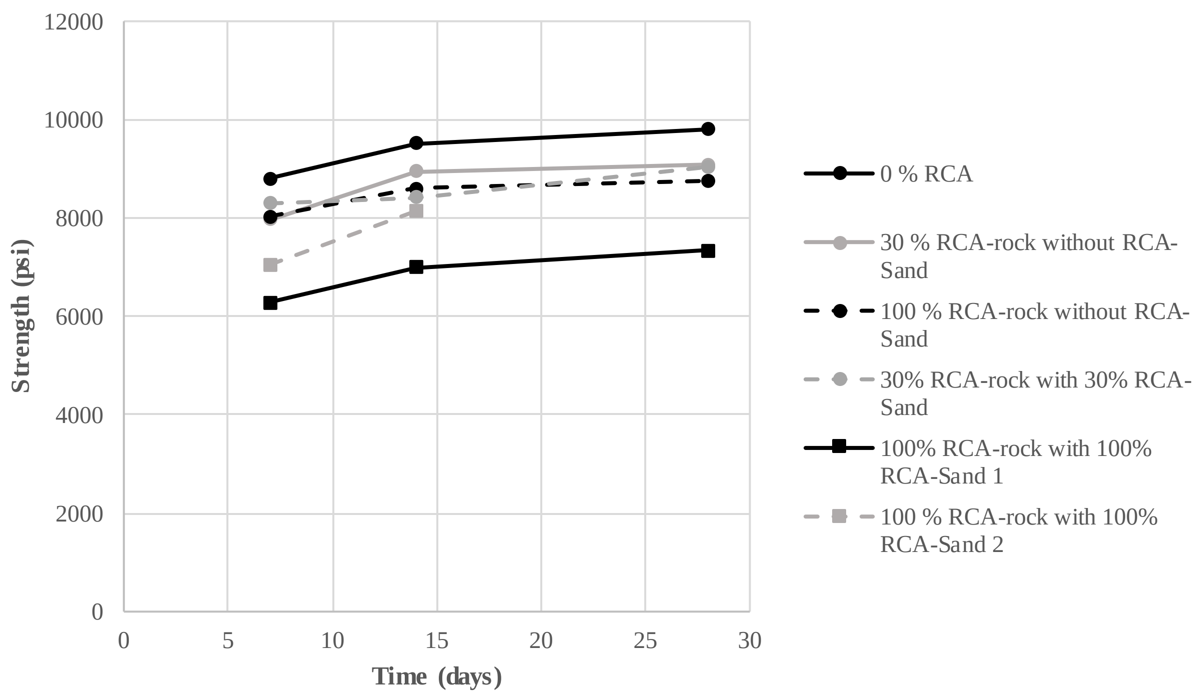


Figure 4.19 RCA compressive strength

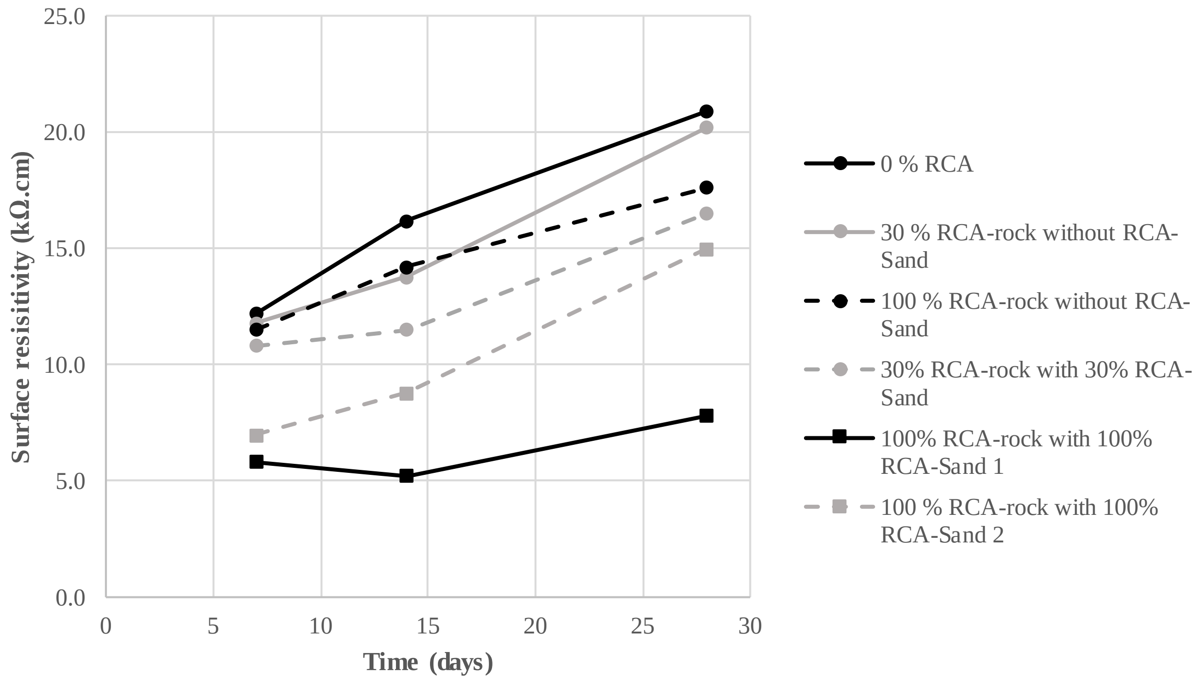
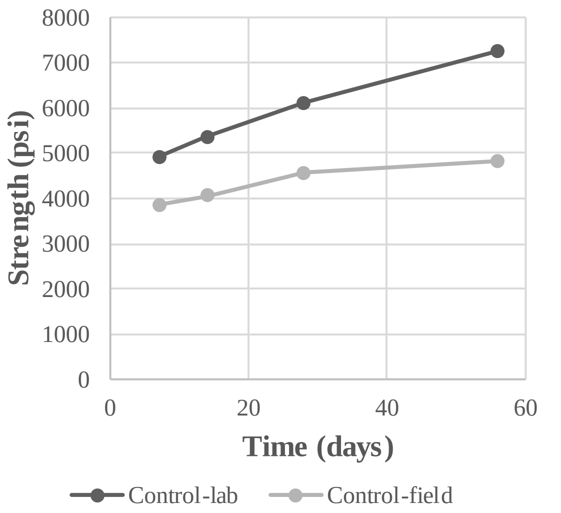


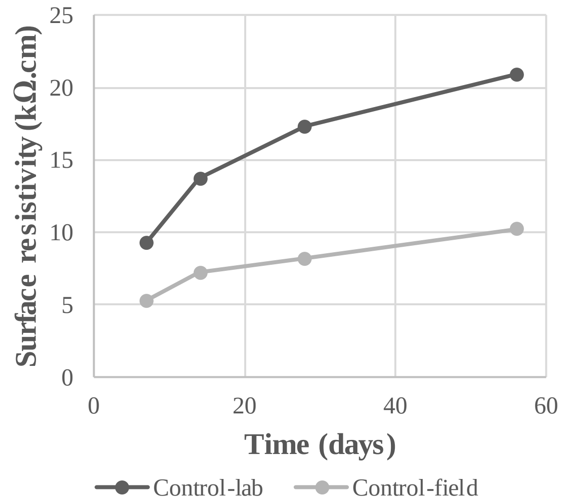
Figure 4.20 RCA surface resistivity results

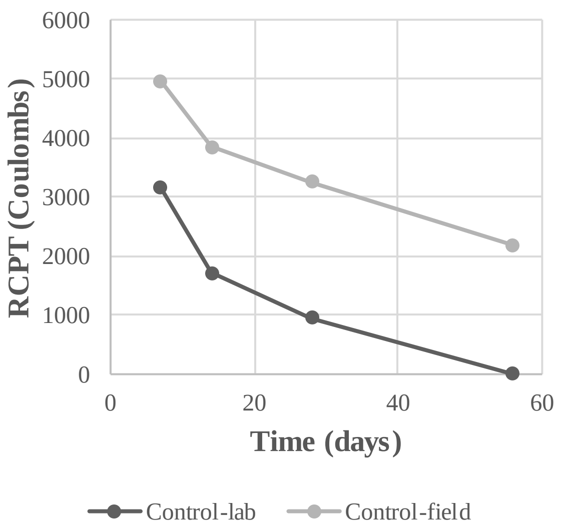
Field vs. Lab

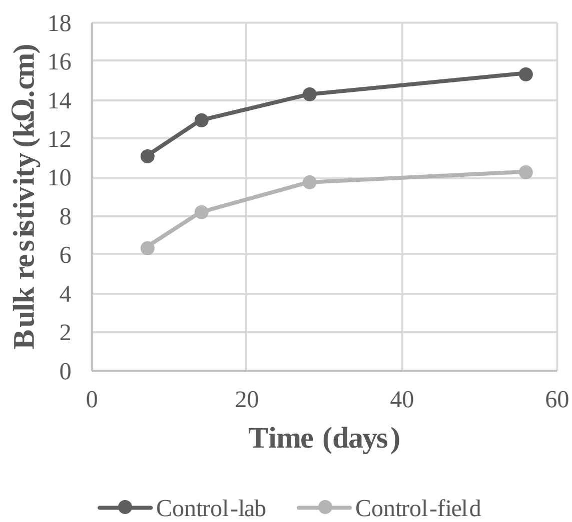
The D4 0.42 mix was selected from the field mixes to be duplicated in the laboratory environment. This mix design is the control mix and will be compared against the other lab mixes. As shown in Table , the lab duplicate has a better strength, better surface and bulk resistivity, and lower penetrability than the field mix. This investigation shows similar results to the Oklahoma State University research (Hartell 2015).

Table 4.11 Field vs. lab results









Penetrability level comparison

Of all the 28-day tests, only 17.31 percent had more than one penetrability category difference. This indicates that while the actual resistivity values may seem very different (e.g., compare Figure to Figure), when using the penetrability classifications to make decisions for a performance specification, the variation will be low when comparing the available mixtures. For the field mixtures, the surface resistivity test tended to predict higher penetrability. For the laboratory study, bulk resistivity testing tended to predict more penetrability, especially may end up providing a too-conservative measurement of penetrability. It can also be concluded that lightweight mixes tend to have more penetrability category differences. Lightweight mixes have 55.5 percent of

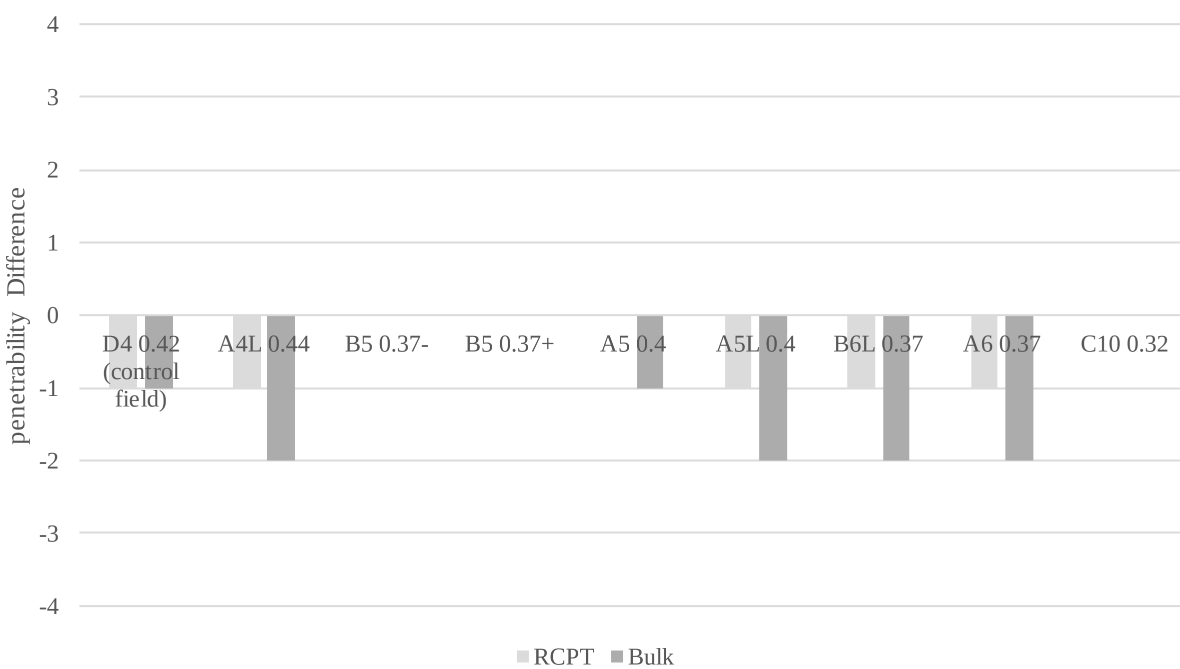


Figure 4.21 Field penetrability level comparison for 28-day tests

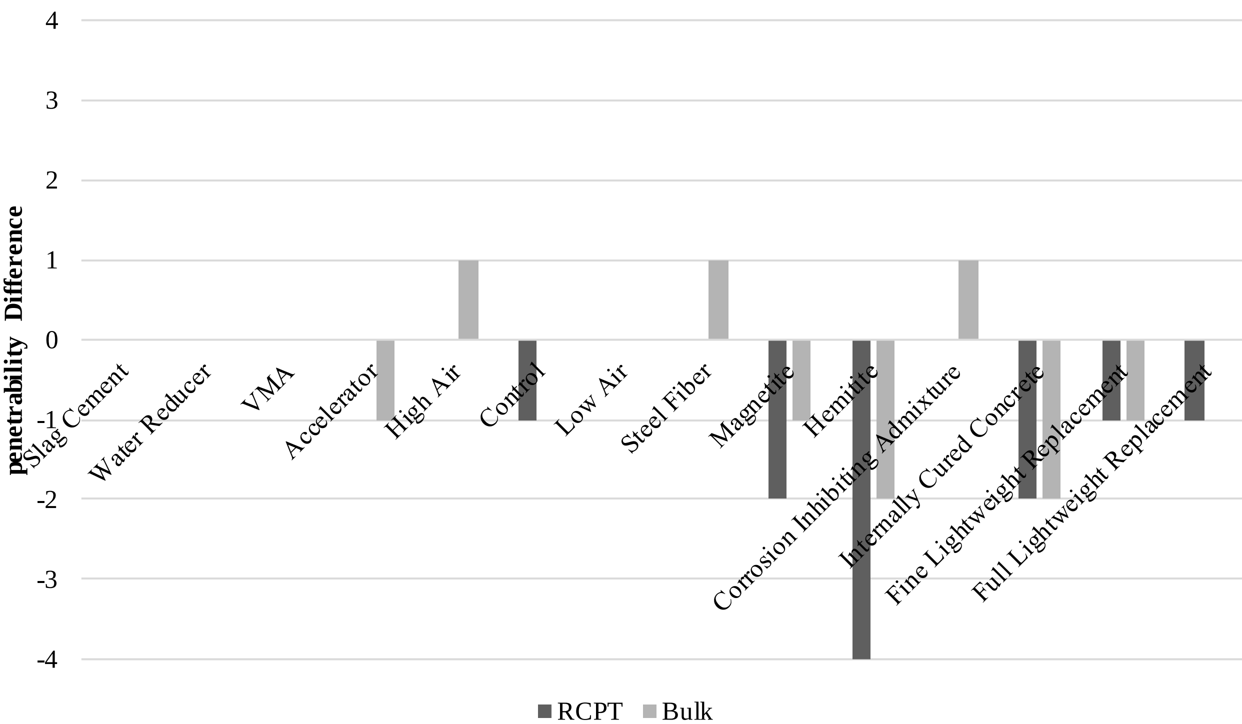


Figure 4.22 Lab penetrability level comparison for 28-day tests

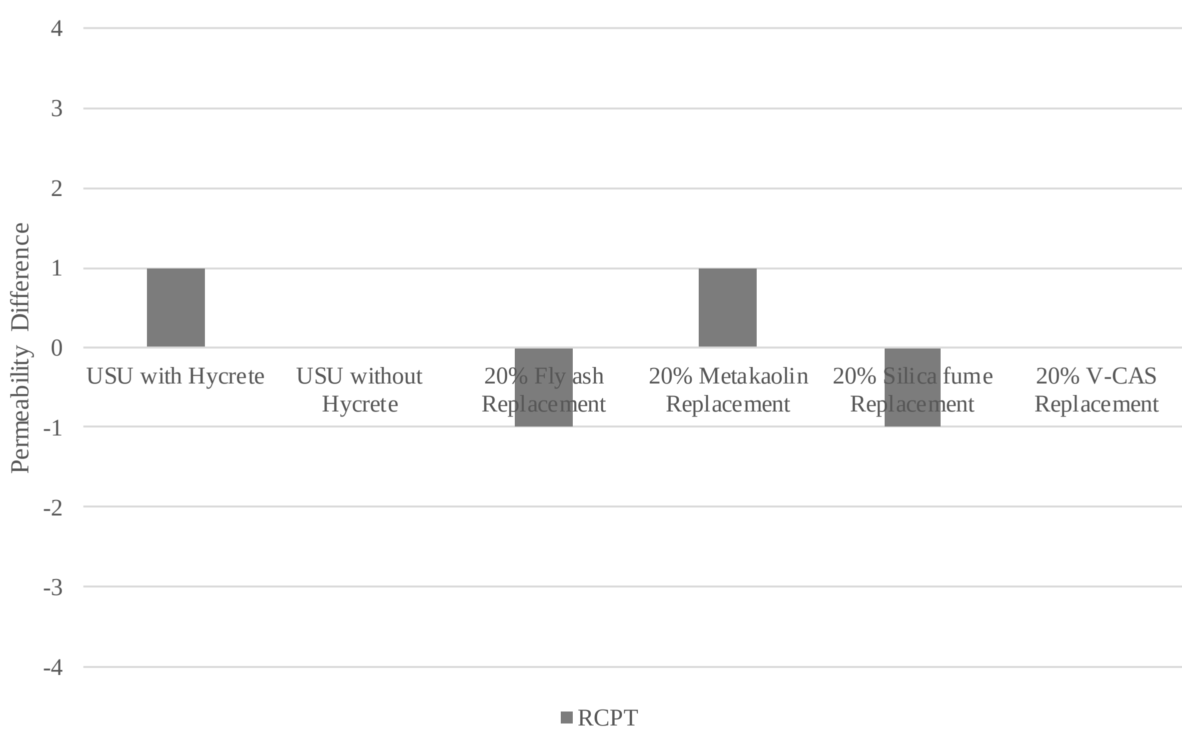


Figure 4.23 USU penetrability level comparison for 28-day tests

Penetrability test ratings

Table shows a comparison of surface resistivity, bulk resistivity and rapid chloride permeability test in five different categories. Six different students that have run these tests rated these tests from best to the poorest. After getting quotes from different manufacturers, the average apparatus cost of each test is shown in Table . As it is apparent, surface electrical resistivity is the highest ranking test in all five categories.

Table 4.12 Penetrability test ratings

Rank	Easiness	Test duration	Preparation time	Chance of error	Apparatus cost ($)
High	Surface	Surface (15 s)	Surface (2 min)	Surface	4012
Medium	Bulk	Bulk (60 s)	Bulk (30 min)	Bulk	5830
Low	RCPT	RCPT (6 h)	RCPT (24 h)	RCPT	8404

Three states study comparisons

In this section, studies conducted in Virginia, Florida and Utah will be compared. In Virginia study, fourteen different lightweight mixes were cast and cured differently. The lightweight aggregates used in this study were shipped from 6 different states. Also, W/CM ratios that the mixes had were 0.35, 0.39, 0.40 and 0.43 (Ozyildirim 2011)

In Florida study, 529 concretes were tested at 28 days. These concretes were collected throughout the state of Florida. Surface electrical resistivity and RCP test were performed at 28 days and a linear correlation between these two were found. This study includes normal weight and lightweight concrete. This correlation is shown in Figure and Figure . (Kessler et al. 2008)

Figure shows the comparison of 6 lightweight mixes (3 field mixes and 3 lab mixes) in this study with the Virginia and Florida 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.

Figure shows the whole comparison of Utah with the other two studies. As it is shown in this figure, 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.

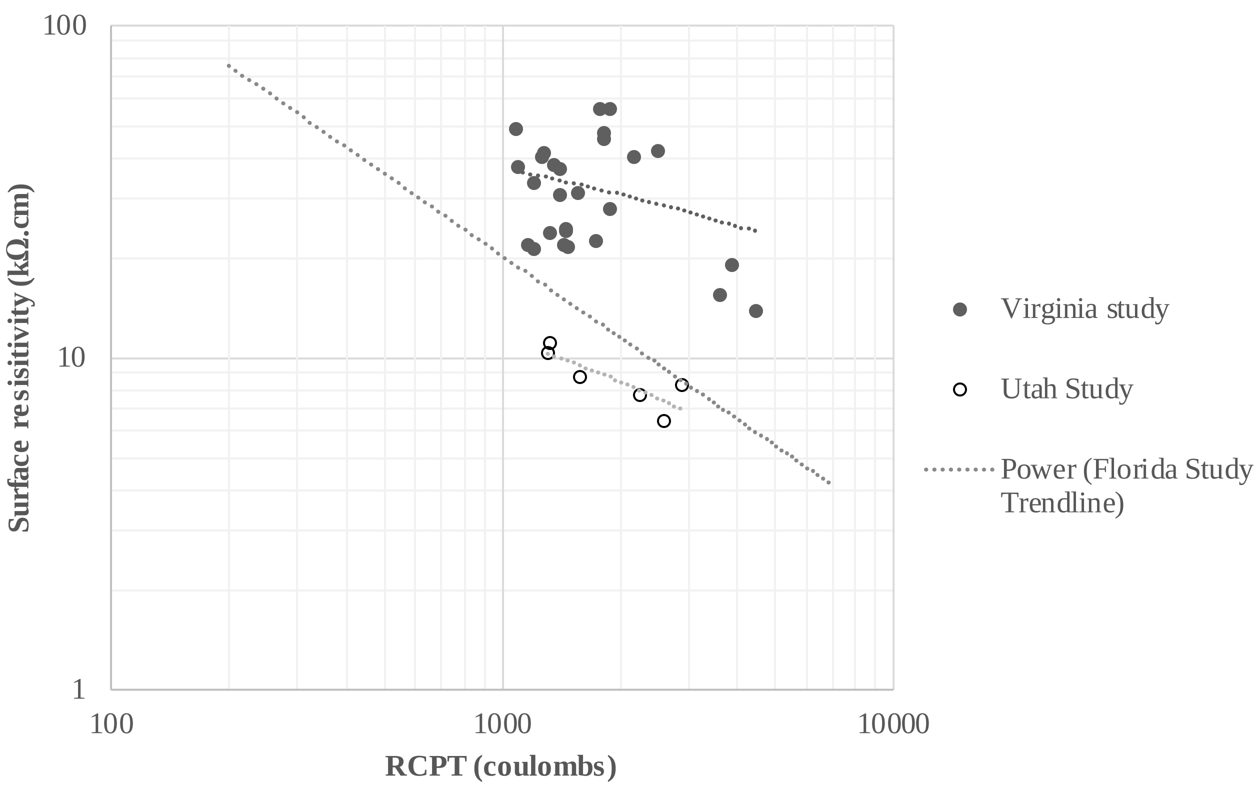


Figure 4.24 Utah Lightweight concrete comparison with Florida and Virginia studies

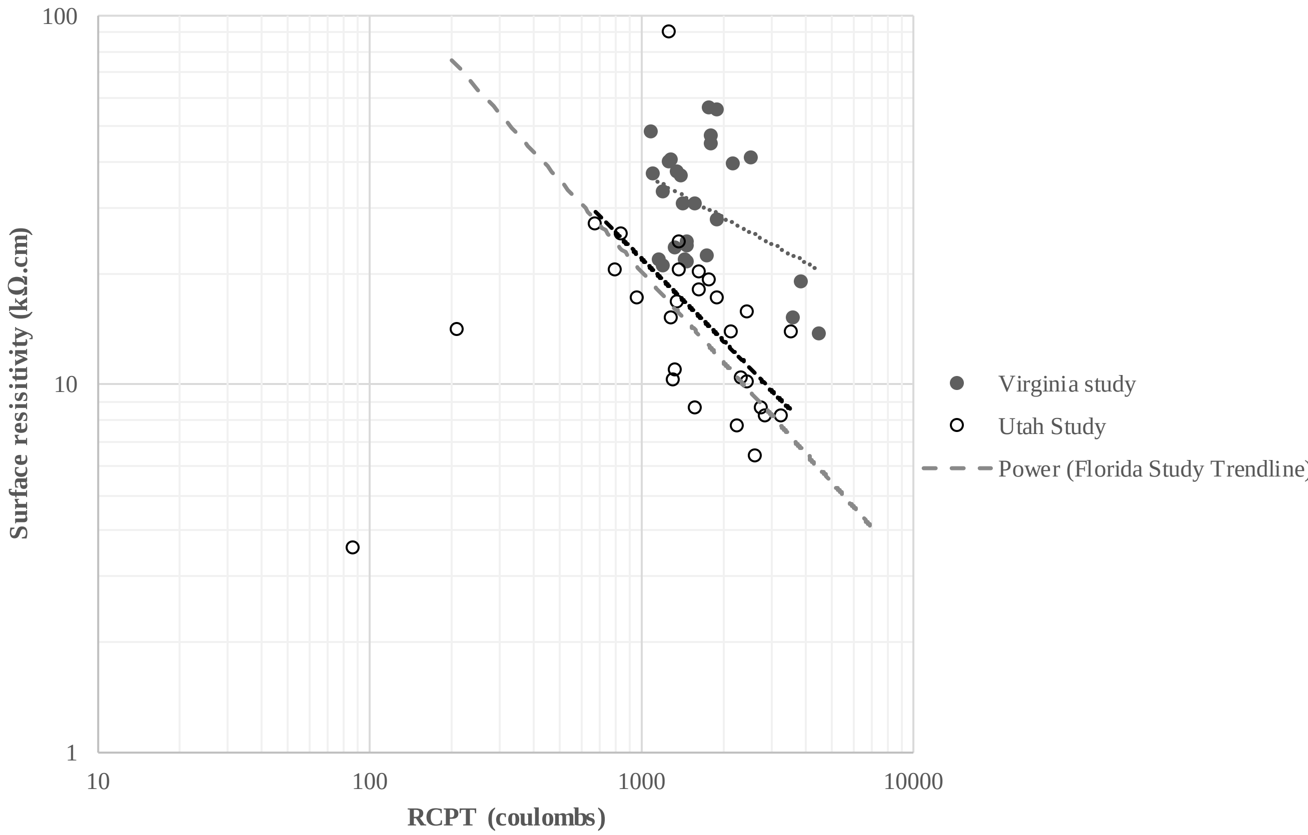


Figure 4.25 Utah Whole study comparison with Florida and Virginia studies

Chapter 5: Conclusions and Recommendations

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 following conclusions can be made from this investigation:

- 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 more accurate estimation of concrete penetrability.

Chloride Penetration	Surface Resistivity (kΩ.cm)	Bulk Resistivity (kΩ.cm)	Rapid Chloride Permeability Test (Columbs)
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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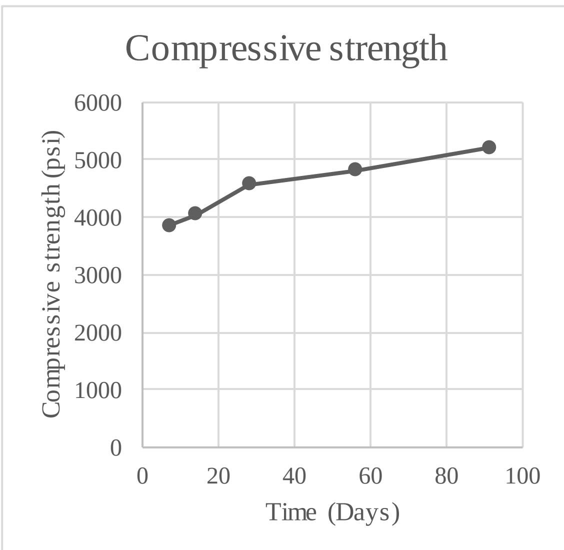
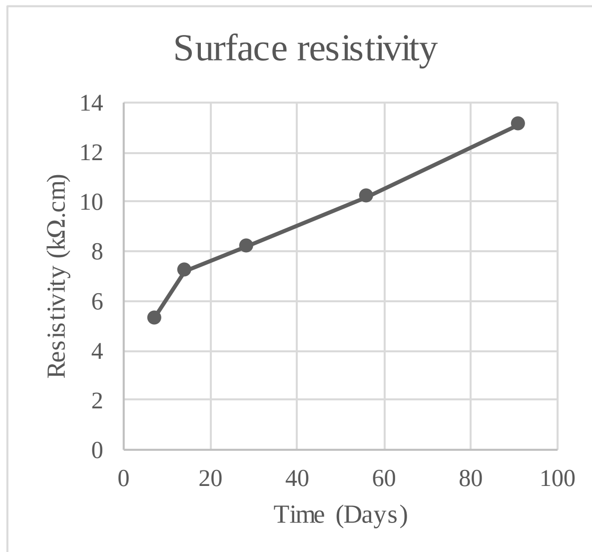
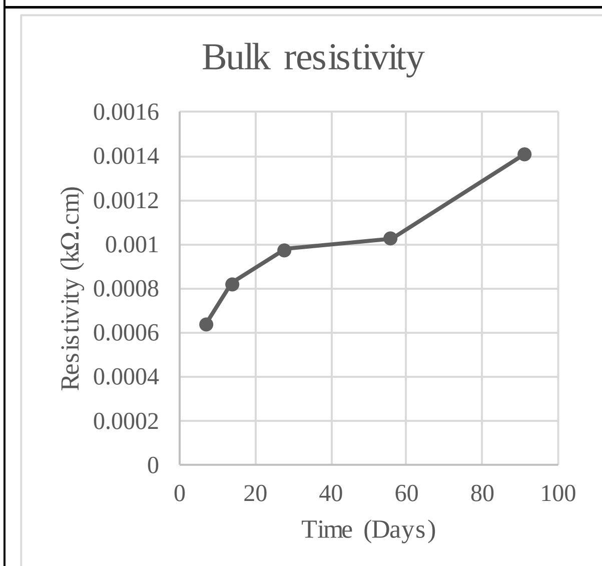
Appendix A: Detailed Field Mix Designs with Plotted Data

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







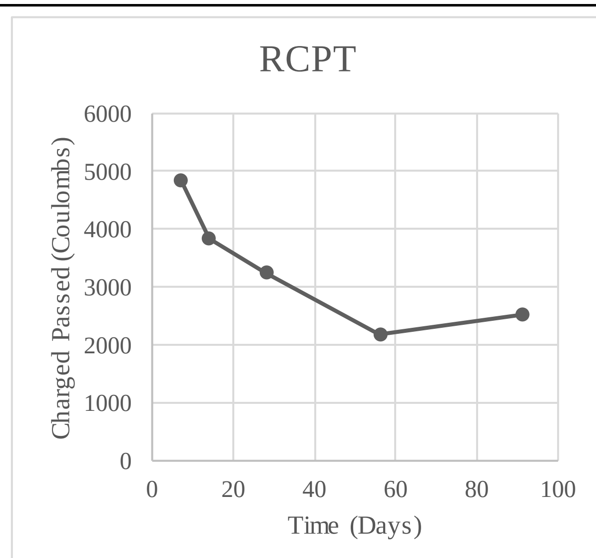
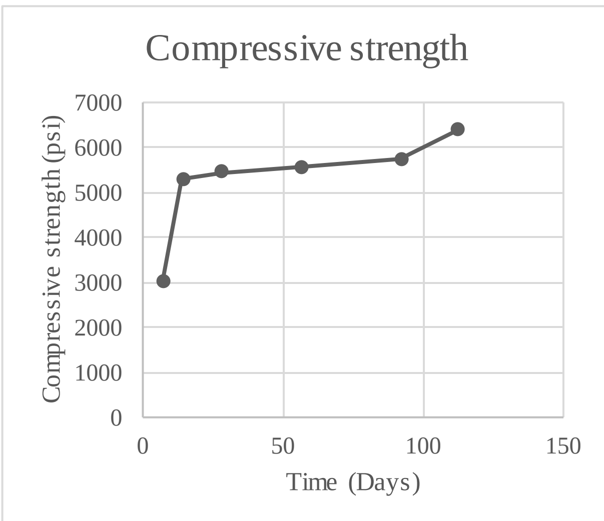


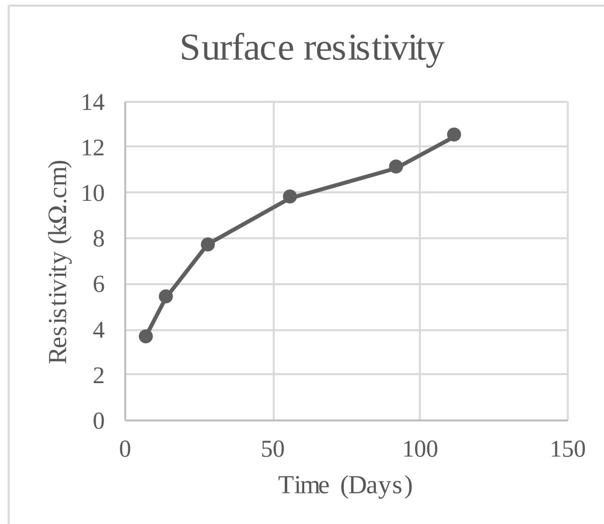
Table A.2 D4 0.42 mix design

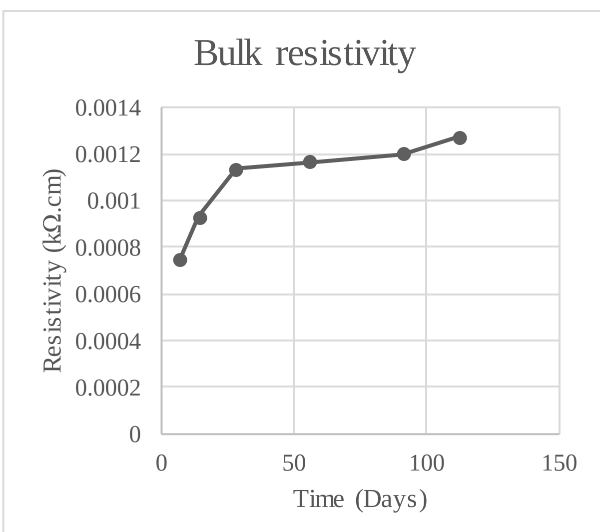
Material Type	Description		Design Quantity	Specific Gravity	Volume (ft3)
Cement	Portland type II/V (Holcim)		489 lb	3.15	2.488
Fly Ash	Fly Ash - F		122 lb	2.35	0.832
Coarse Aggregate	3/4" Rock		1643 lb	2.656	9.913
Fine Aggregate	Sand		1320 lb	2.646	7.995
Water	Potable water (City Water)		254 lb	1.00	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







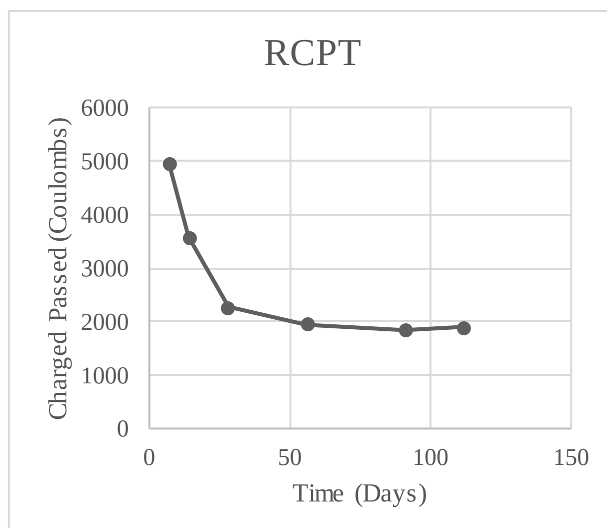
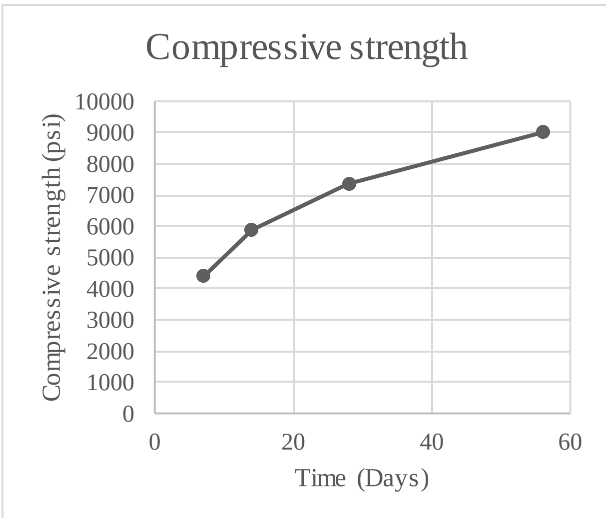


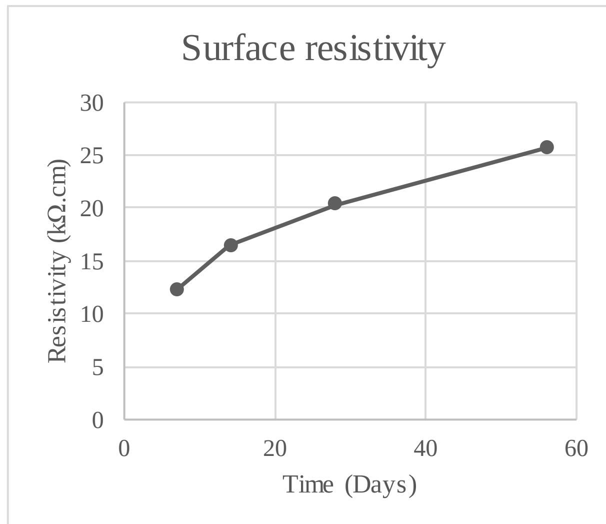
Table A.4 A4L 0.44 mix design

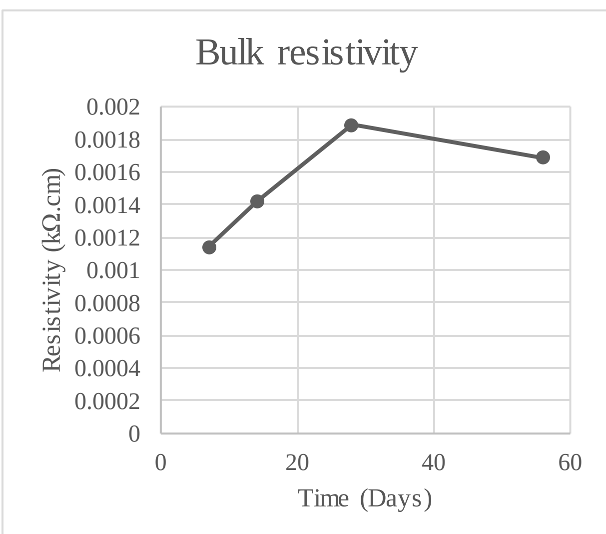
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	LIGHT WEIGHT COARSE	1092 lb	1.77	9.89
Fine Aggregate	SAND - WASHED CONCRETE	1069 lb	2.60	6.59
Water	POTABLE WATER	37.2 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







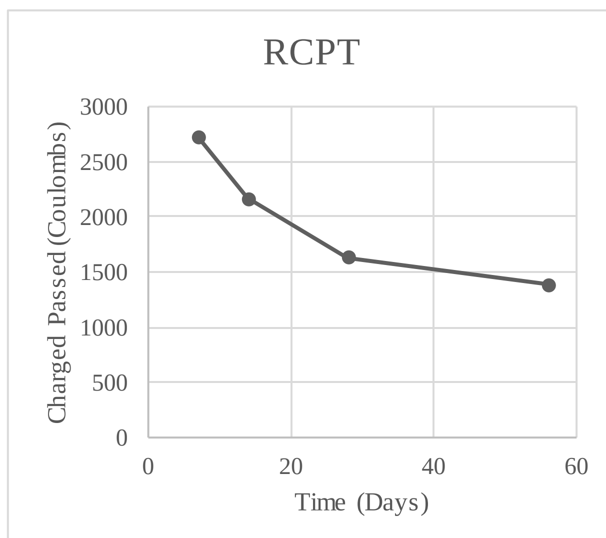
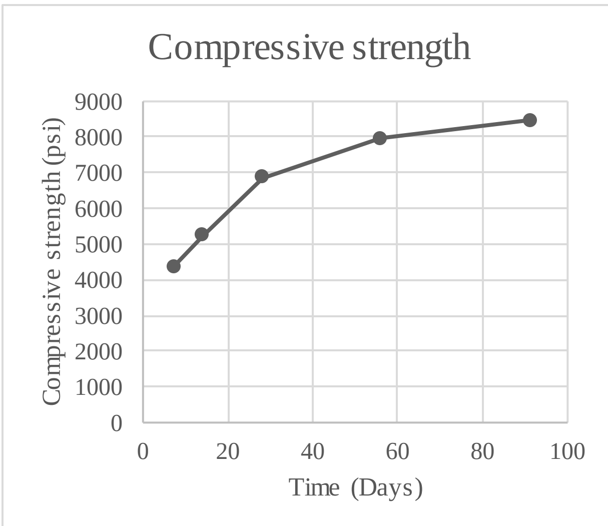


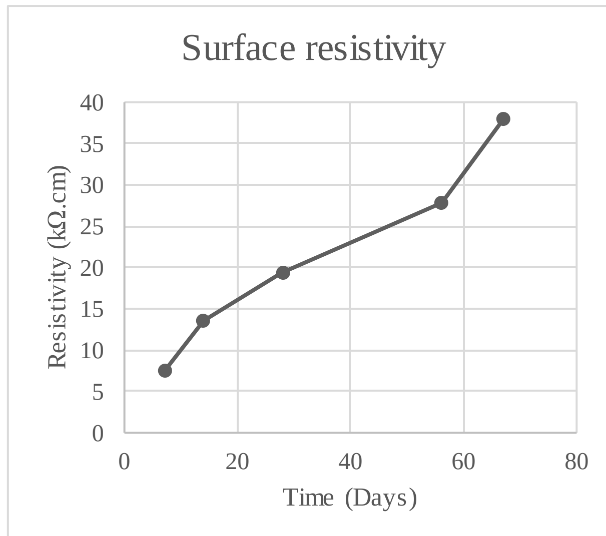
Table A.6 B5 0.37- mix design

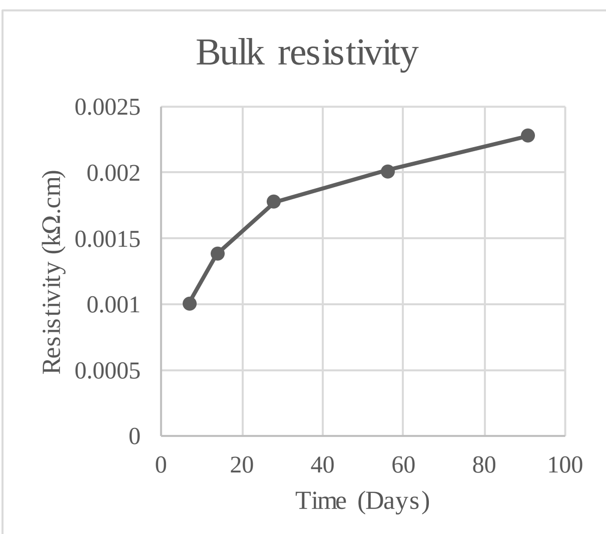
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)	639 lb	3.15	3.25
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)	160 lb	2.60	0.99
Coarse Aggregate	KSG67 - Astm C-33 #67	1550 lb	2.49	9.98
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







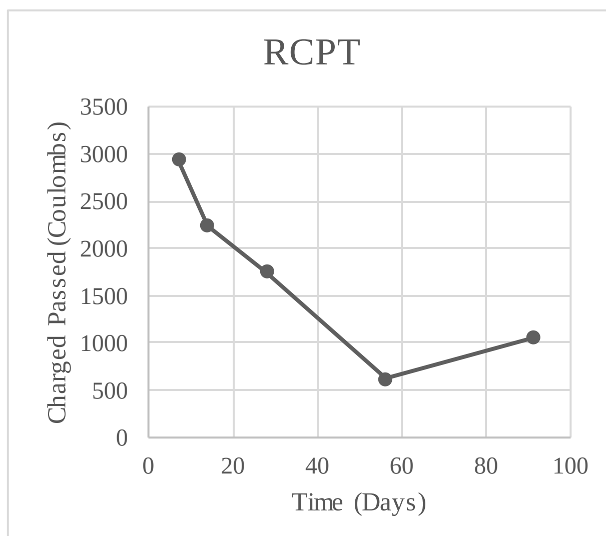
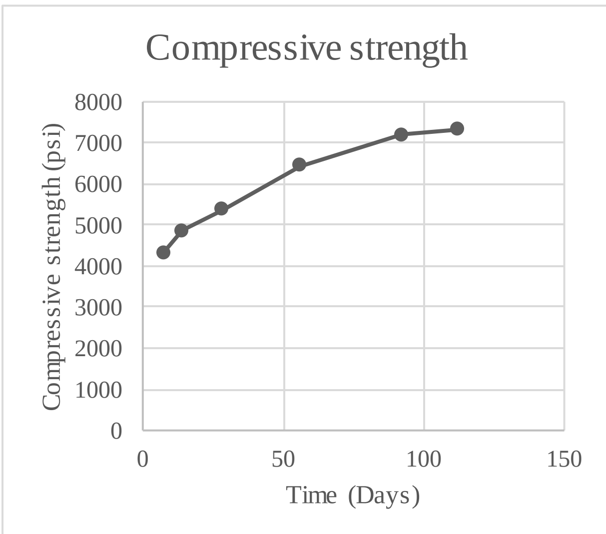


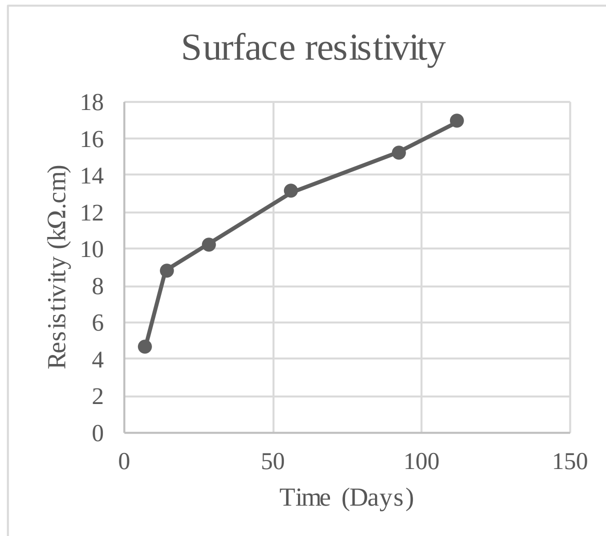
Table A.8 B5 0.37+ mix design

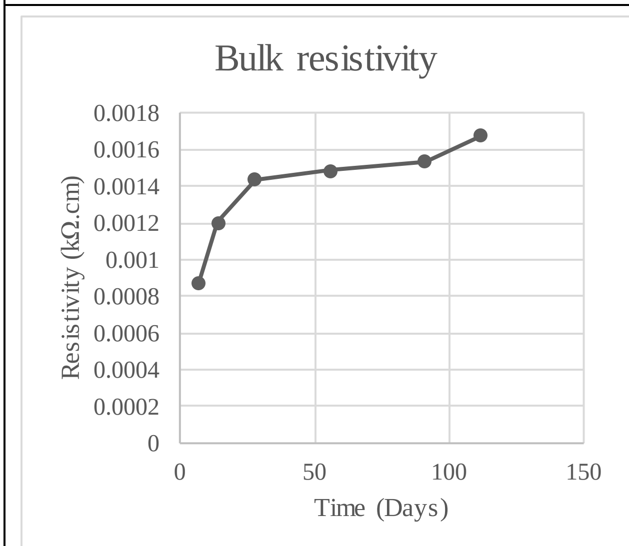
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)	564 lb	3.15	2.87
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)	141 lb	2.60	0.87
Coarse Aggregate	VSG67VRM - Astm C-33 #67 (Valley Sand and 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







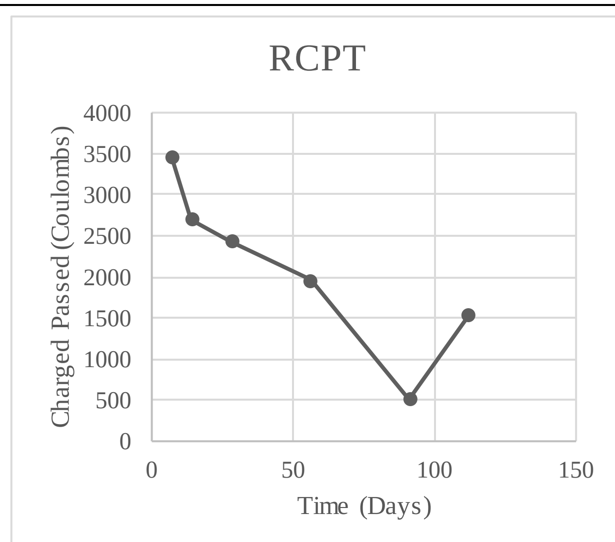
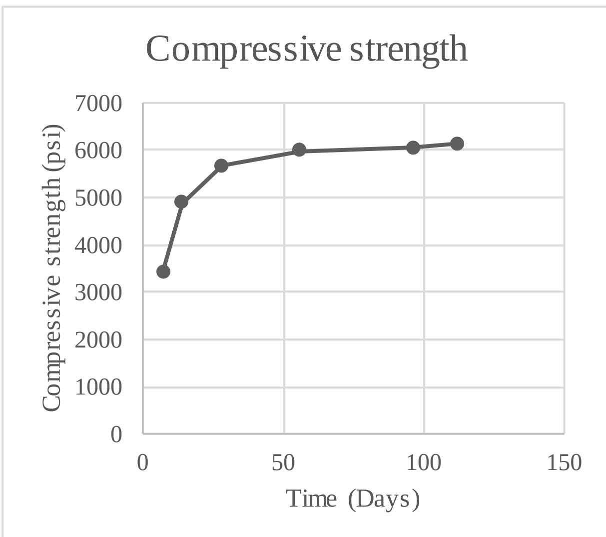


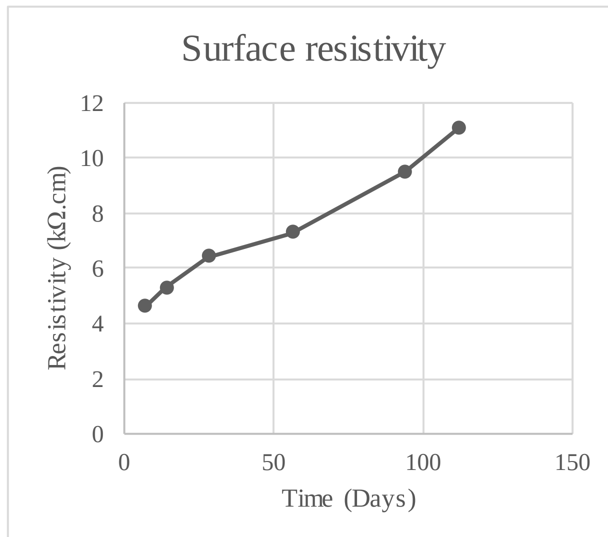
Table A.10 A5 0.4 mix design

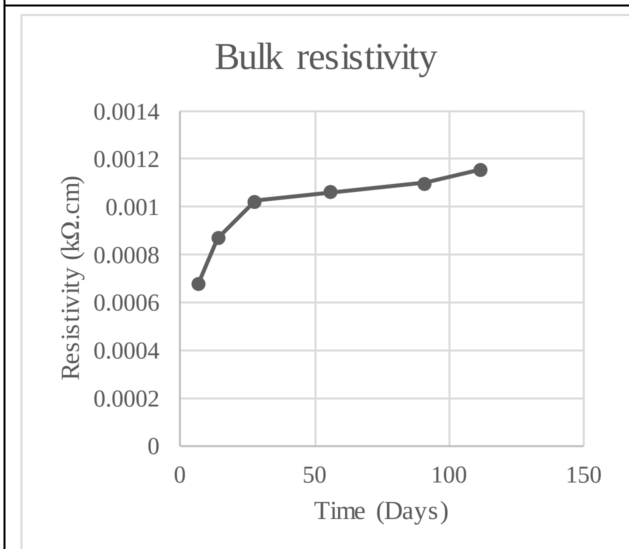
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1689 lb	2.58	10.49
Fine Aggregate	SAND - WASHED CONCRETE	1044 lb	2.60	6.43
Water	POTABLE WATER	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







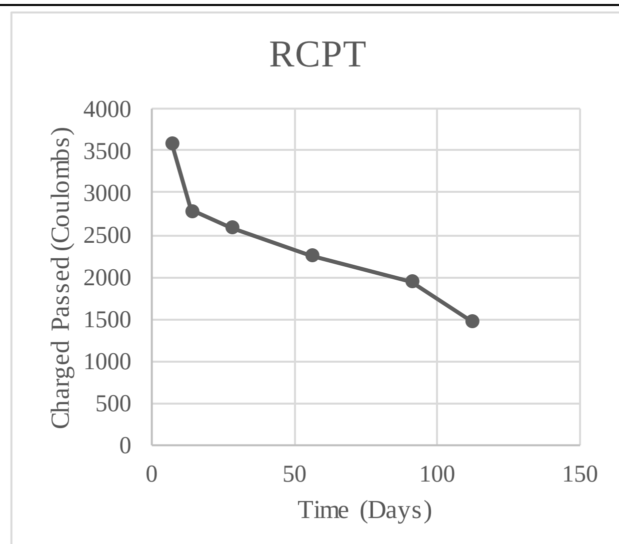
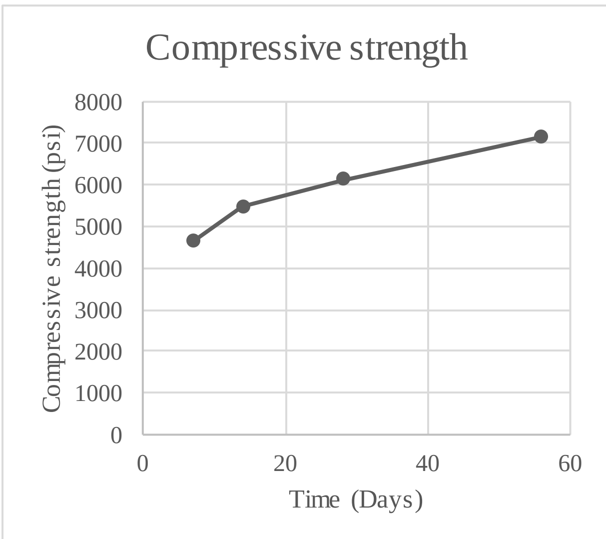


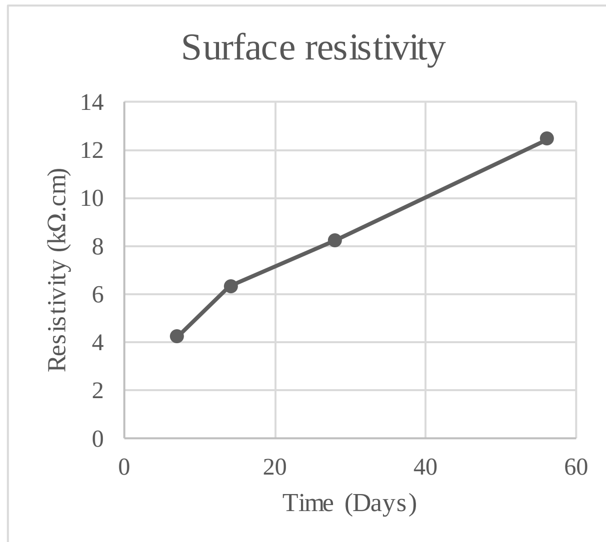
Table A.12 A5L 0.4 mix design

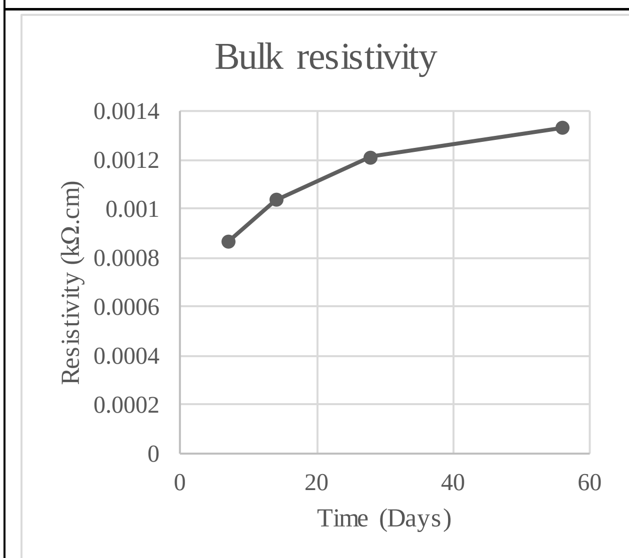
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	564 lb	3.15	2.87
Fly Ash	TYPE F FLY ASH, ASTM C 618	141 lb	2.30	0.98
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1676 lb	2.58	10.41
Fine Aggregate	LIGHT WEIGHT FINES	353 lb	1.84	3.07
Fine Aggregate	SAND - WASHED 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







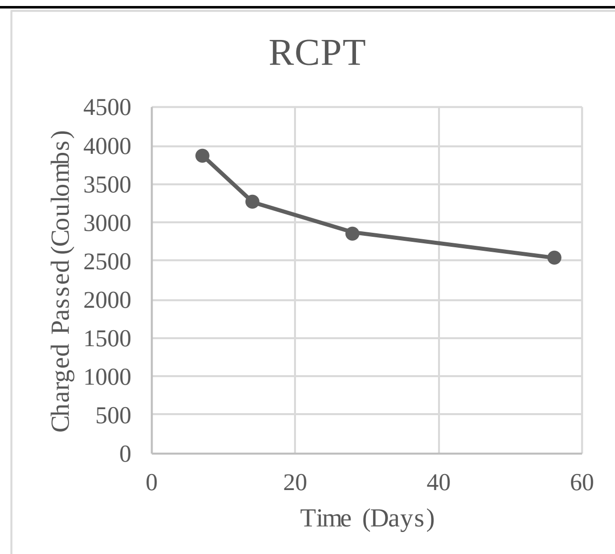
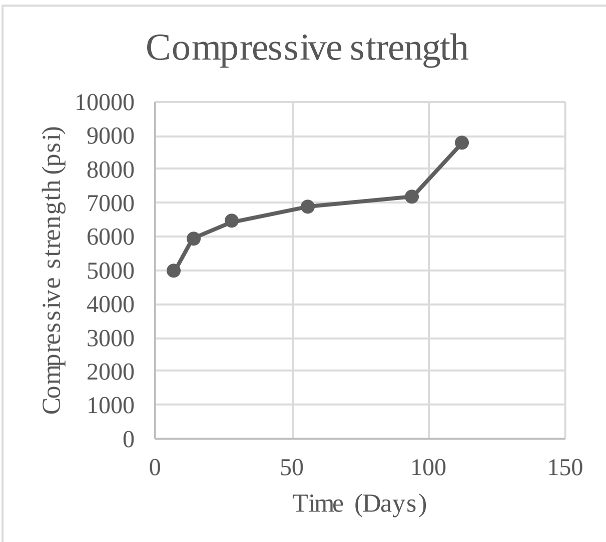


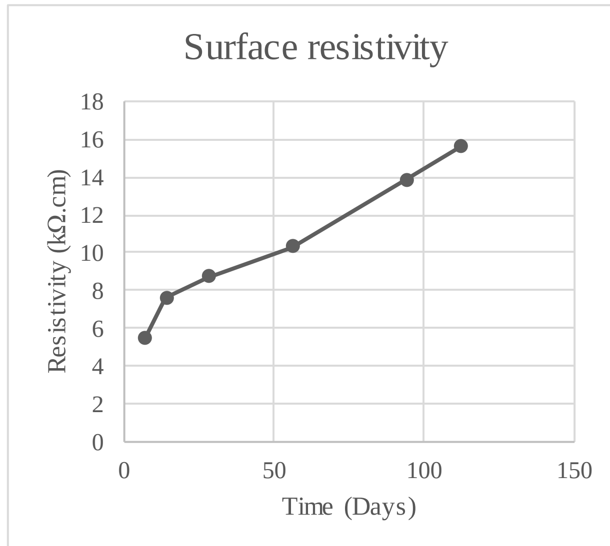
Table A.14 B6L 0.37 mix design

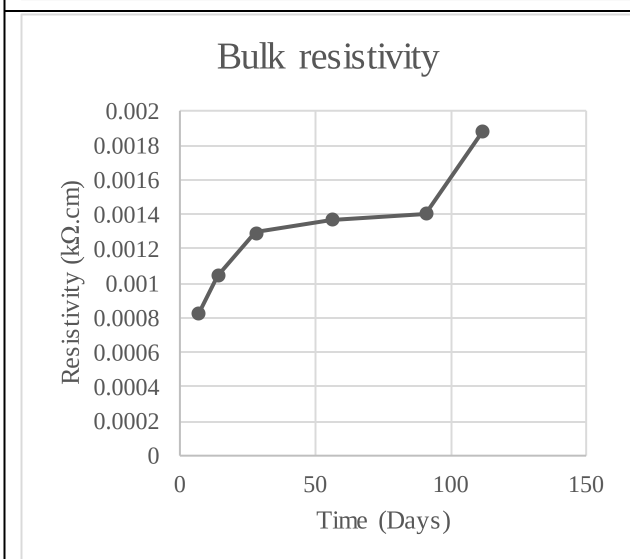
Material Type	Description		Design Quantity	Specific Gravity	Volume (ft3)
Cement	Cement CEM04 - HolcimType II/V Cement (Holcim Cement)		640 lb	3.15	3.26
Fly Ash	Mineral Additive Fly Ash - F - Fly Ash, Class F Headwater (Headwate)		160 lb	2.60	0.99
Coarse Aggregate	UTECA - UTELITE c-330 #67 (UTELITE AGGREGATES)		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







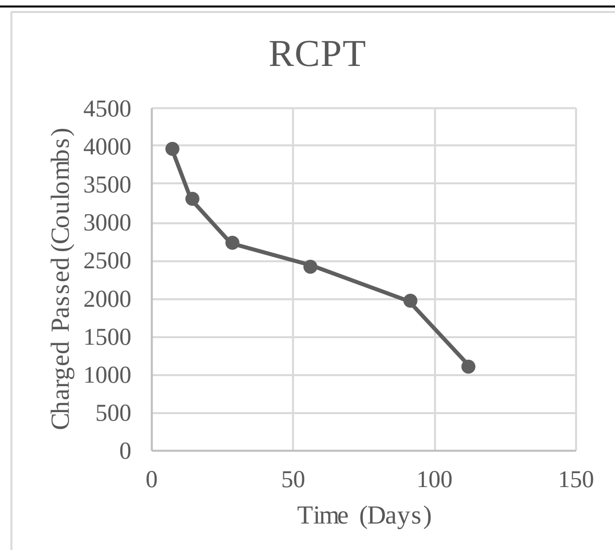
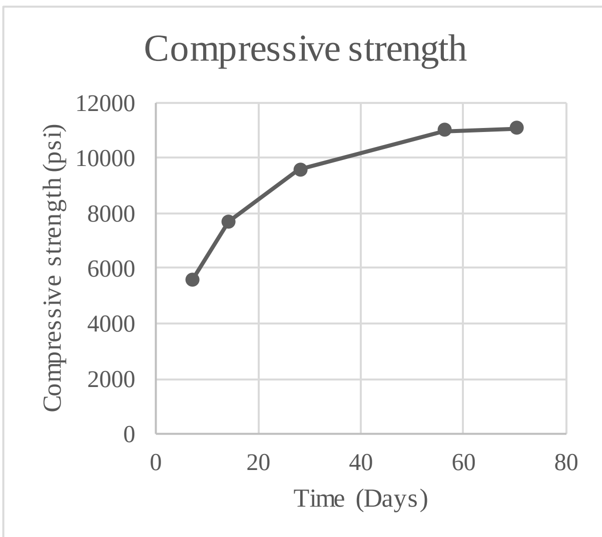


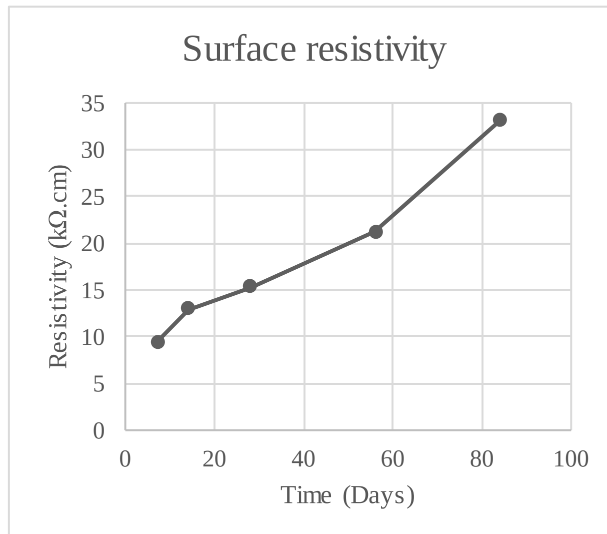
Table A.16 A6 0.37 mix design

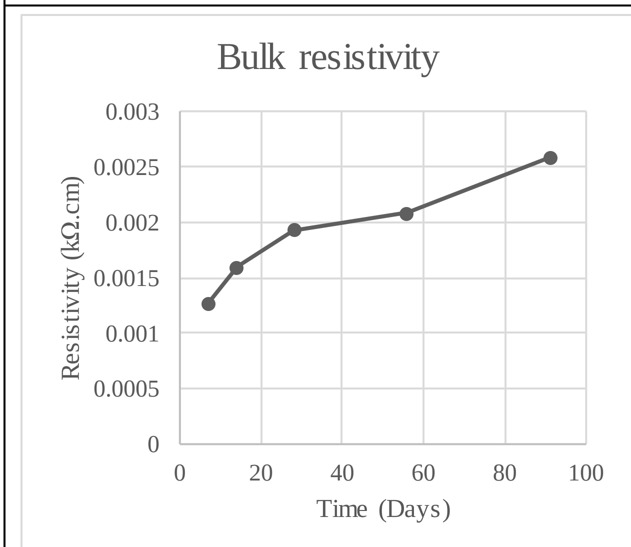
Material Type	Description	Design Quantity	Specific Gravity	Volume (ft3)
Cement	CEMENT TYPE II-V	602 lb	3.15	3.06
Fly Ash	TYPE F FLY ASH, ASTM C 618	150 lb	2.30	1.05
Coarse Aggregate	ROCK - 3/4" X #4 WASHED	1613 lb	2.58	10.02
Fine Aggregate	SAND - WASHED CONCRETE	1084 lb	2.60	6.68
Water	POTABLE WATER	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







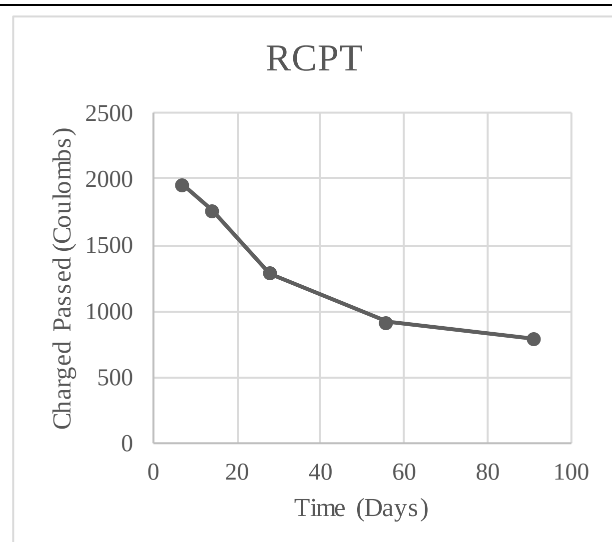


Table A.18 C10 0.32 mix design

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