VERMONT

AGENCY OF TRANSPORTATION

DEVELOPMENT OF COST-EFFECTIVE RAPID-SETTING CONCRETE FOR IMPROVED BRIDGE JOINT PERFORMANCE

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16. Abstract

Vermont Agency of Transportation has adopted use of the accelerated bridge construction (ABC) approach to deliver bridge construction and reconstruction projects. While ABC projects enjoy high material quality due to a large fraction of precast and prefabricated elements, connections between these elements must be placed in-situ. These are often treated as a "weak link" due to potential risk for inferior performance and concerns of lower durability to repeated freeze-thaw cycling. The focus of this research study was to conduct a comprehensive laboratory investigation of rapid-setting concrete (RSC) materials that are commonly used for field-placed ABC connections. Further, the variations were evaluated to explore potential for hybrid performance and proportion-based specifications. The current performance-based specifications for RSC have lower risks associated with them, however, they result in higher project costs and increased laboratory and personnel resources. Assessment of durability, specifically resistance of material to degrade under repeated freezing and thawing and its ability to prevent chloride ingress were one of the focus points of this research. The results of this study indicate that currently used RSC materials have high resistance to freeze-thaw damage and ABC projects using these materials for connections can use bare decks. This research supports a hybrid performance and proportion-based RSC specification approach.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Vermont Agency of Transportation (VTrans) has adopted use of the accelerated bridge construction (ABC) approach and has led the nation in using ABC to successfully deliver bridge construction and reconstruction projects. While ABC projects enjoy high material quality due to a large fraction of precast and prefabricated elements, connections between these elements must be placed in-situ. These are often treated as a “weak-link” in the ABC approach due to potential risk for inferior performance. VTrans has adopted the use of rapid-setting concrete (RSC) for construction of connections between precast elements in ABC, which follows the current state of practice. This research study assessed the durability and structural performance of RSC used in current VTrans ABC projects through laboratory experimental evaluations. This research also explored standard mix designs for RSC ABC projects, assessing material costs and alternatives to derive and optimize design mixes. This comprehensive report summarizes research and development activities undertaken through three primary research tasks of the study: Task-1 State of the Art and Practice Review; Task-2: Evaluaiton of Current VTrans RSC Materials; and, Task-3: Development of Standardized RSC Mixture Specifications for use in ABC projects.

1.2 RAPID SETTING CONCRETE IN ABC PROJECTS

Rapid setting concrete forms the backbone of current ABC projects. RSC is a type of concrete designed to achieve its structural performance properties, or majority of them, in a short time window (typically less than 24 hours) after initial casting. While not limited to ABC, field placed bridge connections using ultra-high-performance concrete (UHPC) have become common practice in the last decade. Graybeal (2019) reported that more than 200 state transportation agency bridges have been constructed using field cast UHPC connections between 2009-2018. A large share of these utilize proprietary products such as Holcim Ductal®. The cost of UHPC is often between \$2,500-\$10,000/yd^3 and lack of non-proprietary mixes can often become a challenge in helping lower the costs. As reported by Graybeal (2019), this is the main motivator for transportation agencies to consider their own standard "proportion-based" UHPC mixes.

1.2.1 General Introduction on Accelerated Bridge Construction

The Federal Highway Administration's Accelerated Bridge Construction manual (Culmo 2011) defines ABC as:

> *ABC is bridge construction that uses innovative planning, design, materials, and construction methods in a safe and cost-effective manner to reduce the onsite construction time that occurs when building new bridges or replacing and rehabilitating existing bridges.*

Use of ABC is continually increasing by transportation agencies across the country to reduce construction time and minimize delays for public traffic. The FHWA ABC manual recommends that any in-place cast within ABC, such as a connection, may be done using innovative materials that expedite placement times such as the use of rapid-set/early-strength-gain materials or UHPC. These materials must meet requirements in terms of strength and durability, while also curing and attaining these strength requirements at a faster rate than normal Portland cement concrete (PCC); this usually results in a significantly higher material cost. ABC bridges are typically used along major routes of traffic to minimize traffic disruption, however, can often be used wherever they seem feasible and worthwhile for the public sector at large.

1.2.2 General Introduction on Rapid Setting Concrete in Transportation Applications

Rapid setting concrete is a specific mixture of concrete optimized to have fast curing times in order to facilitate faster construction. While there is not a unique definition for RSC, typically industry standard is for RSC to achieve design strength properties in less than 24 hours, typically within 6-8 hours after introduction of water to the mix. The majority of RSC uses ASTM C150 Type I or Type III cement, with various additives and accelerators as regulated and/or recommended by state DOTs. In terms of transportation agency applications, RSCs are used primarily in two functions, as a repair material for already existing bridges and PCC pavements, and in construction of precast element connections. While significant research exists in the first application of using RSC for repair, there is lack of extensive research on use of RSC in connections. Specifically with respect to long term durability assessments and development of standardized mix designs for use by agencies. Furthermore, the current approach for specifying RSC has been limited to each transportation agency using their own material specification without presence of a nationally available (such as, AASHTO) specification.

1.3 REPORT SCOPE AND ORGANIZATION

This report provides a review of existing literature that exists on durability and structural performance assessment of RSC used in ABC applications. Thereafter it discusses the Phase I (Task-2) and Phase II (Task-3) laboratory experimentation completed over the course of this study and finally presents key findings and recommendations of the research. The report is organized into nine chapters. Chapter 2 discusses literature review and findings with respect to laboratory characterization and transportation agencies. Chapter 3 discusses mix design criteria and laboratory test methods used in the Phase I (Task 2) experimentation. Chapters 4 and 5 present laboratory test results and data analysis from the Phase I Experimentation. Chapter 6 discusses the experimental plan for the Phase II (Task 3) laboratory evaluations. Chapters 7 and 8 discuss Phase-II (Task 3) laboratory results, and data analysis. Chapter 9 provides a summary of findings and makes recommendations on the basis of this study.

CHAPTER 2: SUMMARY OF LITERATURE ON RAPID SETTING CONCRETE

2.1 INTRODUCTION

This chapter summarizes a review of literature on the RSC used in transportation applications. Main focus of the review was on laboratory characterization methods for RSC that are used to assess their durability and used to propose a proportion based material designs. While the first emphasis of the research team was to conduct a review of literature specifically for RSC used in ABC projects, minimal published literature was found on this topic. Specifically, there is a significant lack of literature on durability assessment of RSC used for ABC connections. Most previous and current research efforts have focused on structural performance of field placed connections used in ABC. Thus, the research team expanded the review of literature to also include select works on RSC used in transportation infrastructure applications in general. A summary of literature review presented in this chapter focusses on mix design of RSC with emphasis on effects of various RSC constituent materials on mechanical properties and durability. It should be noted that there is significant literature on various alternative cement (such as, magnesium phosphate) based RSC that have been proposed and commercialized. In the present effort, research was limited to RSC made using Portland cements and blended cements with predominantly calcium silicate-based chemistries. Since most previous research efforts on RSC have focused on discussing effects of RSC composition on performance in terms of curing times, mechanical properties, and durability, the first part of this chapter is organized in terms of these three categories.

2.1.1 Curing Time

Time is a limiting factor in RSC design as the goal for ABC projects is to have short construction times and minimal impact to public traffic. Studies conducted by Nebraska DOT showed that changes in water to cementitious content (w/cm) ratios do not greatly affect set times. (Gholami et al., 2019). However, the difference between chloride-based accelerators and non-chloride-based accelerators was significant. While use of chloride-based accelerators typically outperforms non-chloride-based accelerators in reducing the set time, they increase corrosion potential of RSC. Cement type and accelerating admixture dosage have been found to be the most common variables affecting the curing time of RSC used in transportation applications (Dave et al. 2014). The interactions between admixtures can also have a significant adverse effect on the curing times; works by Brooks et al. (2000) demonstrated that while shrinkage reducing admixtures by themselves provide minimal delay in curing rates, when used with appreciable dosage of super plasticizing admixtures (which are often common in RSC), significant retardation can occur in curing times. While not commonly used in RSC, use of certain pozzolanic supplementary cementitious materials (fly ash and slags) can significantly alter curing rates. Pozzolans are often considered in bridge application concrete due to improvements in durability performance, especially to lower alkali silica reactivity (ASR) potential and improve chloride penetration resistance. Ozyildirim and Sharifi (2020) have shown that RSC with SCM can still cure at a fast rate achieving 3,000 psi compressive strength at 10 hours. Many researchers have assessed effects of curing conditions (temperature, use of curing compounds, wetting and steam curing) on the curing rates of RSC and RSC type materials used in transportation applications (for example, Fladr and Broukalova 2019, Yang et al. 2015, and Dave et al. 2014, and Graybeal 2006). Current VTrans rapid setting concrete special provision requires wet-curing until specified strength is met, thus in the current review, curing conditions are not discussed.

2.1.2 Mechanical Properties

2.1.2.1 Compressive and Flexural Strength

Strength of concrete is an almost universally adopted performance measure. Compressive strength is the most commonly used measure, however, in context of RSC connections in ABC, it is also important to assess flexural strength due to moment transfer demand from connections (although often ABC designs are conducted with the assumption of no moment transfer capacity from connections). Several previous efforts have shown that w/cm, cement content and cement type play the most significant roles in strength development of RSC (examples include, Dave et al. 2014 and Gholami et al. 2019). The rate of strength gain is often important for RSC used in ABC due to faster construction pace. Items discussed in previous sections on curing rate directly relate to the rate of strength gain. The ultimate strength is directly dependent on RSC composition. Most of the previous research that explored use of field cast UHPC bridge connections also investigated use of different types of fiber reinforcement and dosage (examples include Ebrahimpour et al. 2018, Phares et al. 2019, and Ozyildirim and Sharifi 2020). There is not a universal recommendation with respect to the fiber dosage in UHPC connection mixes; depending on fiber type, an optimization through dosage assessment needs to be conducted. The most important finding of the literature review with respect to strength development has been on interactions between various chemical admixtures. For example, shrinkage reducing admixtures can adversely interact with high range water reducers to impact strength development rate.

2.1.2.2 Bond Strength

Since field cast connections must bond well with precast elements to ensure both structural integrity as well as to ensure good durability, it is important to assess RSC mixtures in context of their bonding ability. A number of bond evaluation methods exist. Li et al. (1999) evaluated durability of RSC bond by exposing specimens to deicing chemicals and freeze-thaw cycling and subsequently conducting pull-off tests. Ebrahimpour et al. (2018) utilized flexural testing of beams with cast connections in the middle to evaluate bond strengths. Dave et al. (2014) and Dailey et al. (2015) used pull-out strength, slant shear and flexural testing (static and cyclic) to evaluate RSC used in repair of PCC pavement slabs. All these efforts have shown that surface preparation of existing concrete is critical to achieve high bond performance and that shrinkage potential of RSC could result in poor bond performance, especially after undergoing repeated freezing and thawing. Ebrahimpour et al. (2018) also observed that addition of 1.5 lbs./yd^3 of polypropylene fiber and shrinkage reducing admixture helped improve flexural bonding strength of connections. Behfarnia (2010) evaluated bond strengths of repair concretes after freeze-thaw conditioning. Their research found surface preparation as well as silica fume (presence of silica fume improved performance) to have a significant effect on retention of bond strength after freeze-thaw conditioning. General research found by Mater suggests that the roughening of the surface produces higher bond strength (Mater, 2019). This includes preparations to the edges such as wire brushing, jack hammering, pressure washing, and sand blasting.

2.1.3 Durability

Due to exposure to the elements of nature, durability performance of RSC used in ABC is an important factor to consider. The NCHRP Research Results Digest 355 Titled: Summary of Cast-In-Place Concrete Connections for Precast Deck Systems (National Academies, 2011) states that:

> *The closure pour (CP) material to precast unit interface is an area of concern for durability. The focus in this area must be on minimizing cracking in this location to reduce intrusion of water that may result in corrosion.*

While the majority of RSC have low permeability due to high cementitious contents, often they can have high shrinkage and cracking potential for the same reason. Graybeal (2011) reported cracking in field cast connections in Utah DOT bridges due to very high cementitious contents of UHPC connections. Further, presence of reactive silica in aggregate can result in high ASR potential. Indiana DOT evaluated six commercially available RSC mixes and found that chloride ion penetration was sub optimal, and failure occurred during freeze thaw cycles (Barde et al. 2006); this has resulted in Indiana DOT requirements for freeze-thaw testing of RSC for qualified product list approval. Gholami et al. (2019) demonstrated use of non-chloride-based accelerators to increase penetration resistance. Their efforts also demonstrated that as long as paste amount is kept constant, Portland cement amount can be reduced to limit shrinkage potential that can result in the loss of connection durability due to microcracking and debonding from precast element. Ozyildirim and Sharifi (2020) utilized a combination of silica fume and class F fly ash to achieve high permeability resistance in the development of high early strength repair mixtures for Virginia DOT. Dave et al. (2014) evaluated freeze-thaw durability of rapid setting repair mixtures for Minnesota DOT. The outcome of this effort recommended that freeze-thaw testing is critical in durability assessment of rapid setting mixtures used in transportation applications.

2.1.4 Field Performance of ABC Connections

There is a large amount of literature that discusses structural performance of ABC connections under a variety of static and dynamic loading (including seismic performance). Examples include USDOT Pooled Fund Study TPF-5(217) that evaluated UHPC connections for bridges in Iowa and New York (Graybeal 2012), Washington State DOT effort to assess seismic and ductility performance of bent connections (Khalegi, 2012) and Idaho Transportation Department research by Ebrahimpour et al. (2020) to evaluate fiber reinforced high strength concrete connections. While many trials on field structural performance exist, none have explicitly assessed durability of ABC connections after long term service in cold climate regions. Further, when select studies have discussed in-service durability, such as examples discussed in FHWA ABC manual, these are through qualitative assessments and for bridges with water-proofing membranes.

2.2 SUMMARY OF CURRENT PRACTICES FOR RSC SPECIFICATION

This section summarizes a review of current practices of various states transportation agencies that routinely utilize RSC materials. Selecting sources that provide general recommendations for materials used in ABC connections is also briefly discussed. In order to provide the reader with appropriate context, the current VTrans special provision that is commonly used to specify RSC used in ABC connections is presented first. Various RSC mix designs as well as performance properties samples tested by VTrans are included in this section. Thereafter, general requirements for composition of RSC by various agencies are discussed and finally, current RSC specifications used by VTrans' peer transportation agencies are presented.

2.2.1 Current VTrans Practices

The current special provision used by VTrans for specifying RSC used in ABC connections is presented in this section. The following subsections provide a summary of special provision provided to the research team by VTrans personnel.

2.2.1.1 Mix Design and Placement

The air content used in mix design shall be 7 ± 1.5%. The mix shall not exhibit segregation at the slump/spread being used. The self-consolidating concrete (SCC) mix shall be less than or equal to one on the Visual Stability Index. The spread range will be established for the initial submittal of mix for approval. The J-Ring Test will be conducted per ASTM C1621. The upper and lower ranges of the spread shall not have a difference of greater than 2 inches between the J-Ring and spread test or VSI greater than 1. Spread test, ASTM C1611, will be done for the production mix only, unless the VTrans Engineer requests J-Ring testing to be done.

2.2.1.2 Admixtures

The mix may contain shrinkage–compensating admixture such that there will be no separation of concrete from adjacent precast units. The Contractor shall include results for the unrestrained shrinkage test method, ASTM C 157 by procedure 11.1.2 and readings for a minimum of 28 days after the curing period is complete. The maximum shrinkage allowed shall be 0.04%. Testing shall be performed by an independent lab that is CCRL accredited in AASHTO T 30 or ASTM C 1260.

2.2.1.3 Testing Requirements

Current VTrans practices use the target of a 28-day compressive strength of 5000 psi. The surface resistivity of the test mix is measured at 56 days and based upon AASHTO T 358, following its classification system. Surface resistivity can be submitted earlier than 56 days as prescribed by AASHTO if the requirements are already met, however 56-day test results will be complied regardless of the results of earlier tests.

A portable compression testing machine calibrated in accordance with Section 5 of ASTM C 39 shall be provided by the Contractor and available on-site for cylinder testing of field-cured cylinders for construction progress. There shall also be a handheld grinding stone included with the compression testing machine. The handheld grinding stone will be used to grind the top of the cylinders to remove any sharp projections on the cylinder surface. All testing and equipment shall conform to ASTM C 39. Testing shall be performed, and equipment operated by, a qualified Agency project individual(s). The individual(s) shall be trained in the operation of the machine by the owner or representative of the machine who is proficient in the operations and functions of the machine.

If an independent lab is proposed to be used to test the field-cured cylinders instead of a portable compression testing machine, the Contractor shall submit documentation providing verification for the following:

1. Calibration of the compression machine in accordance with Section 5 of ASTM C 39.
2. Compression machine meets the requirements of ASTM C 39.
3. Proficiency of the technician who will be performing the test methods.

The State at any time reserves the right to perform an independent proficiency of the technician for the test methods used and review of the testing facility.

The quantity of Special Provision (High Performance Concrete, Rapid Set) to be measured for payment will be the number of cubic yards of concrete placed in the complete and accepted work, as determined by the prismoidal method using dimensions shown on the plans or as directed by the Engineer, including the volume of precast concrete stay-in-place forms, but excluding the volume of steel or other stay-in-place forms and form filling materials. No deductions will be made for the volume of concrete displaced by steel reinforcement, structural steel, expansion joint material, scuppers, weep holes, conduits, tops of piles, scoring, chamfers or corners, inset panels of 1.5 inches or less in depth, or any pipe less than 8 inches in diameter.

2.2.1.4 Submittals

Contractors must submit a mix design for approval a minimum of 14 days prior to placement of concrete. In addition, the contractor must produce and place a 2 cubic yard trial batch, at a location agreed upon by the Contractor and the Engineer 21 days and 7 days prior to first placement. The purpose of this trial batch is to demonstrate that the mix can produce the wet test results within the specified ranges. The Engineer shall be given a minimum notice of seven (7) calendar days prior to the trial batch pour. The trial batch shall be poured in the presence of the Engineer and the Composite Materials Engineer. The trial batch shall be produced and poured in the same manner, estimated concrete temperature, and time frames that will occur during construction. The slump/spread shall be within +/- 2 inches for conventional mix or +/- 3 inches for SCC, but still be within the established range limits for conventional or SCC. J-Ring test will be done for SCC mix with the difference between the J-Ring and spread test not greater than 2 inches. The Contractor shall provide qualified personnel to test spread, air content, and temperature of the trial batch. A trial batch will be required for each mix design used on the project. If SCC will be used in work with a sloped finished surface, the Contractor shall produce a mock-up during the trial batch to demonstrate that the mix can be finished with the sloped surface.

2.2.2 VTrans ABC Connection RSC Designs and Performance Properties

VTrans provided three distinct mix designs and a large dataset of compressive strength results of previous VTrans RSC materials with the research team. Further, five detailed lab reports of RSC materials were also provided. This section presents the three mix designs that have been shared with the research team along with laboratory testing results. Both mix design and the lab properties were used in developing experimental matrix that is discussed in chapter 4 of this report.

A summary of mix designs approved by VTrans are summarized in Table 2-1. As can be seen in the summary, the three mixes are designed with a total cementitious content (Portland cement and supplementary cementitious materials) of ranging from 730 to 900 lbs./yd^3. Two of the designs are for conventional concrete whereas one is for a SCC. The first and third mixes use regular Type-I/II Portland cement, whereas the second mix uses blended cement. Mix-1 is expected to have slightly lower paste volume due to lower w/cm. For mix-2, two different designs were approved with only difference in the fine aggregate source. All three mixes use air entrainer and shrinkage reducing admixtures. To retain slump without retarding setting time, mix-1 utilizes a workability retaining admixture, whereas mix-2 and mix-3 use an accelerating admixture. Lastly, mix-3 also consists of an air-entraining admixture.

Table 2-1 Summary RSC Mix Designs Approved by VTrans

Constituents (lbs./yd^3)	Mix-1 (RS-070)	Mix-2 (RS-231)	Mix-3 (RS-010)
Type	Conventional	SCC	Conventional
Portland Cement	425	-	584
Slag	425	-	-
Silica Fume	50	-	-
Blended Cement	-	900	-
Fly Ash	-	-	146
Water	267	284	255
w/cm	0.297	0.316	0.37
Coarse Aggregate	1484 (3/4 inch)	1587 (3/4 inch)	1566 (3/4 inch)
Fine Aggregate	1203 (FM: 2.70)	1069* (FM: 2.65)	1291
Air Entrainer	Yes (6% target)	Yes (6% target)	Yes (6% target)
HRWR	Yes	Yes	Yes
Other Admixtures	SRA, Workability Retaining	SRA, Accelerating	SRA, Accelerating., Air Entraining, HRWR
Workability	Slump max. 9 inch	Spread: 18 (min) – 28 (max) inch	Slump: 4.5 (min) – 7.5 (max) inch

w/cm: Water to cementitious materials ratio; HRWR: High range water reducing admixture; SRA: Shrinkage reducing admixtures.
* Two different fine aggregate sources have been approved for this proportion.

Five VTrans test reports for 2021 RSC materials along with four years of RSC compressive strength data (as part of VTrans acceptance testing) for VTrans bridge projects were shared with the research team. The laboratory measured properties for the five set of 2021 RSC materials are provided in Table 2-2. The first five results (A – D) are for design RS-070 which is a SCC with 26-28 inch spread, whereas result E represents a high workability conventional concrete with 8 inch slump. The distinction of result E is also evident in terms of lower air content. Strength evolution data for seven sets of RSC materials (as distinguished by the approved mix identification, such as, 070, 260 etc.) in terms of yearly averages is plotted in

Figure 2-1. The 28-day strengths for these appear to range between 6,000 psi and 10,000 psi. From these plots it appears that VTrans' requirement of 5,000 psi is often achieved in less than 7 days, with some mixes taking much shorter of a time span (less than 2 days). A 3,000 psi strength value which is often used to allow demolding or formwork removal (commonly referred to as stripping strength) appears to be achieved in 24 hours or less for most of these mixtures.

Table 2-2 Other properties (w/cm, air content and workability) for VTrans RSC mixes (2021)

ID/Design	w/cm	Air Content (%)	Slump/Spread (inch)
B/RS-070	0.256	6.9	28
D/RS-070	0.27	6.8	28

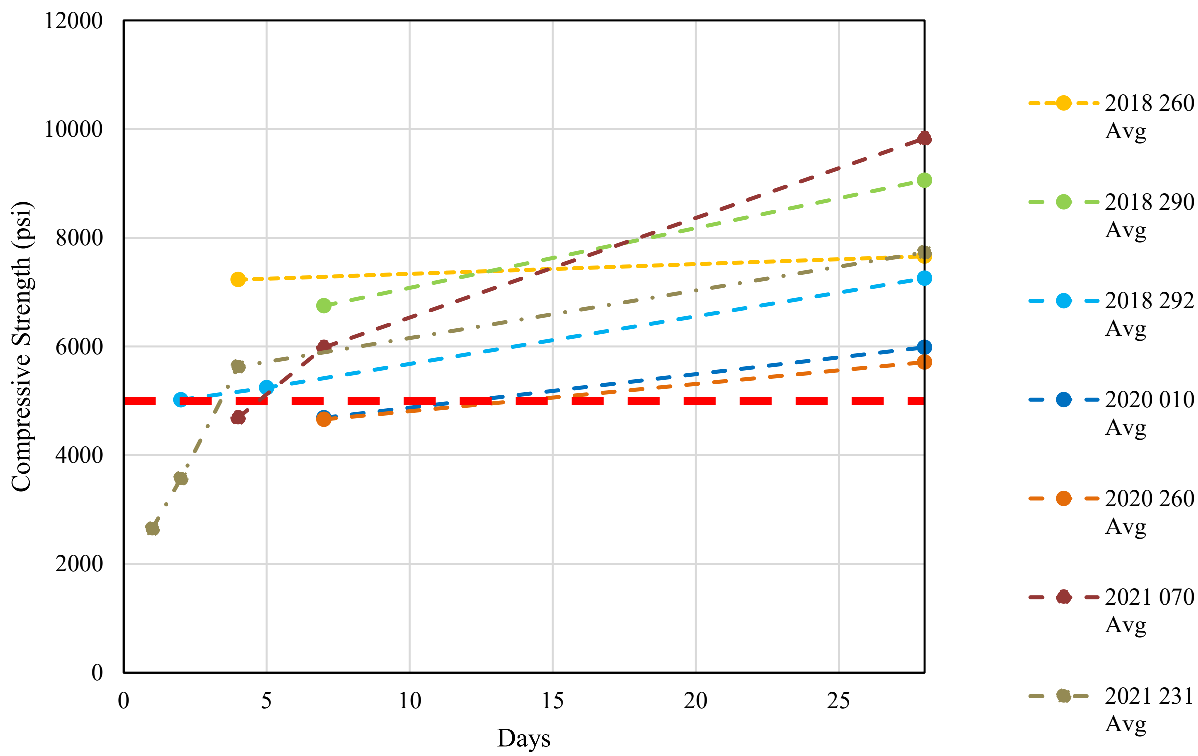

Figure 2-1 Strength evolution of VTrans RSC mixes (average values for each design is plotted)

2.2.3 State of the Practice for RSC Specification

Several approaches are used for current RSC designs across the country. Dave et al. (2014) and Gholami et al. (2019) have summarized approaches adopted by different transportation agencies to specify RSC. As summarized in NCHRP RRD 355, performance-based specification approaches are most common for specifying cast in-place connection materials used with prefabricated bridge elements (National Academies 2011), nonetheless, agencies often restrict constituent material types and quantities. FHWA TechBrief HRT-13-100 proposes various proportioning limits that can be used to develop a non-proprietary UHPC (Graybeal, 2013). A brief review of various transportation agency requirements for constituent materials used in RSC is presented in subsequent subsections.

2.2.3.1 Cement Type and Amount

A summary of the cement types and amounts specified by several state transportation agencies in the United States is summarized by Gholami et al. (2019), this information is reproduced in Table 2-3.

Table 2-3: Cement type and amount specified in transportation agency RSC specifications (reproduced from Gholami et al. 2019)

State	Cement type	Amount of cement in lb/yd^3 (kg/m^3)
California	Proprietary cement mixtures	NA
	Type III Portland cement	
Colorado	Type I/III Portland cement	Minimum 660 (392)
Florida	Type II Portland cement	800–950 (475–504)
Illinois	Calcium aluminate cement	Minimum 675 (400)
	Rapid hardening cement	600–625 (356–371)
Kansas	Type I/III Portland cement	Minimum 658 (400)
Maryland	Type III Portland cement	870–915 (560–543)
Nebraska	Type I/II Portland cement	Minimum 752 (446)
	Type III Portland cement	Minimum 799 (474)
New Jersey	Type I/II Portland cement	Minimum 799 (474)
North Carolina	Type I/II Portland cement	Minimum 754 (447)
	Regulated set Portland cement	Minimum 612 (363)
	Rapid setting cement	Minimum 651 (386)
Washington	Type I/II Portland cement	Minimum 705 (418)
	Type III Portland cement	Minimum 750 (445)
Wisconsin	Type I/III Portland cement	840–900 (498–534)

Note: NA = not available .

According to the FHWA TechNote on Design and Construction of Field-Cast UHPC Connections, a minimum of 1000 lbs./yd^3 of Portland cement content and maximum allowable w/cm of 0.25 is required (Graybeal, 2019).

Very few instances in literature were found that explicitly indicate that transportation agencies may limit amount or type of supplementary cementitious material (SCM) for RSC. One example of restriction is for Minnesota DOT which limits the fly ash substitution to 15% and slag substitution to 35% for high early strength concrete used in pavement and bridge repairs. It is more common to let the performance limits in terms of strength gain and durability requirements (such as permeability and ASR potential) control the amount and type of SCM used in RSC.

2.2.3.2 Chemical Admixtures

Accelerators are most commonly used in RSC, especially those using Portland cements. While calcium chloride is the most well-established and economical accelerator, the presence of chloride can increase corrosion in reinforcing bars and accelerate slab cracking due to shrinkage, therefore most states prohibit its use in RSC (Gholami et al. 2019). Shrinkage reducing admixture is also commonly used to limit the high shrinkage potential of RSC due to high cementitious material contents. Virginia DOT explicitly requires shrinkage reducing admixture for all RSC used in bridge repair when cracking is anticipated (Ozyildirim and Sharifi, 2020). According to Graybeal (2019) the use of accelerators, polycarboxylate-based superplasticizers, and phosphonate-based superplasticizers is most common in UHPC used in field cast connections. The most common approach for limiting allowable chemical admixtures is for agencies to allow products on the agency’s approved or qualified product lists (APL/QPL).

2.2.3.3 Fibers

Use of fibers allows significant increase in structural capacity of cast in-place bridge connections, especially when connections are expected to have structural contributions. FHWA ABC manual discusses the significance of UHPC fiber type and dosage in ensuring that sufficient moment transfer capacity is present (Culmo, 2011). A number of recent efforts have focused on developing alternative UHPC designs to proprietary products with emphasis on identifying suitable fiber type and dosage. For example, Phares et al. (2019) developed UHPC for Iowa DOT for use in cast in-place bridge connections using steel fibers. Similarly, Ebrahimpour et al. (2020) optimized polypropylene fiber type and dosage for the Idaho Transportation Department for bridge connections. A majority of the efforts identifying fiber type and dosage for connection mixes are recent and most current agency specifications do not explicitly limit fiber types in RSC beyond use of APL/QPL.

2.2.3.4 Aggregate

For agencies that do not rely entirely on performance-based specifications for RSCs, the aggregate restrictions are typically the same as those for other structural and non-structural concrete in the agency's standard specifications. Typically, these include gradation, maximum size, freeze-thaw durability, and ASR potential. FHWA TechNote on Design and Construction of Field-Cast UHPC Connections recommends maximum aggregate size be limited to less than 0.25 times the fiber length and no greater than 0.125 inch for field cast UHPC bridge connections (Graybeal 2019).

2.2.4 State of Practice for RSC Performance Requirements

Use of performance-based specifications is the current state of the practice for RSC used by transportation agencies. NCHRP RRD 355 recommends the performance specifications for cast in-place connection mixtures used with precast deck systems on the basis of long-term performance observations of bridge decks conducted by Russell and Ozyildirim (2006) and Tepke and Tikalsky (2007). These recommendations are presented in Table 2-4. The mechanical performance in this recommendation is through compressive strength and bond strength limits. The durability requirements are satisfied by limiting shrinkage amount, chloride penetration and freeze-thaw performance requirements.

Table 2-4 Performance specifications recommended by NCHRP RRD 355 (Reproduced from National Academies, 2011)

Performance Characteristic	Test Method	Performance Criteria		
Compressive Strength (CS), ksi	ASTM C39 modified	$6.0 \leq CS$ @ 8 hours (overnight cure) @ 7 days (7-day cure)		
Shrinkage[1] (S), (Crack age, days)	AASHTO PP34 modified	$20 < S$		
Bond Strength (BS), psi	ASTM C882 modified	$300 < BS$		
Chloride Penetration[2] (ChP), (Depth for percent chloride of 0.2% by mass of cement after 90-day ponding, in.)	ASTM C1543 modified	$ChP < 1.5$		
Freezing-and-Thawing Durability (F/T), (relative modulus after 300 cycles)	ASTM C666 Procedure A modified	Grade[3] 1 $70\% \leq F/T$	Grade 2 $80\% \leq F/T$	Grade 3 $90\% \leq F/T$

[1]No S criterion need be specified if the CP material is not exposed to moisture, chloride salts or soluble sulfate environments.
[2]No ChP criterion need be specified if the CP material is not exposed to chloride salts or soluble sulfate environments.
[3]Grades are defined in Table 4.

The FHWA TechNote on Design and Construction of Field-Cast UHPC Connections by Graybeal (2019) is an excellent resource for material specifications of RSC connections. This document provides a detailed summary and significance of each performance specification requirement. A summary of various measurements that are commonly applied to UHPC connections is reproduced from the FHWA TechNote in Table 2-5. It should be noted that the use of the tests shown in the table is geared more towards either approval of proprietary material or to prescribe a material.

Table 2-5 Materials tests commonly applied to UHPC connections (reproduced from Graybeal 2019)

Test Method	ASTM	Material Vetting	QA/QC	QA/QC Frequency	Acceptance Criteria
Flow	C1856 (C1437 mod.)	Yes	Yes	Once per mix	• Flow range from 7 to 10 inches (178 to 254 mm).
Compressive strength	C1856 (C39 mod.)	Yes	Yes	At least once per 25 yd^3 (19 m^3) or once per 12-hour shift	• >14 ksi (97 MPa) after 4 days.[a] • >17.5 ksi (120 MPa) after 28 days. • >14 ksi (97 MPa) before application of construction or live loads.
Chloride ion penetrability	C1856 (C1202)[b]	Yes	Not common	N/A	• ≤500 coulombs by 28 days.
Freeze–thaw resistance	C1856 (C666A mod.)	Yes	Not common	N/A	• RDM ≥ 90 percent after 300 cycles.
Shrinkage	C1856 (C157 mod.)	Yes	Not common	N/A	• ≤800 microstrain at 28 days. • Consider curing scenarios.

QA/QC = quality assurance/quality control; N/A = not applicable; RDM = relative dynamic modulus of elasticity.
[a]14 ksi is the strength at which UHPC is mature enough to be fully loaded and at which the rebar development length equations are applicable. The 4-day limit can be shortened if desired to accelerate construction by applying heat and accelerators.
[b]While ASTM C1856 says that test method C1202 is not applicable to UHPC mixtures with metallic fibers, many mixtures with metallic fibers can, in fact, be successfully tested using method C1202.[(9)] Some mixtures, especially those with longer fibers that touch each other, cannot be tested using method C1202. In those cases, a permeability test such as ASTM C1543 may be considered, with the results compared against the permeability of a highly durable conventional concrete.[(48)]

2.2.5 Practices of Peer States Transportation Agencies

The research team reviewed RSC specifications of a few peer transportation agencies to VTrans. Mainly agencies that have comparable climatic conditions were considered. Within New England, both New Hampshire and Massachusetts DOTs have rapid setting concrete material specifications. Brief summaries of these are presented next.

2.2.5.1 New Hampshire Department of Transportation

The New Hampshire Department of Transportation (NHDOT) currently has specifications for rapid set concrete as a patching material. These specifications have requirements for compressive strength at three different time increments, bond strength, and length changes.

NHDOT also specifies maximum mass loss due to freeze-thaw cycles, something to take note of as the current study will undertake freeze thaw testing of VTrans RSC materials. NHDOT divides their RSC specifications into 3 categories, Cementitious, Polymer-Modified, and Polymer Concrete. The NHDOT specification requirements for RSC are presented in Table 2-6. As evident from this table, the specifications are performance-based, they however lack a workability requirement, which is important for RSC connection materials.

Table 2-6: NHDOT RSC Specifications (reproduced from the NHDOT Standard Specifications for Road and Bridge Construction)

Rapid-Hardening Patching Material		
Cementitious		
Property	**Test Method**	**Requirement**
Compressive Strength, 3-hour	ASTM C109	500 psi min.
Compressive Strength, 1-day	ASTM C109	2000 psi min.
Compressive Strength, 7-day	ASTM C109	4000 psi min.
Bond Strength, 1-day	ASTM C 882	1000 psi min.
Length Change	ASTM C 157	±0.100%
Freeze-Thaw Mass Loss	AASHTO T 161 Procedure A	1.0% max.
Durability Factor	AASHTO T 161 Procedure A	95% min.
Polymer-Modified		
Property	**Test Method**	**Requirement**
Compressive Strength, 3-hour	ASTM C109	500 psi min.
Compressive Strength, 1-day	ASTM C109	2000 psi min.
Compressive Strength, 7-day	ASTM C109	4000 psi min.
Bond Strength, 1-day	ASTM C 882	1000 psi min.
Length Change	ASTM C 157	±0.100%
Freeze-Thaw Mass Loss/Gain	AASHTO T 161 Procedure A	1.0% max.
Durability Factor	AASHTO T 161 Procedure A	95% min.
Polymer Concrete		
Property	**Test Method**	**Requirement**
Compressive Strength, 3-hour	ASTM C 579	500 psi min.
Compressive Strength, 1-day	ASTM C 579	2000 psi min.
Compressive Strength, 7-day	ASTM C 579	4000 psi min.
Bond Strength, 1-day	ASTM C 882	1000 psi min.
Length Change	ASTM C 531	±0.100%

2.2.5.2 Massachusetts Department of Transportation

The Massachusetts Department of Transportation (MassDOT) has specifications for patching RSC that are similar to that of the NHDOT, in that the MassDOT specifies strengths of concrete at different durations. These limits are also dependent on where RSC is used for patching purposes, whether on horizontal surfaces or vertical/overhead. These requirements can be seen in Table 2-7. In addition to these standard specifications for patching RSC, MassDOT has also used special provisions to specify UHPC for ABC connection pours, these have followed almost identical requirements to those discussed in FHWA TechNote on Design and Construction of Field-Cast UHPC Connections.

Table 2-7: MassDOT RSC patching material specifications (reproduced from the MassDOT Standard Specifications for Road and Bridge Construction)

HORIZONTAL FAST SET			AASHTO/ASTM Test Method
Initial Set		20-30 Minutes	T 131
Final Set		≤ 60 Minutes	
Compressive Strength	2 Hours	≥ 2,000psi	T 106 / C 109
	1 Day	≥ 4,000psi	
	7 Days	≥ 6,000psi	
Tensile Strength	28 Days	≥ 400psi	T 198
Flexural Strength	1 Day	≥ 600psi	C 78
	7 Days	≥ 750psi	
Slant Shear Bond Strength	1 Day	≥ 1,500psi	C 882*
	7 Days	≥ 2,500psi	
Resistance to Freeze Thaw (Applies to 3rd Party Independent Testing)			
Freeze Thaw Mass Loss	300 cycles	≤ 6%	T 161/ C 666 (Procedure A)
Durability Factor		≥ 90%	
Chloride Ion Penetration	28 Days	≤ 2000 Coulombs	T 277/C 1202
VERTICAL/OVERHEAD PATCHES			AASHTO/ASTM Test Method
Initial Set		≤ 45 Minutes	T 131
Final Set		≤ 3 Hours	
Compressive Strength	4 Hours	≥ 200psi	T 106 / C 109
	1 Day	≥ 2500psi	
	7 Days	≥ 4000psi	
Slant Shear Bond Strength	7 Days	≥ 1750psi	C882
Resistance to Freeze Thaw (Applies to 3rd Party Independent Testing)			
Freeze Thaw Mass Loss	300 cycles	≤ 6%	T 161/ C 666 (Procedure A)
Durability Factor		≥ 90%	
Chloride Ion Penetration	28 days	≤ 2000 Coulombs	T 277/ C 1202

* As modified by ASTM C928

2.2.5.3 ASTM C928

Multiple state DOTs across the United States such as Minnesota and North Dakota default their specifications for RSC to ASTM C928. ASTM C928 provides standard performance requirements for RSC after 3 hours, 1 day, 7 days, and 28 days. These requirements can be seen in Table 2-8.

Table 2-8: Required Properties for RSC from ASTM C928 Specifications (reproduced from ASTM C928 Specifications)

	3 h	1 day	7 days	28 days
Compressive Strength, min, MPa [psi]				
R1 concrete or mortar	3.5 [500]	14 [2000]	28 [4000]	[B]
R2 concrete or mortar	7.0 [1000]	21 [3000]	28 [4000]	[B]
R3 concrete or mortar	21 [3000]	35 [5000]	35 [5000]	[B]
Bond strength, min, MPa [psi]				
R1, R2, and R3 concrete or mortar	—	7 [1000]	10 [1500]	—
Length change, based on length at 3 h, max, %				
R1, R2, and R3 concrete or mortar	allowable increase after 28 days in water allowable decrease after 28 days in air			+0.15 –0.15
Consistency of concrete or mortar[C]			concrete slump, min, mm [in.]	Flow of mortar, min, %
R1 consistency after 15 min after addition of mixing liquid			75 [3]	100
R2 and R3 consistency at 5 min after addition of mixing liquid			75 [3]	100
Scaling resistance to deicing chemicals after 25 cycles of freezing and thawing				
Concrete, max visual rating			2.5	
Mortar, max scaled material[D]			5 kg/m² [1 lb/ft²]	

[A] It is recognized that other characteristics of rapid-hardening concrete repair materials might need consideration. Such characteristics might be necessary in some environments and applications; however, to impose specification limits on all products is considered beyond the scope of this specification. Optional considerations with suggested methods of test may include tests for the following:

Time of setting	Test Method C403/C403M
Flexural strength	Test Method C78
Freeze thaw	Test Method C666/C666M, Procedure A
Sulfate expansion	Test Method C1012

[B] The strength at 28 days shall be not less than the strength at 7 days.

[C] Slump or flow requirements are waived for materials intended for vertical or overhead applications.

[D] A 250-mm [10-in.] square spalled to an average depth of 3 mm [⅛ in.] for 100 % of its surface would have about 10 kg/m² [2.0 lb/ft²] of scaled material.

While ASTM C928 can provide a good baseline for specifications, it should be kept in mind that ASTM C928 is developed explicitly for repair mixtures and not UHPCs that are common as ABC connection materials.

2.3 SUMMARY OF FINDINGS FROM LITERATURE

2.3.1 Summary of Literature Review

Chapters 2 presented a review of literature on the RSC used by transportation agencies with specific emphasis on field cast connections in bridges. Limited information is available on laboratory characterization of RSC used in ABC connections, especially in terms of durability evaluation. Significant previous and ongoing research has been focused on conducting field trials with UHPC connections, assessing structural performance of UHPC, and developing non-proprietary UHPC mixes. Key findings of the literature review are presented next.

2.3.2 Key Findings

The aim of this literature review was to determine the current state-of-the-art with respect to design and laboratory evaluation of the RSC and the current state-of-the-practice for their specification. The key findings of this review can be summarized as:

- Use of proprietary UHPCs (such as, Lafarge-Holcim Ductal) is the most common for field-cast connections in ABC.
- It is widely acknowledged in literature that RSC used in connections needs to have high durability performance to ensure longevity of ABC bridges. Freeze-thaw resistance and chloride penetration resistance are the most common durability performance measures in use.
- Bonding of RSC to prefabricated elements is important to ensure good long-term durability. Surface preparations as well as use of shrinkage reducing admixtures are most identified approaches to provide good long term bond performance.
- Due to high cementitious contents, shrinkage as well as brittleness are a concern that need to be addressed in designing RSC.
- Use of superplasticizers or high range water reducers and accelerating admixtures is prevalent in RSC used by transportation agencies in bridge connections.

- Usage of fibers is common to achieve the ductility response and tensile capacity of UHPC used in connections that allow or moment transfer.

Above findings were considered in identifying the suitable laboratory tests to evaluate current RSC used in VTrans ABC connections as well as to develop a partial factorial experimental matrix that will allow research team to conduct the first step toward proposing standard proportion-based RSC designs.

CHAPTER 3: EXPERIMENTAL PLAN FOR PHASE-I LAB EVALUATION (TASK-2)

3.1 INTRODUCTION

This chapter presents an experimental design that has been prepared for Phase I (Task-2) of this project. Using this experimental design, the researchers were able to satisfy two technical objectives of this study: (1) durability concerns with the currently used RSC materials in ABC connections (Phase I of the research study); (2) recommend standardized proportion-based mixes for use in future ABC projects (Phase II of the research study). It should be noted that for the second objective, this experimentation (Phase-I) only served as a first step, a second step was undertaken in the Phase II (Task-3) experimentation of this study.

3.2 EXPERIMENTAL DESIGN

A partial factorial experimental design was chosen using three VTrans approved RSC designs (RS-070, RS-231, and RS-010) as baselines. The primary variations considered in this design were cementitious material content, air content, workability, and aggregate sources and are presented in Table 3-1, Table 3-2, and Table 3-3. The first set of baseline and variations (SCC-1) were based on VTrans RS-070 design for SCC. The second set (PCC-2) were based on approved conventional concrete design RS-231. The third set (PCC-3) were based on VTrans RS-010 for conventional concrete. It should be noted that all materials were designed with the minimum target compressive strengths of 3,500 psi at 2-days, and 5,000 psi at 28-days to meet the current VTrans special provision for RSC. The 2-day strength requirement was based on test results for RSC that have been shared by VTrans to the research team. This early strength requirement also ensures the accelerated construction pace of ABC projects.

Table 3-1: Phase I Mix Design Attributes for Cementitious Quantities (yellow shading indicates base mix design, red shading indicates alterations lower than base mix design, green indicates higher, no shading indicates no change)

ID	*Total Cementitious Content (lbs./yd³)*	*Total Portland Cement (lbs./yd³)*	*%PC Replacement*	*Total Slag (lbs./yd³)*	*Total Class F Fly Ash (lbs./yd³)*	*Total Silica Fume (lbs./yd³)*
SCC-1 (RS-070)	900 (P,S,F)	425	52.78%	425	-	50
SCC-1a	800 (P,S,F)	400	52.78%	400	-	47
SCC-1b	1000 (P,S,F)	500	52.78%	500	-	58
SCC-1c	900 (P,S,F)	450	52.78%	450	-	53
PCC-2 (RS-231)	900 (B)	657	27%	198	45	-
PCC-2a	750 (B)	548	27%	165	38	-
PCC-2b	825 (B)	602	27%	182	41	-
PCC-2c	1050 (B)	767	27%	231	53	-
PCC-2d	900 (B)	657	27%	198	45	-
PCC-2e	1200 (B)	876	27%	264	60	-
PCC-3 (RS-010)	730 (P, FA)	730	20%	-	146	-
PCC-3a	900 (P, FA)	800	20%	-	180	-

P: Portland cement; S: Slag; F: Silica fume; FA: Fly Ash; B: Blended cement; Original: Aggregate source used in approved design; Alter: Aggregate source other than one used in design approval.

Table 3-2: Phase I Mix Design Attributes for Target Fresh Properties, w/cm Ratio, and Aggregate Sources (yellow shading indicates base mix design, red shading indicates alterations lower than base mix design, green indicates higher, blue shading indicates aggregate source change no shading indicates no change)

ID	*w/cm Ratio*	*Target Air Content (%)*	*Target Workability (Slump/Spread, inch)*	*Coarse Aggregate Source*	*Fine Aggregate Source*
SCC-1 (RS-070)	0.297	6	27 (Spread)	Calkins Pit	Calkins Pit
SCC-1a		6	23 (Spread)	Calkins Pit	Calkins Pit
SCC-1b		6	27 (Spread)	Calkins Pit	Nadeu Pit
SCC-1c		6	18 (Spread)	Ireland Pit	Calkins Pit
PCC-2 (RS-231)	0.315	6	8 (Slump)	Ireland Pit	Nadeau Pit
PCC-2a		6	6 (Slump)	Ireland Pit	Calkins Pit
PCC-2b		4.5	8 (Slump)	Calkins Pit	Nadeau Pit
PCC-2c		7.5	6 (Slump)	Ireland Pit	Nadeau Pit
PCC-2d		4.5	9 (Slump)	Wallingford Crushed Stone	Pike IND
PCC-2e		6	8 (Slump)	Ireland Pit	Nadeau Pit
PCC-3 (RS-010)	0.35	6	6 (Slump)	Wallingford Crushed Stone	Pike IND
PCC-3a		6	6 (Slump)	Ireland Pit	Nadeu Pit

Original: Aggregate source used in approved design; Alter: Aggregate source other than one used in design approval.

Table 3-3: Phase I Mix Design Attributes for Admixtures (yellow shading indicates base mix design no shading indicates no change)

ID	Air Entrainer	High Range Water Reducer	Workability Retainer	Shrinkage Reducing Admixture
SCC-1 (RS-070)	5 oz/cwt	7.5 oz/cwt	4.7 oz/cwt	192 oz/yd^3
SCC-1a	5 oz/cwt	6.5 oz/cwt		
SCC-1b	5 oz/cwt	7.5 oz/cwt		
SCC-1c	5 oz/cwt	5.7 oz/cwt		
PCC-2 (RS-231)	40 oz/ yd^3	6.7 oz/cwt	5 oz/cwt	128 oz/yd^3
PCC-2a	40 oz/ yd^3	6.1 oz/cwt		
PCC-2b	35 oz/ yd^3	6.7 oz/cwt		
PCC-2c	45 oz/ yd^3	6.1 oz/cwt		
PCC-2d	35 oz/yd^3	6.9 oz/cwt		
PCC-2e	40 oz/yd3	6.7 oz/cwt		
PCC-3 (RS-010)	1.2 oz/yd^3	11.6 oz/cwt	32 oz/cwt	64 oz/yd^3
PCC-3a	1.2 oz/yd^3	11.6 oz/cwt		

cwt: 100 lbs. cement.

3.2.1 Cementitious Content

Cementitious content of any concrete is one of the most important variables since it directly impacts cost, strength, and durability. Between the three Phase I (Task-2) baseline designs, the experiment evaluated the use of Portland cement with SCMs (slag and silica fume) and blended cements as binder types. SCC-1 utilized Type I/II Portland cement (47.5%), along with slag (47%) and silica fume (5.5%). The slag corresponding to ASTM C989 class 100 and silica fume conforming to ASTM C1240 was used in this study. PCC-2 utilized a blended cement produced by Lafarge Canada (Tercem 3000) which consisted of Type I/II Portland cement (73%), slag (22%), and class F fly ash (5%). PCC-3 utilized Type I/II Portland cement (83.3%) as well as ASTM C618 class F fly ash (16.7%).

Overall %PC replacement was higher than in many other parts of the country. This was due to concerns with alkali-silica reaction (ASR) among New England states such as Vermont. ASR is a material degradation mechanism that occurs when reactive high silica content aggregate particles and alkali in Portland cement react, damaging concrete over time. Aggregates commonly found in Vermont are high in silica, therefore higher amounts of Portland cement replacement and higher SCM contents are commonplace for New England transportation infrastructure projects that are exterior and exposed to moisture.

3.2.2 Target Air Content

High air content leads to higher durability, but at the cost of lower strength. The amount of entrained air also influences the workability of RSC. Data collected by VTrans and the experience of project advisory panel determined that air entrainment levels of 6% were commonly seen for in-situ placed RSC material on VTrans projects. Therefore, an air entrainment of 6% was used as the baseline in the experimental design. The air content variations were achieved through air entraining admixture dosage and the high-range water reducer amount was adjusted to compensate for workability change.

3.2.3 Target Workability

For SCC-1, the variations in workability ranged over allowable limit of 18–28 inch spread, for PCC-2 and PCC-3, the variations represent the range of 4.5 inch slump (typical low-end limit for high workability conventional concrete) to 7.5 inch as seen in Table 3-2. Workability adjustments were mostly achieved through high-range water reducer, HRWR (ASTM C494 Type F) along with commercially available workability retaining admixture.

3.2.4 Aggregate Sources

The main objective of aggregate source variations was to determine the effects of aggregate source change on properties of RSC to ensure that proportion-based RSC designs were feasible across the state of Vermont with different aggregate geological sources. The first baseline design (SCC-1) had both coarse and fine aggregate from the same VTrans approved sand and gravel producer. Two coarse and two fine aggregate sources in addition to those on baseline were evaluated. The VTrans approved aggregate sources were used in conjunction with the State geological maps to identify aggregates that are geologically distinct. Second baseline design PCC-2 was already evaluated and approved by VTrans for two fine aggregate sources. In addition, two coarse aggregate and two fine aggregate sources from the VTrans approved list were evaluated. Third baseline PCC-3 was already evaluated and approved by VTrans for coarse and fine aggregate sources and had one variation using approved VTrans coarse and fine aggregate sources. The final aggregate sources used in this experiment included Calkins Pit in Coventry, Vermont; Ireland Pit in Williston, Vermont; and Wallingford Crushed Stone in Wallingford, Vermont for coarse aggregate, and Calkins Pit; Nadeau Pit in Johnson, Vermont; and Pike Industries in Danby, Vermont for fine aggregates. An overview lithology map of Vermont and aggregate source location can be seen in Figure 3-1.

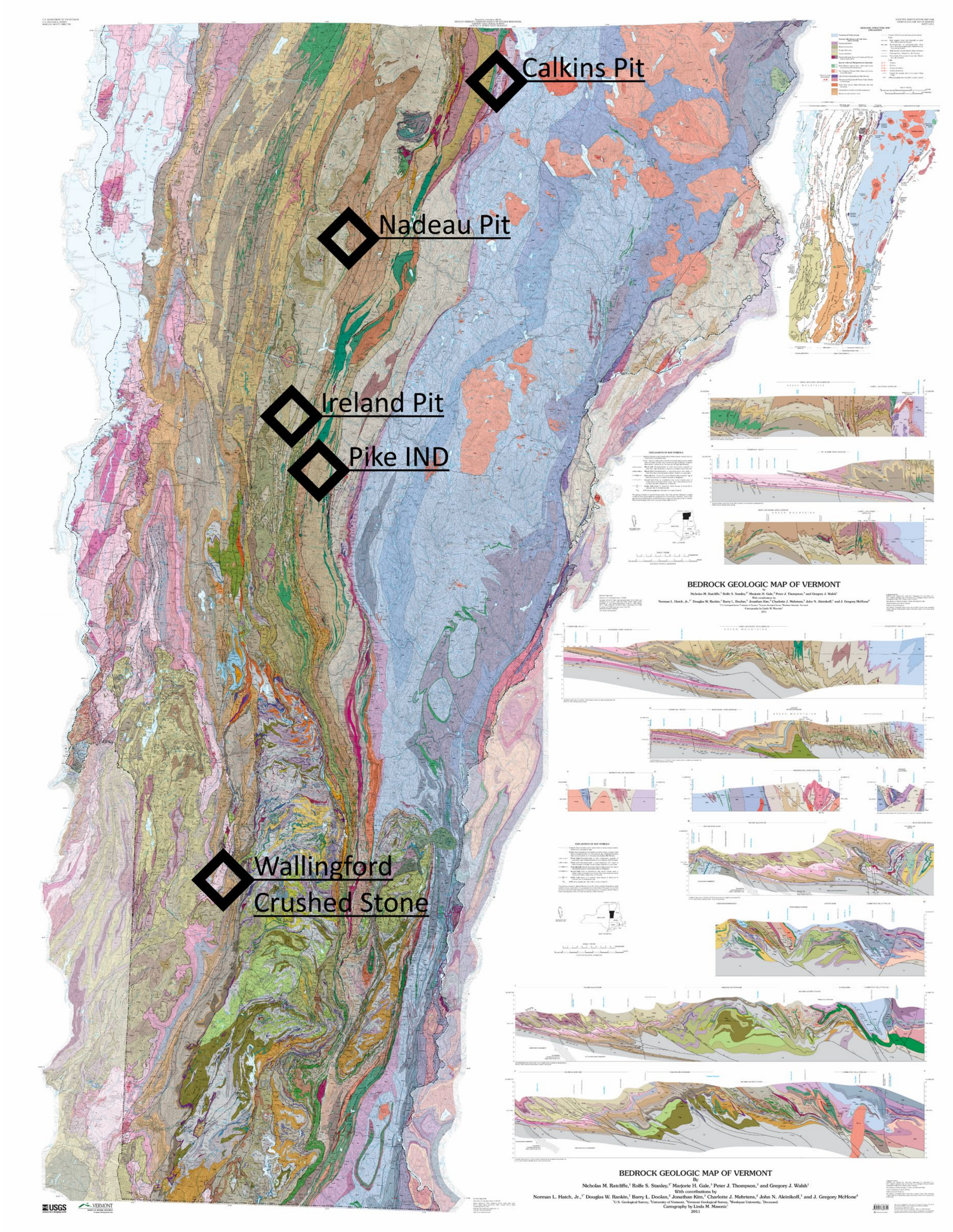

Figure 3-1: Aggregate Lithology Map of Vermont and Aggregate Source Location

3.3 LABORATORY TEST METHODS

3.3.1 Fresh Properties

The ASTM C1611 (spread) and ASTM C143 (slump) were used to measure workability, and visual stability index was recorded as well for SCC mixes using ASTM C1611.Finally, the air contents of the mixes were measured using ASTM C231 procedure as seen in Figure 3-2.

Figure 3-2: Air Content meter

3.3.2 Shrinkage

The ASTM C157 test procedure was followed to measure the shrinkage potential of various RSC mixtures evaluated in this study. The ASTM standard evaluates lengths of specimen at 24 hours and 28 day durations using a length comparator as seen in Figure 3-3

Figure 3-3: Shrinkage Test

3.3.3 Flexural Strength

This study adopted ASTM C78 procedure for testing beams with third-point loading. The selected beam size was 6 inch by 6 inch by 24 inch (18 inch span length) as seen in Figure 3-4. Measurements were taken on 7 and 28 days after placement.

Figure 3-4: Flexural Strength Test

3.3.4 Compressive Strength and Elastic Modulus

Compressive strength is the most widely accepted measure of concrete quality. ABC projects using concrete need to have an appreciable rate of strength gain, as deemed acceptable by designs and specifications. Compressive strength was directly tested using compression tests on 4 inch by 8 inch cylindrical concrete specimens following ASTM C39 as seen in Figure 3-5. Concrete gains its strength over time, a critical reason as to why rapid setting concrete is being analyzed for ABC as higher strengths are desired at earlier times than in standard structural concrete. Therefore, compressive strength testing was conducted at 1, 2, 7, and 28 days for experimentation. In addition, fully cured specimens were used for companion testing of unconditioned and freeze-thaw conditioned specimens. A minimum of three and maximum of four specimens were tested. During compressive strength measurements, specimens were also tested to measure elastic modulus using stress at 45% of compressive strength as a criteria.

Figure 3-5: Compressive Strength Test Specimen After Failure

3.3.5 Bond Shear Strength

Bond shear strength is the laboratory measurement used to estimate the bond strength between RSC and the precast ABC elements. This is critical for these designs as the RSC being used is connecting pre-cast elements together on bridges. Therefore, the ability to bond the precast concrete with the in-place cast connection is of high priority to ensure long term performance of ABC projects. This study used the slant shear test for bond shear strength put forth by ASTM C882. Prior to laboratory batching mix iterations, the substrate material was created using the PCC-2 mix design. Cylindrical specimens were placed and allowed to cure for 28 days before being cut in half at a 45-degree angle using a saw. These “half” cylinders were then wire brushed by hand for approximately 10 seconds to better simulate rough in-field connections and returned to the curing chamber. During each batch “half” cylinders were taken out, re-wire brushed by hand for an additional 10 seconds, and placed back into plastic molds. New material was then cast on top of the substrate inside the mold. An example of a bond shear specimen post testing showing the clear distinction between new material and substrate can be seen in Figure 3-6**.**

Figure 3-6: Bond Shear Strength Specimen

3.3.6 Durability & Freeze Thaw Conditioning

Durability of RSC in cold climate regions is critical to ensure that bridges constructed with ABC approaches have long serviceability and limited needs for extensive repairs. Further, one of the main objectives of the present study is to determine if use of membranes is necessary on ABC bridges to limit the potential for degradation of RSC connections used in VTrans bridges. This study adopted multicycle freeze-thaw (F/T) conditioning to assess the durability potential of RSCs. The ASTM C666 conditioning procedures were used to conduct rapid freeze-thaw conditioning of specimens. A companion specimen approach was used where for each mechanical test, one set of replicate specimens were stored in a curing room, and a second set were conditioned for 300 freeze-thaw cycles. At every 100 cycles, the conditioned samples were evaluated using surface resistivity measurements and mass loss in addition to visual observations and photographic evaluations to document degree of freeze-thaw damage. As per recommendation from project TAC, a 3% solution of sodium chloride was used for the F/T conditioning. This provided severe corrosion potential similar to actual bridge conditions when treated with salt during winter months.

The ASTM C666 conditioning procedures dictate prismatic specimens to be used, however the research team opted for cylindrical specimens in order to perform the compressive and bond shear tests described above. To best comply with ASTM C666, stainless steel molds were created with the intent to provide a small gap of 1/8 inch to 1/32 inch between the concrete specimen and the steel mold as required by ASTM C666. This was achieved by rolling the steel to the desired radius, then adding small diameter wires welded to the bottom of the mold, creating the required gap on all sides. These molds were inserted into the chamber for cylindrical molds to sit in. These molds can be seen in the accompanying Figure 3-7, Figure 3-8, Figure 3-9, and Figure 3-10 below.

Figure 3-7: Stainless Steel Mold for Freeze Thaw Conditioning Chamber

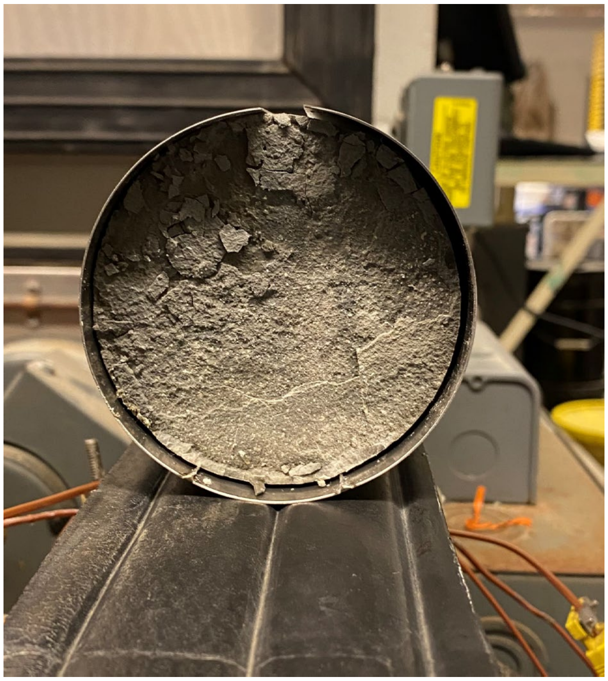

Figure 3-8: Stainless Steel Mold for Freeze Thaw Conditioning Chamber with Cylindrical Specimen Inserted

Figure 3-9: Stainless Steel Mold for Freeze Thaw Conditioning Chamber Placed Inside Freeze Thaw Chamber

Figure 3-10: Freeze Thaw Conditioning Chamber with Specimens Undergoing Conditioning

3.3.7 Surface Resistivity

Surface resistivity measurement of concrete is a non-destructive test to determine the permeability and ability of concrete to transmit ions (specifically, chloride ions) that can be detrimental in terms of corrosion potential for steel reinforcement. The ASTM C1876 (equivalent to AASHTO T-358) method that uses four-point Wenner probes was used. Due to the non-destructive nature of test, researchers were able to measure surface resistivity on specimens during the freeze-thaw conditioning process to assess changes in permittivity of RSC at 100, 200, and 300 cycles. In addition, resistivity measurements were taken at 7, 14 (start of F/T conditioning) and 28- days. Two samples were measured during each testing interval. Figure 3-11 shows this device and one of the specimens used for this test.

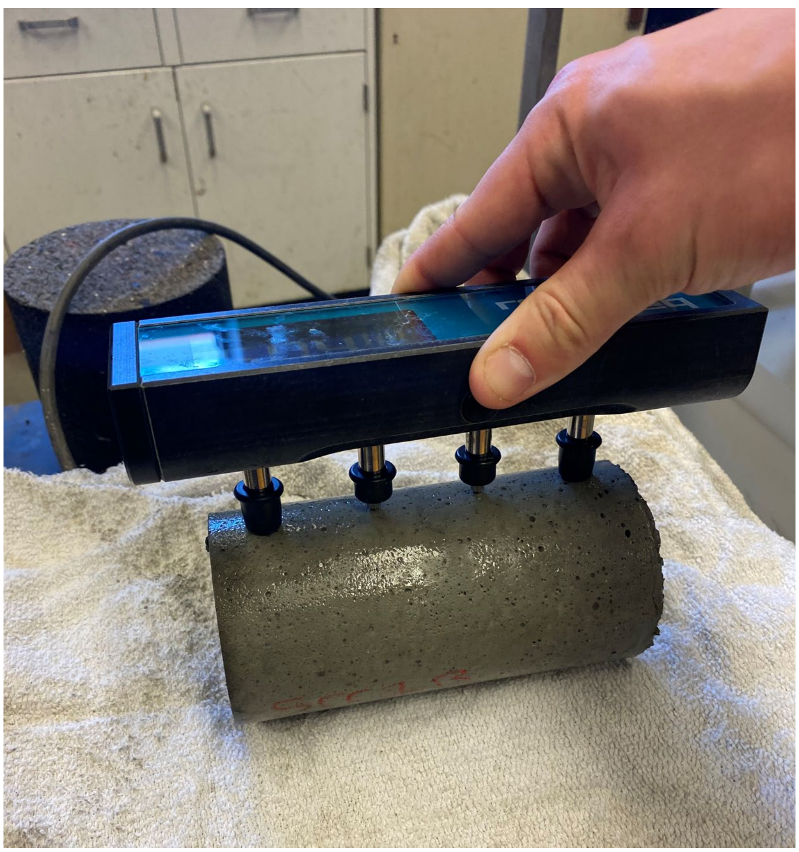

Figure 3-11: Surface resistivity test

CHAPTER 4: LABORATORY TEST RESULTS FOR PHASE-I EXPERIMENT (TASK-2)

4.1 INTRODUCTION

This chapter presents the laboratory measured properties for all the testing conducted in Phase I (Task-2) of this study. This chapter presents the results with brief descriptions to make some comparative evaluations between different mixtures evaluated in this task. However, the next chapter presents a more detailed analysis with respect to mix constituents and its effects on fresh and hardened RSC properties, including use of statistical testing to identify most influential constituents and their proportions with respect to their effects on the properties. Summary plots and discussions are presented in this chapter, as measured properties and data for all tests are provided in the appendix to this report.

4.2 TEST RESULTS

4.2.1 Fresh Properties

Fresh property results were consistently close to their target values for air content as well as spread/slump values. These results can be seen in Table 4-1. In several instances multiple batches were made with alterations of admixtures until the measured air content and workability were closer to the target values. In general, a maximum variation of 1% for air content, 1 inch for slump workability and 3 inch for spread workability was determined to be acceptable for this study. Visual stability index was also recorded for all SCC mixes. Two iterations saw a VSI of 0, indicating a highly stable mix with no bleeding and segregation, and two iterations had a VSI of 1, indicating no segregation and only minor bleeding. Overall, the VSI of SCC mixes were within acceptable parameters.

Table 4-1: Fresh Properties for All Mix Iterations

Mix Design	Target Air Content	Measured Air Content	Target Slump (inch)	Measured Slump (inch)	Target Spread (inch)	Measured Spread (inch)	Visual Stability Index
SCC-1	6.0%	5.2%	n.a.	n.a.	27	24.25	0
SCC-1a	6.0%	5.3%	n.a.	n.a.	23	20	1
SCC-1b	6.0%	5.9%	n.a.	n.a.	27	25	1
SCC-1c	6.0%	4.9%	n.a.	n.a.	18	15.5	0
PCC-2	6.0%	5.1%	8	7.75	n.a.	n.a.	n.a.
PCC-2a	6.0%	5.0%	6	6.25	n.a.	n.a.	n.a.
PCC-2b	4.5%	4.9%	8	8.25	n.a.	n.a.	n.a.
PCC-2c	7.5%	7.4%	6	6	n.a.	n.a.	n.a.
PCC-2d	4.5%	4.2%	9	9.5	n.a.	n.a.	n.a.
PCC-2e	6.0%	6.1%	8	8.5	n.a.	n.a.	n.a.
PCC-3	6.0%	5.4%	6	6.25	n.a.	n.a.	n.a.
PCC-3a	6.0%	5.3%	6	6.25	n.a.	n.a.	n.a.

n.a.: Not applicable.

4.2.2 Shrinkage

Requirements set forth by ASTM C596 dictate a maximum allowable shrinkage of 0.40%. All mix iterations except for PCC-2e had a lower shrinkage amount than this threshold. The PCC-2e mixture had the highest cementitious content of all iterations, which led to it slightly exceeding the maximum allowable shrinkage by 0.017%. These results can be seen in Figure 4-1. Overall results were favorable and indicated that shrinkage would not need to be tested during Phase II.

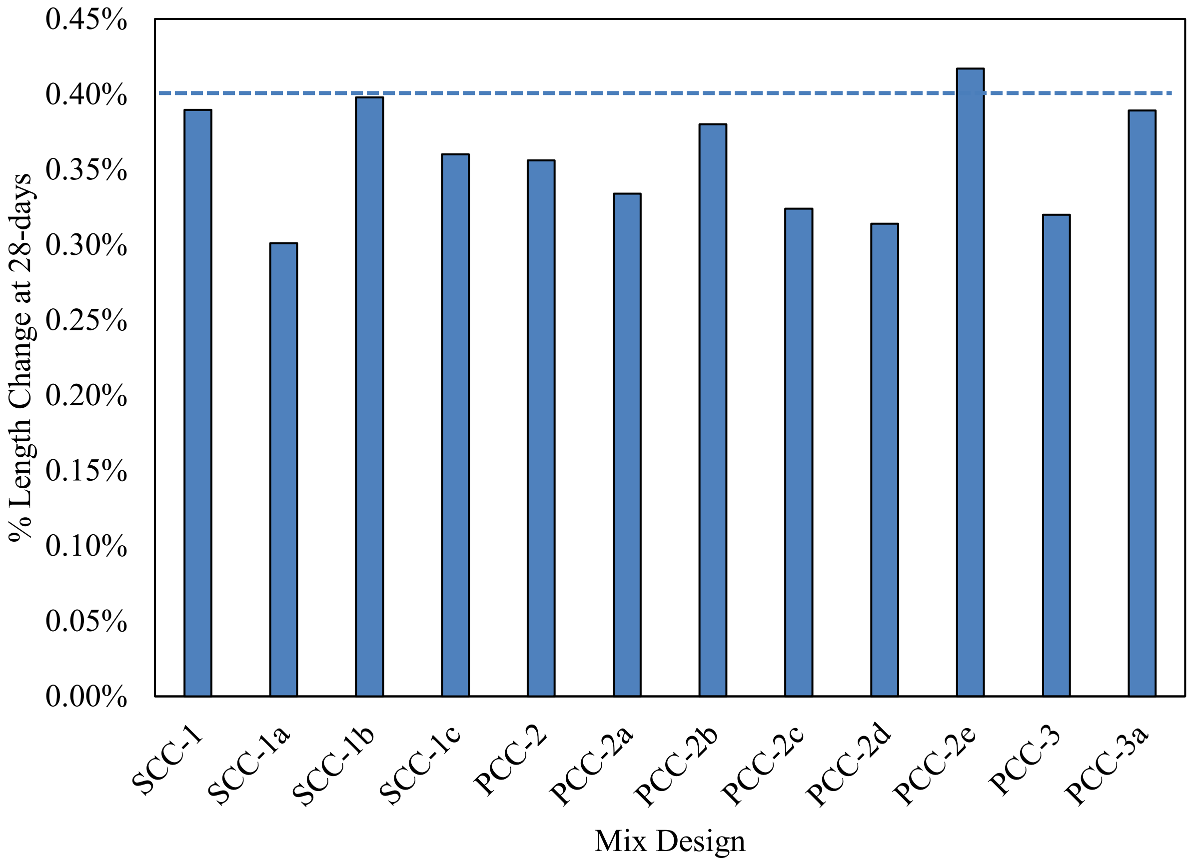

Figure 4-1: 28 Day Shrinkage Values for All Mix Iterations (threshold value shown with dashed line)

4.2.3 Flexural Strength

The modulus of rupture of the RSC mixes were evaluated to obtain additional mechanical performance parameters and can be seen in Figure 4-2. The moduli of rupture are important for these mixtures since field placed ABC connections can experience a high degree of bending moments imposed upon them. This measurement allows an insight on potential moment transfer capacities of these connections. The lab experimentation during Phase I yielded moduli results that significantly exceeded values for typical structural concrete, around 600-800 psi after 28 days. Based on this observation the flexural strength testing was not included during the Phase II (Task-3).

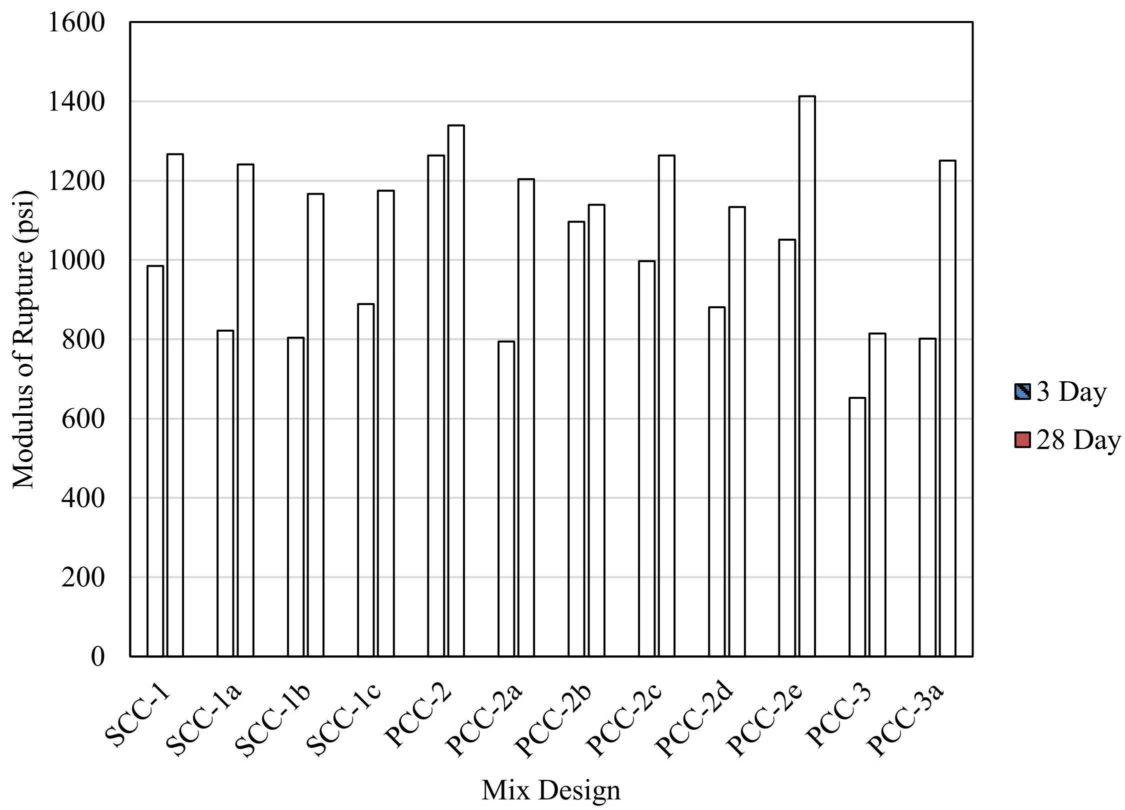

Figure 4-2: Flexural Strength at 3 and 28 days for All Mix Iterations

4.2.4 Compressive Strength

Compressive strength results are seen in Figure 4-3 and Figure 4-4. For comparison purposes, the compressive strength data of the three baseline materials (RS-010, RS-070 and RS-231) from the testing conducted on the field sampled materials (as part of the quality assurance process) are also plotted (shown with dashed lines). Variations from replicates tests also had low compressive strength, with a maximum variation of 500 psi. This indicates that the lab batches were well-mixed and homogenous, and testing procedures were repeatable. The minimum 2 day requirement of 3500 psi and 28 day requirement of 5000 psi are also indicted on the plots. A majority of the mix iterations met and exceeded these requirements, only the mix iterations on SCC did not meet the expected 2 day requirement of 3500 psi. The failing mixes still exceeded 3000 psi and thus were deemed to be acceptable for conducting durability testing and for use of their results in the subsequent statistical analyses. It should be noted that most of the field materials exhibited significantly higher strengths. It should also be noted that most of the tests on field materials were conducted with specimens that underwent accelerated curing (higher temperature).

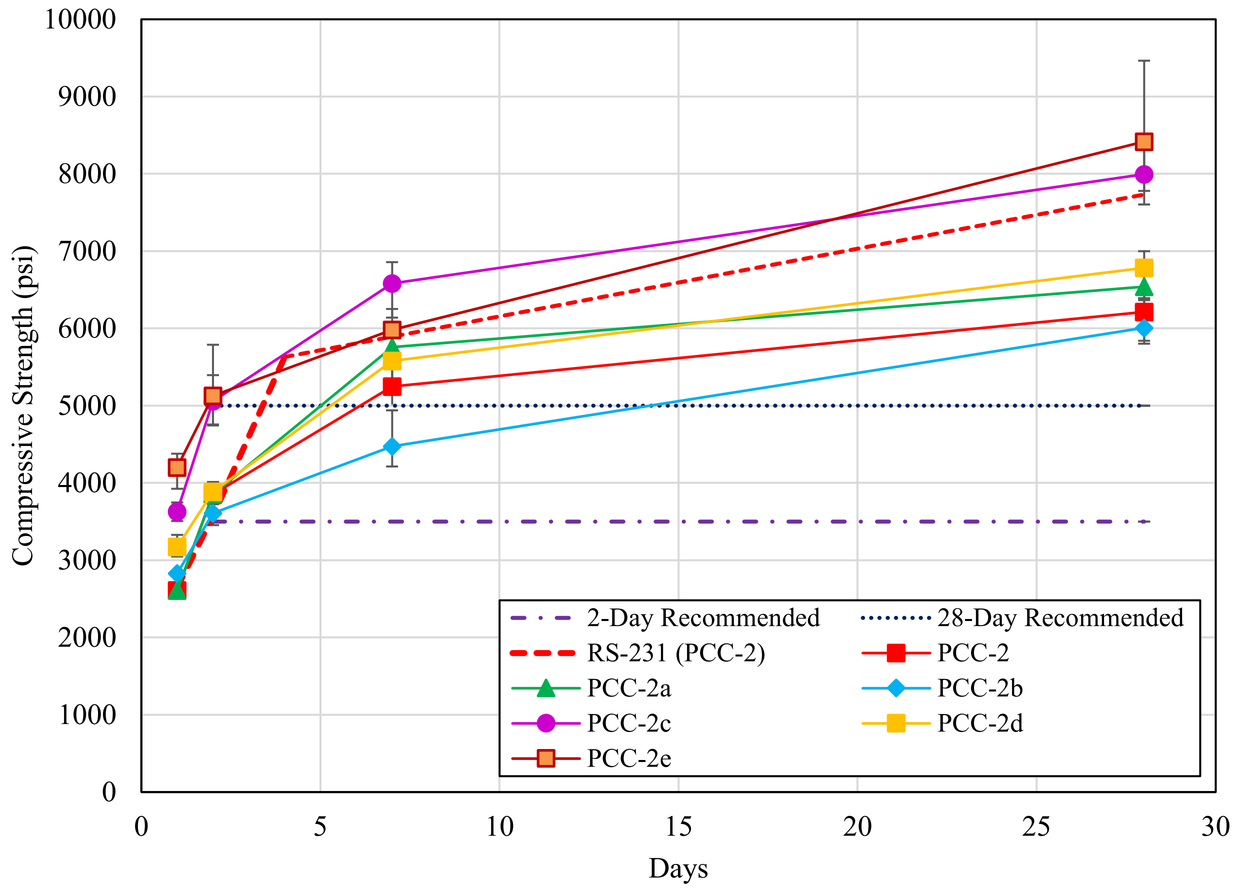

Figure 4-3: Compressive Strengths for PCC-2 Mixes (error bars indicate maximum and minimum values of replicate tests)

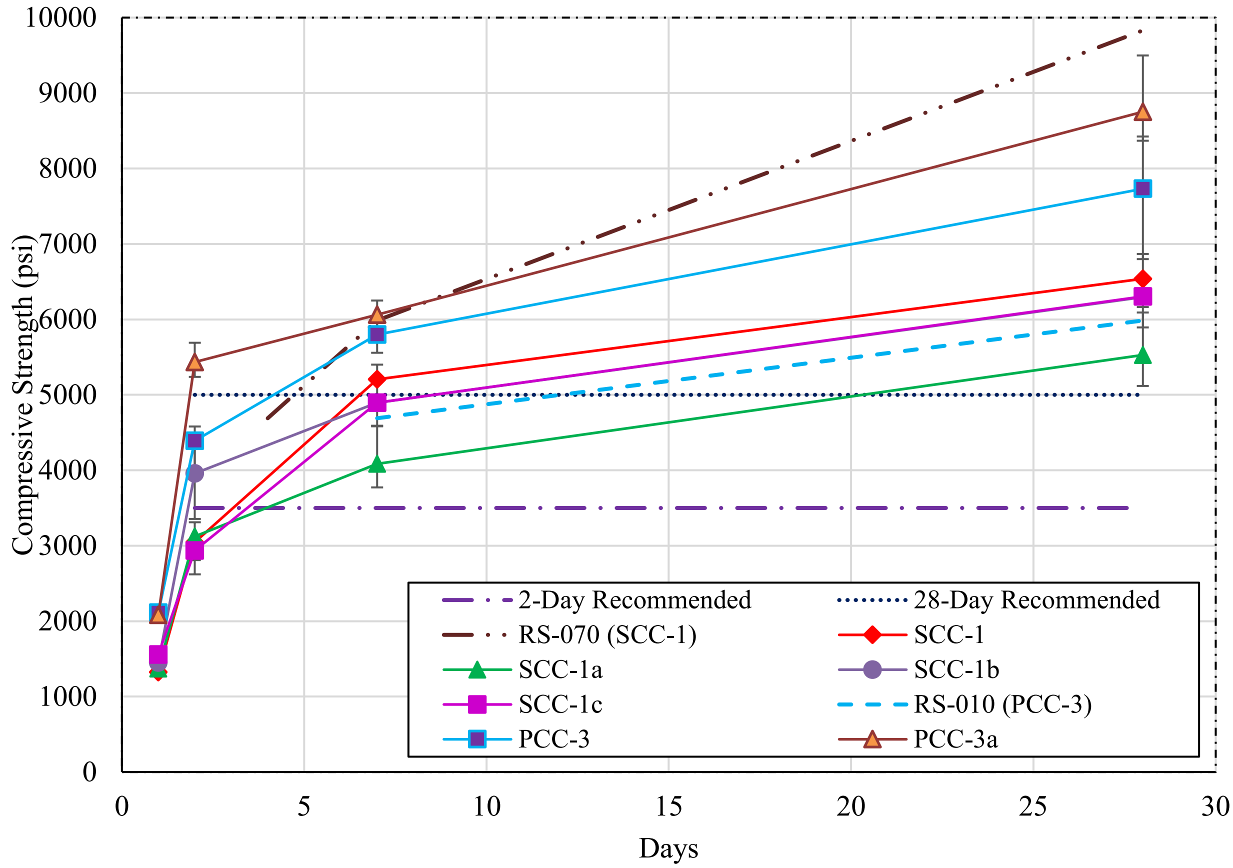

Figure 4-4: Compressive Strengths for SCC-1 and PCC-3 Mixes (error bars indicate maximum and minimum values of replicate tests)

4.2.5 Bond Shear Strength

The ACI repair manual recommends a minimum bond strength of 1000 psi using the slant shear bond test after 7 days, and 2900 psi after 28 days for repairs conducted on structural concrete. Results for bond shear strength meet or exceed these recommendations on average as shown in Figure 4-5 and Figure 4-6. Some replicates for PCC-2a and PCC-2c were below the 28 day value, but overall values exceeded recommendations. These results indicate that there would be little concern about debonding for the currently evaluated materials.

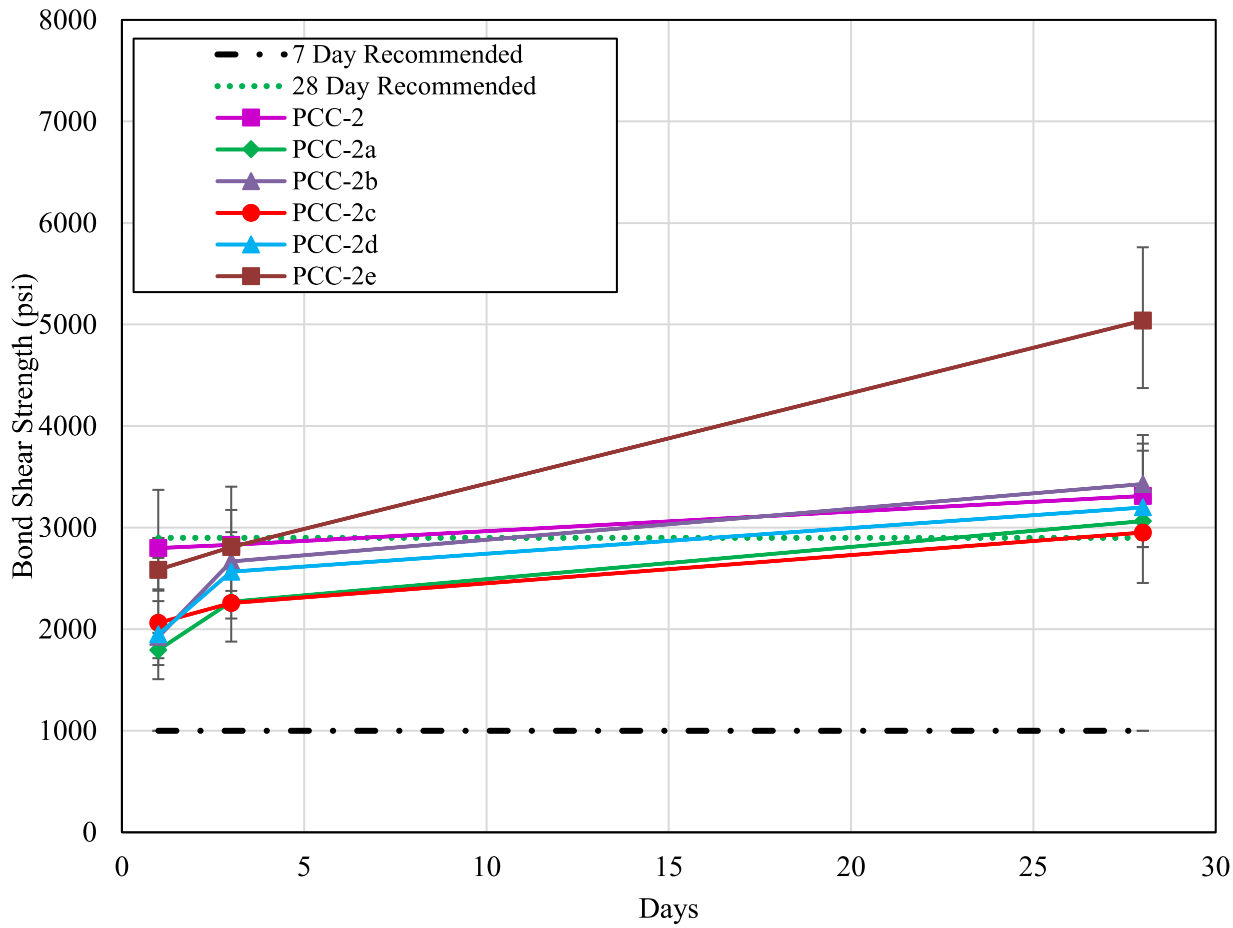

Figure 4-5: Bond Shear Strengths for PCC-2 Mixes (error bars indicate maximum and minimum values of replicate tests)

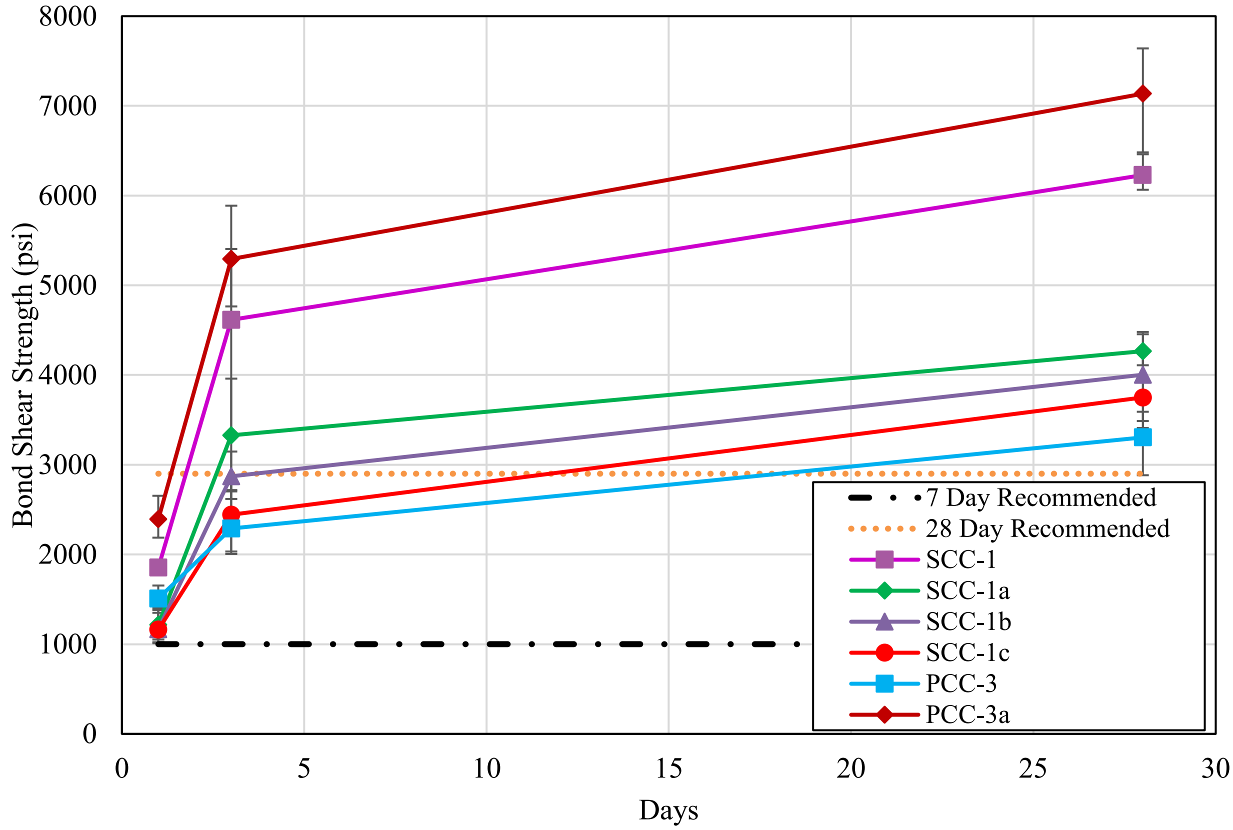

Figure 4-6: Bond Shear Strengths for SCC-1 and PCC-3 mixes (error bars indicate maximum and minimum values of replicate tests)

4.2.6 Durability

Mass loss results from the freeze-thaw conditioning generally show 1%-2% mass loss for cylindrical compression samples at 100 cycles, 3%-5% at 200 cycles, and 4%-8% at 300 cycles as seen in Figure 4-7. On average, mixes with higher cement content experienced greater mass loss, attributed to increased scaling on the surface of the specimens, with the notable exception of PCC-2e, the highest cementitious content batch of all mix iterations.

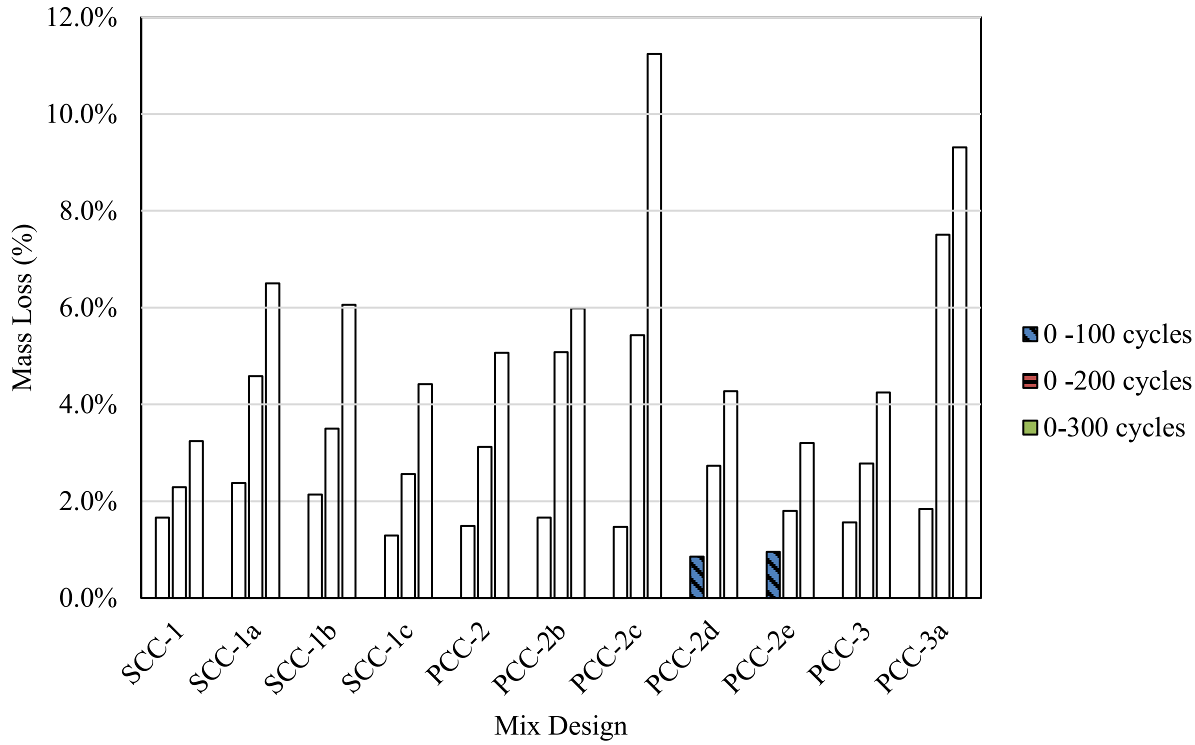

Figure 4-7: Mass Loss Measurements for Compressive Strength Specimens after Freeze-Thaw Conditioning for All Mix Iterations

Durability results for compressive strength specimens put through conditioning have shown specimens retained on average over 90% strength compared to unconditioned specimens. Indicating the conditioning of specimens has not had a large effect on compressive strength. These results can be seen in Figure 4-8.

Durability results for SCC-1 and PCC-3 bond shear strength specimens put through freeze thaw conditioning have seen an average of 90% bond shear strength retention when compared to unconditioned specimens. PCC-2 bond shear specimens have retained 40% strength due to some specimens' bonds breaking during the conditioning process. These breaks were directly on the bond shear connection and were not a resultant of external stress, but rather the result of the bond shear connection degrading and eventual breakage over the course of the freeze thaw conditioning. These results can be seen in Figure 4-9. An example of specimens before and after conditioning, along with the bond shear breakage seen in the chamber, are shown in in Figure 4-10, Figure 4-11, Figure 4-12, and Figure 4-13.

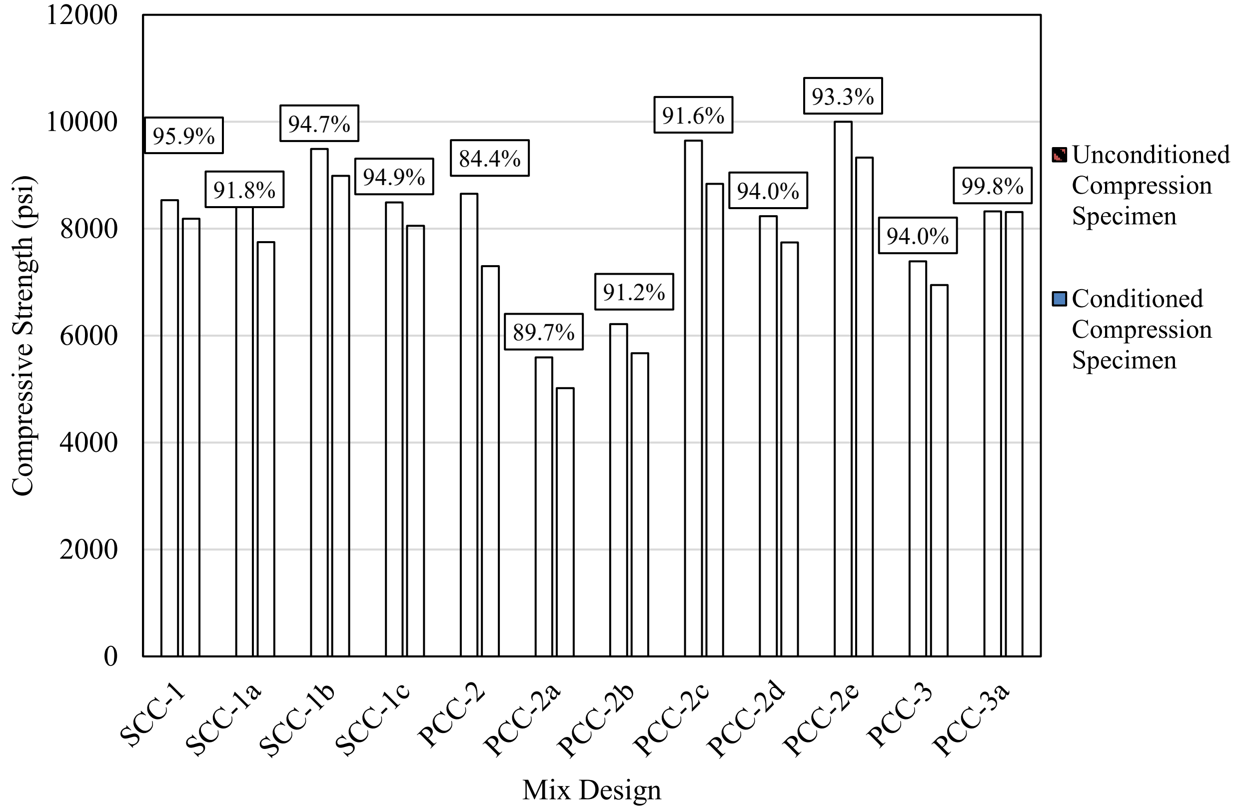

Figure 4-8: Durability Results for Compressive Strength Specimens (numbers on top of bars indicate the value of conditioned compressive strengths as percent of unconditioned compressive strengths)

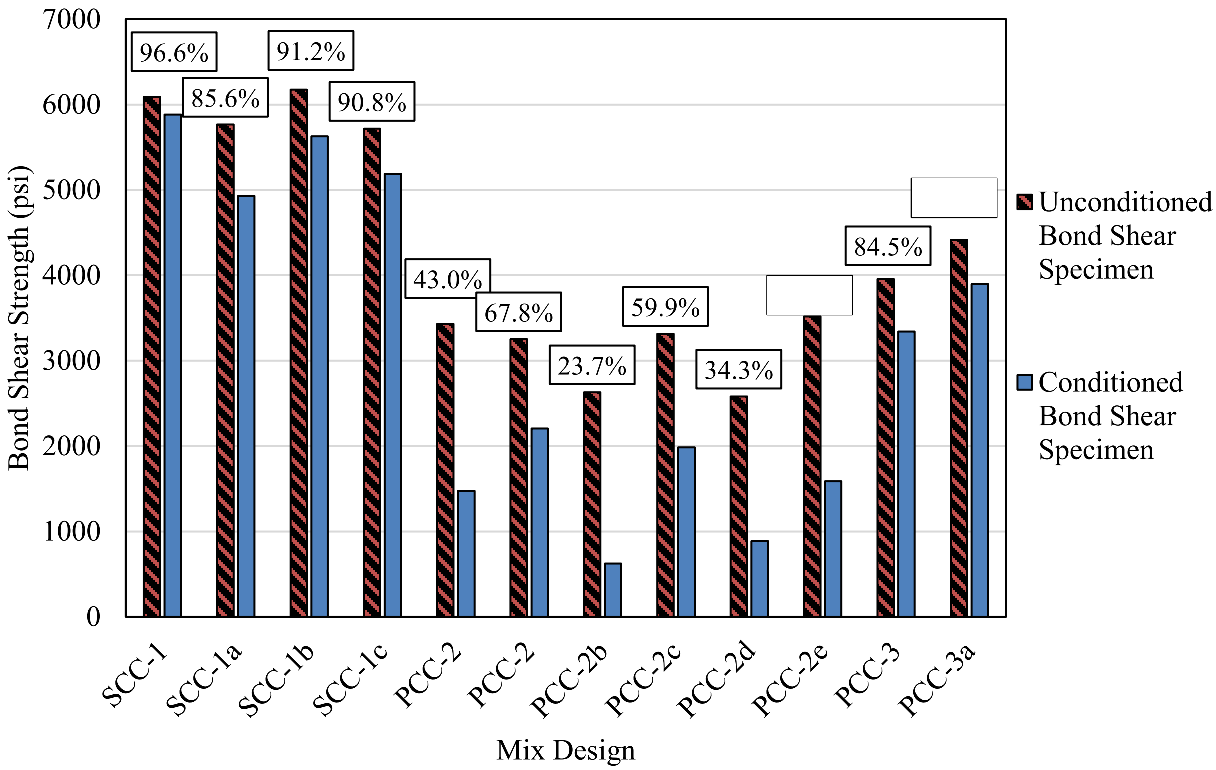

Figure 4-9: Durability Results for Bond Shear Strength Specimens (numbers on top of bars indicate the value of conditioned compressive strengths as percent of unconditioned compressive strengths)

Figure 4-10: Mix Iteration PCC-2d Compressive Strength Specimens Before Conditioning

Figure 4-11: Mix Iteration PCC-2d Compressive Strength Specimens After Conditioning

Figure 4-12: Mix Iteration PCC-2d Bond Shear Strength Specimens Before Conditioning

Figure 4-13: Mix Iteration PCC-2d Bond Shear Strength Specimens After Conditioning

4.2.7 Surface Resistivity

Results of mix iterations for surface resistivity can be seen in Figure 4-14. Surface resistivity measurement results are plotted for control samples at 7, 14 and 28 days and companion freeze-thaw conditioned samples after 100, 200 and 300 cycles. Surface resistivity values increase until 100-200 cycles, indicating continued C-S-H growth and reduction in chloride ion penetration potential. After 100-200 cycles, the values level off or slightly decrease. Almost all measurements exceeded 5 kΩ (very low permeability category). A minimum value of 5 kΩ is used by several DOTs in United States, for example the New Hampshire Department of Transportation (2015) uses this threshold for concrete exposed to severe freeze-thaw conditions along with use of deicing chemicals.

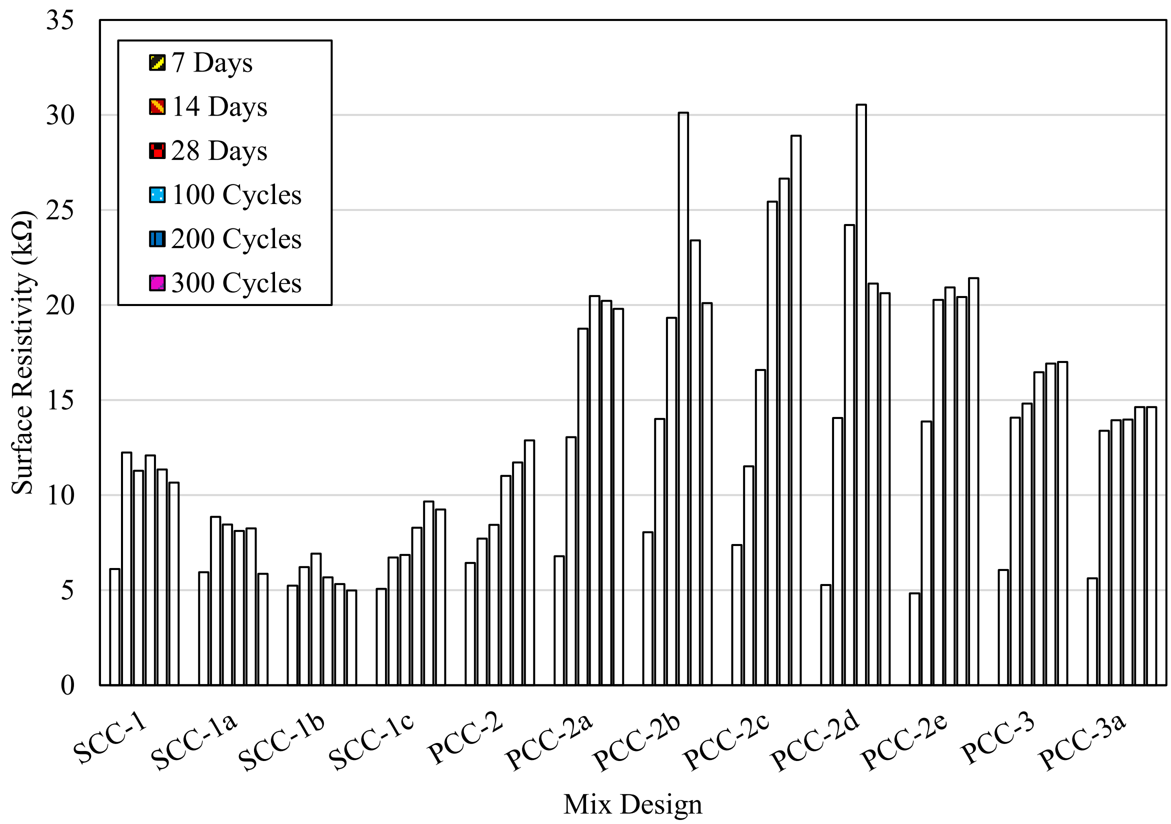

Figure 4-14: Surface Resistivity for All Mix Iterations

CHAPTER 5: DATA ANALYSIS FOR PHASE-I EXPERIMENT (TASK-2)

5.1 INTRODUCTION

This chapter presents an analysis of all the laboratory measurements from Phase I (Task-2) using statistical data analysis as well as through assessment of visual relationships between various parameters. This analysis resulted in developing preliminary findings with respect to durability of currently used RSC by VTrans as well as helped design an experiment for further evaluation in Phase II (Task-3), and provided insight on proportion based RSC mix design limits.

5.2 MULTIVARIATE ANALYSIS INPUTS

Using mix design variables incorporated into the experimental plan and laboratory experimentation results, a multivariate analysis was conducted to assess which variables were significant and how they affected certain results. A Pearson's correlation matrix was generated to find significant relationships between variables, a subset of which (not fully shown due to its size) can be found in Table 5-1. A Pearson's correlation matrix provides the coefficients of linear correlation between a set of variables (ranging from -1 to 1) as seen in the Table. Values approaching 1 represent a greater linear correlation between the two parameters, while a value closer to -1 indicates an inversely proportional linear correlation. A value closer to 0 indicates little to no correlations between the parameters. This allowed the research team to assess the mix design attributes that may significantly have affected the laboratory measured parameters, in doing so, effects of mix design on material properties can be assessed. Direct laboratory results were used, along with multiple fit models applied to the data, such as a logarithmic model fit to early age (1,2, and 7 day) compressive strength evolution, and a linear fit to 3 and 28 day bond strength data. This allowed analysis of the growth rate of compressive and bond shear strength. A table of the lab results used in the analysis can be seen in Table 5-2**.**

Table 5-1: Sample of Pearson's Correlation Matrix Generated for Phase I (shading indicates strength of correlation, with darker shading indicating a greater strength of correlation)

Parameter	*Cement Content*	*SCM Content*	*% PC Replacement*	*w/cm ratio*	*Plastic Temperature (°F)*	*Curing Temperature (°F)*
Compressive Strength – 2-Day	0.360	0.340	0.044	-0.584	0.020	-0.054
Compressive Strength – 28-Day	0.428	0.182	-0.294	-0.692	0.153	0.086
Early Age Comp. Strength- A value	0.234	0.300	0.153	-0.537	0.247	0.174
Early Age Comp. Strength– C value	0.196	0.116	-0.085	-0.745	-0.223	-0.282
Bond Shear 28-Days	-0.077	0.409	0.744	0.298	0.080	-0.007
Surface Resistivity - 7-Day	-0.478	-0.578	-0.257	0.049	0.382	0.515
Surface Resistivity - 14-Day	-0.486	-0.477	-0.087	0.000	0.436	0.544
Surface Resistivity - 28-Day	-0.221	-0.400	-0.327	0.035	0.371	0.504
Surface Resistivity - 100 Cycles	0.158	0.009	-0.200	-0.012	0.151	0.252
Surface Resistivity - 200 Cycles	0.398	0.122	-0.348	-0.120	-0.118	-0.039
Surface Resistivity - 300 Cycles	0.547	0.248	-0.352	-0.188	-0.395	-0.352
Durability - Avg Compressive Strength - % Difference	-0.646	-0.337	0.348	0.588	0.325	0.390
Durability - Avg Bond Shear Strength - % Difference	-0.994	-0.793	0.105	-0.023	0.061	0.119
Mass Loss 0-100 Cycles	-0.049	0.447	0.765	0.429	-0.217	-0.230
Mass Loss 100-200 Cycles	0.428	0.416	0.071	0.043	-0.311	-0.390
Mass Loss 200-300 Cycles	-0.475	0.041	0.706	0.467	-0.383	-0.349

Table 5-2: Multivariate Analysis Lab Result Inputs

Laboratory Testing Properties	
Lab Test	***Parameters***
Compressive Strength	• 2- & 28-day measurements • Early age strength gain rate: A and C parameters from logarithmic model (f'c=A*ln(t)+C) for 1-, 2-, and 7-days
Bond Shear Strength	• Strength gain rate: • M and B parameters from linear model (fbs=M*x+B) for 3 and 28 days • 28-day measurements
Surface Resistivity	• 7, 14, 28-days • 100, 200, 300 freeze-thaw cycles
Durability	• Average compressive strength & bond shear strength • Conditioned (300 freeze-thaw cycles) and unconditioned specimens • Change between conditioned (300 freeze-thaw cycles) and unconditioned samples
Mass Loss	• 0, 100, 200, 300 freeze-thaw cycles

Through above shown correlation analysis, key mix variables that played significant roles in desired and undesired outcomes were determined. Primary variables were total cementitious content, total Portland cement content, total SCMs, and percent of Portland cement replacement with SCMs (% PC replacement) as these were the variables used to develop the mix designs.

5.3 ANALYSIS RESULTS

5.3.1 Portland Cement & Compressive Strength

Figure 5-1 shows how the compressive strength changes with cementitious content. Data analysis from Phase I showed that approximately 800 lbs./yd^3 of cementitious content achieved desired compressive strength of 3500 psi at 2 days and ensured that the strength exceeded 5000 psi at 28 days. In Phase II, 800 lbs./yd^3 achieved the 2 day desired strength for 7 out of 8 mix iterations. Overall, greater amounts of cementitious content led to a higher compressive strength, which was expected as cementitious contents are the key factor for strength gain in concrete. Both phases indicated that for every 100 lbs./yd^3 of cementitious content added, compressive strength increased by approximately 500 psi.

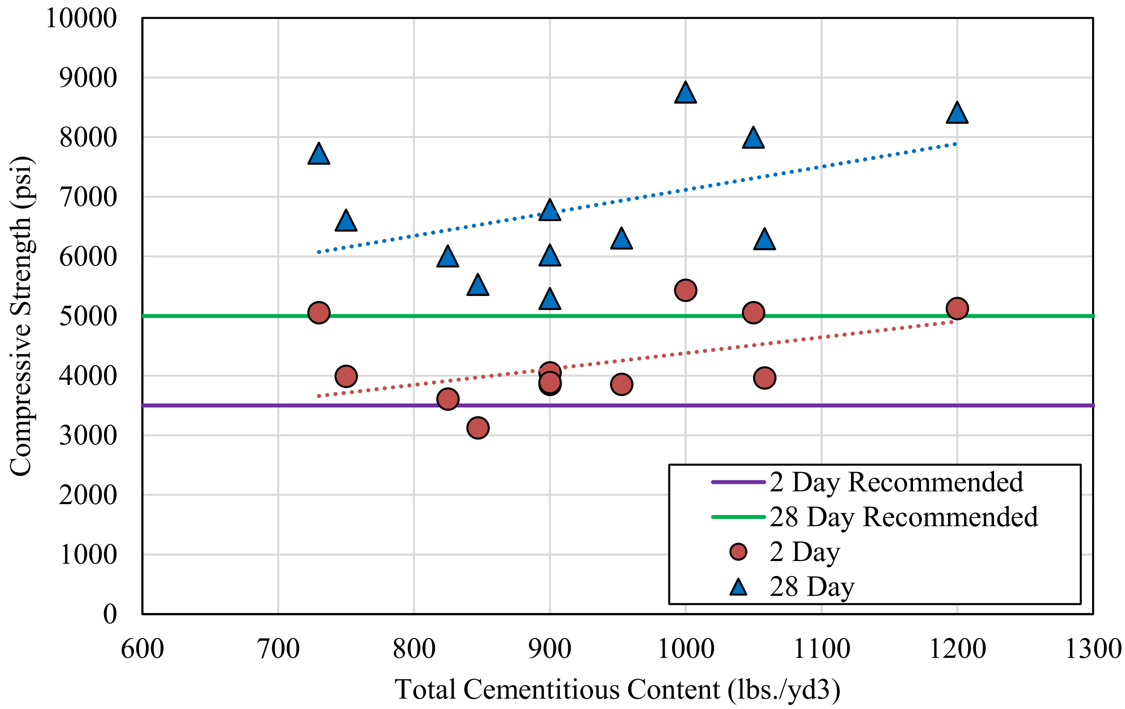

Figure 5-1: Correlation of Total Cementitious Content and 2 & 28 Day Compressive Strength

5.3.2 %PC Replacement & Bond Shear Strength

Analysis showed that % PC replacement had a major effect on bond shear strength with and without freeze thaw conditioning as seen in Figure 5-2. When samples were unconditioned, the majority specimens resulted in bond shear strength values exceeding the 2900 psi ACI repair manual recommendation. With freeze thaw conditioning, multiple PCC-2 mix iterations in Phase I had lower durability bond shear values due to breakage of specimens in the chamber as a result of degradation to their bond connections during conditioning. An example of these breaks along the bond connection can be seen in Figure 4-13. Overall correlation results appear to indicate a quadratic correlation, where very little %PC replacement or high amounts of replacement generate favorable bond shear durability, however around 25%-30% replacement can result in bond connection degradation. This relationship was used to develop %PC replacement values for the Phase II (Task-3) experimental plan, discussed in the following chapter.

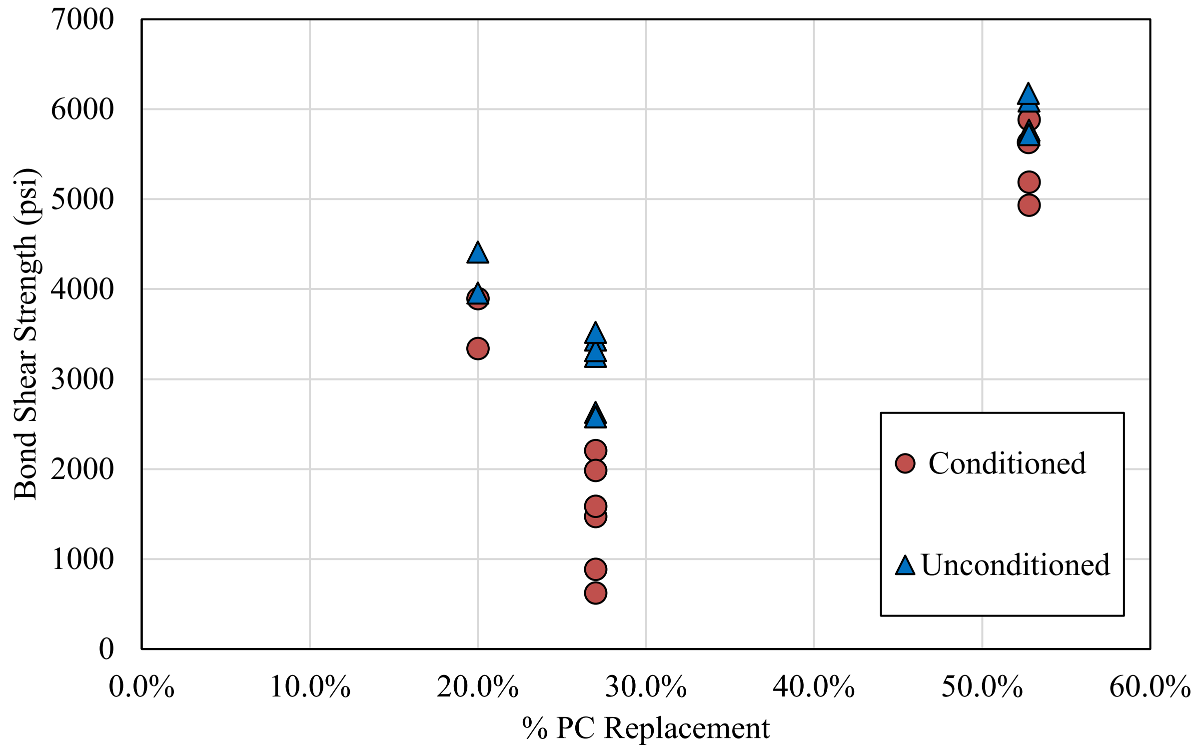

Figure 5-2: Correlation of %PC Replacement and Durability Bond Shear Strength

5.3.3 %PC Replacement & Surface Resistivity

Analysis indicated that increasing %PC Replacement in mix iterations resulted in decreased surface resistivity values, as seen in Figure 5-3 and Figure 5-4. Mix iterations that saw 50% PC replacement or more, had surface resistivity values approaching 5 kΩ after extended conditioning. Limiting %PC replacement would result in better surface resistivity values, however nearly all measurements for mix iterations remained above the 5 kΩ minimum requirement. As a result, higher %PC replacement can be utilized so long as values do not exceed a %PC replacement of greater than 50% to prevent surface resistivity concerns.

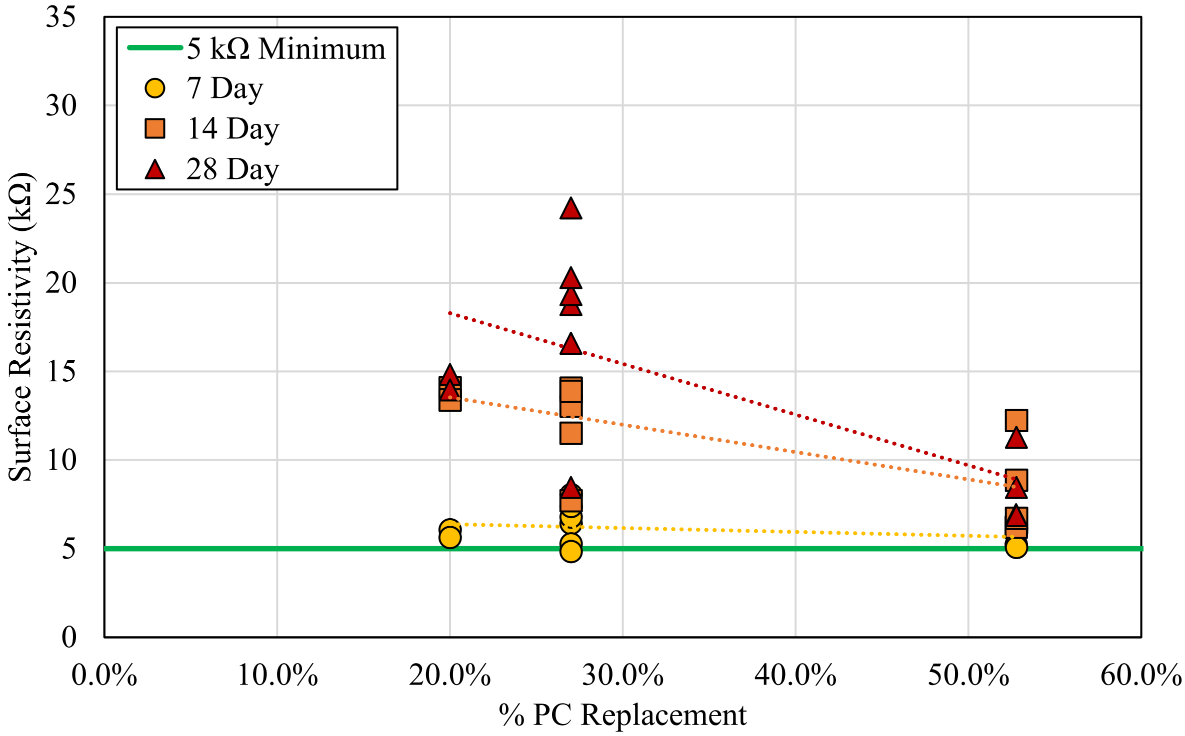

Figure 5-3: Correlation of %PC Replacement and Surface Resistivity without Freeze Thaw Conditioning

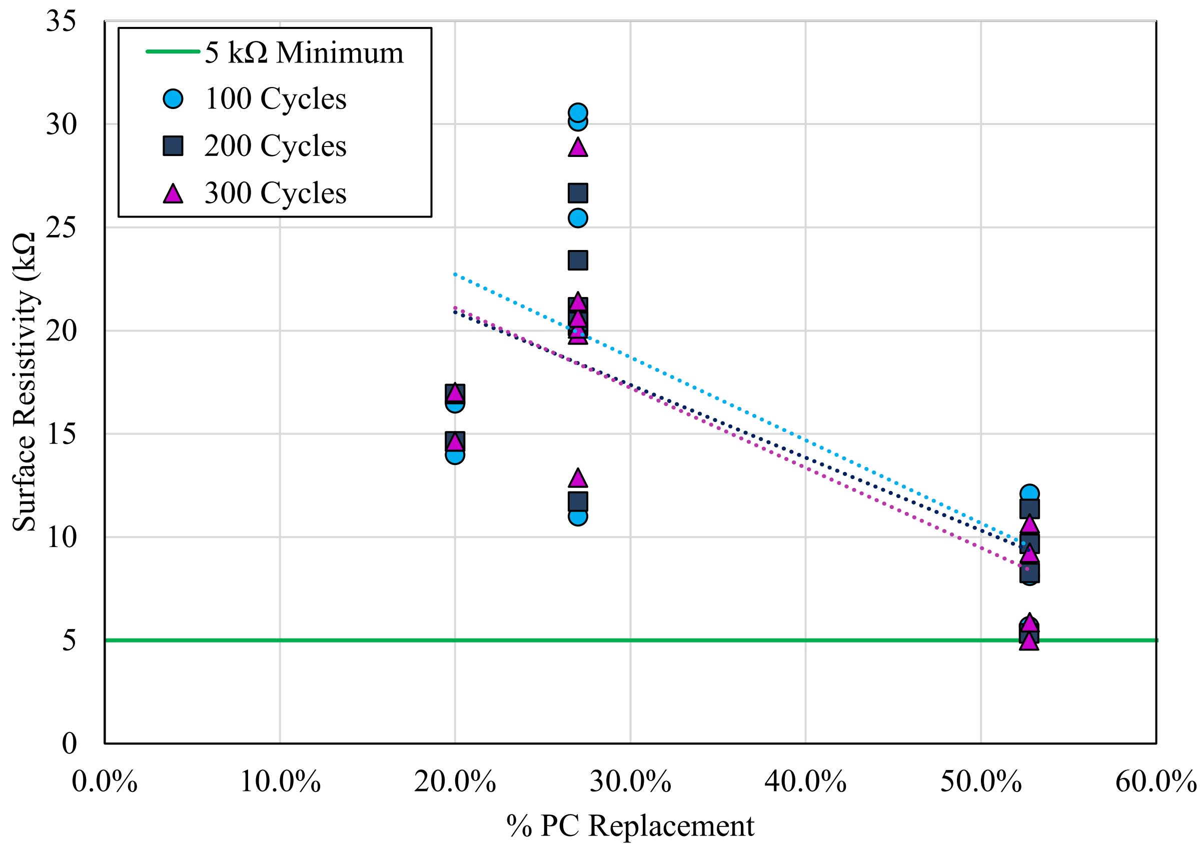

Figure 5-4: Correlation of %PC Replacement and Surface Resistivity with Freeze Thaw Conditioning

5.3.4 Total Portland Cement & Surface Resistivity

Figure 5-5 shows that greater amounts of Portland cement resulted in higher surface resistivity values as curing time increased. This effect increased throughout the freeze thaw conditioning process as seen in Figure 5-6 likely due to the specimen samples still curing while being partially submerged in the freeze thaw chamber. Batches above 400lbs. of Portland cement exceeded this threshold throughout the evaluation period except for SCC-1b, which was close to 5kΩ after 300 cycles. During the conditioning process, the data begins to become more sporadic, likely due to many of the samples having various amount of scaling on the specimen and damage to them during the process as seen in Figure 4-11. This in turn results in more variance in the degree of resistivity as the surface resistivity meter indirectly measures permeability and the concrete's ability to resist chloride ions, and the scaling seen over the course of conditioning results in a rougher surface which is harder for the meter to accurately assess.

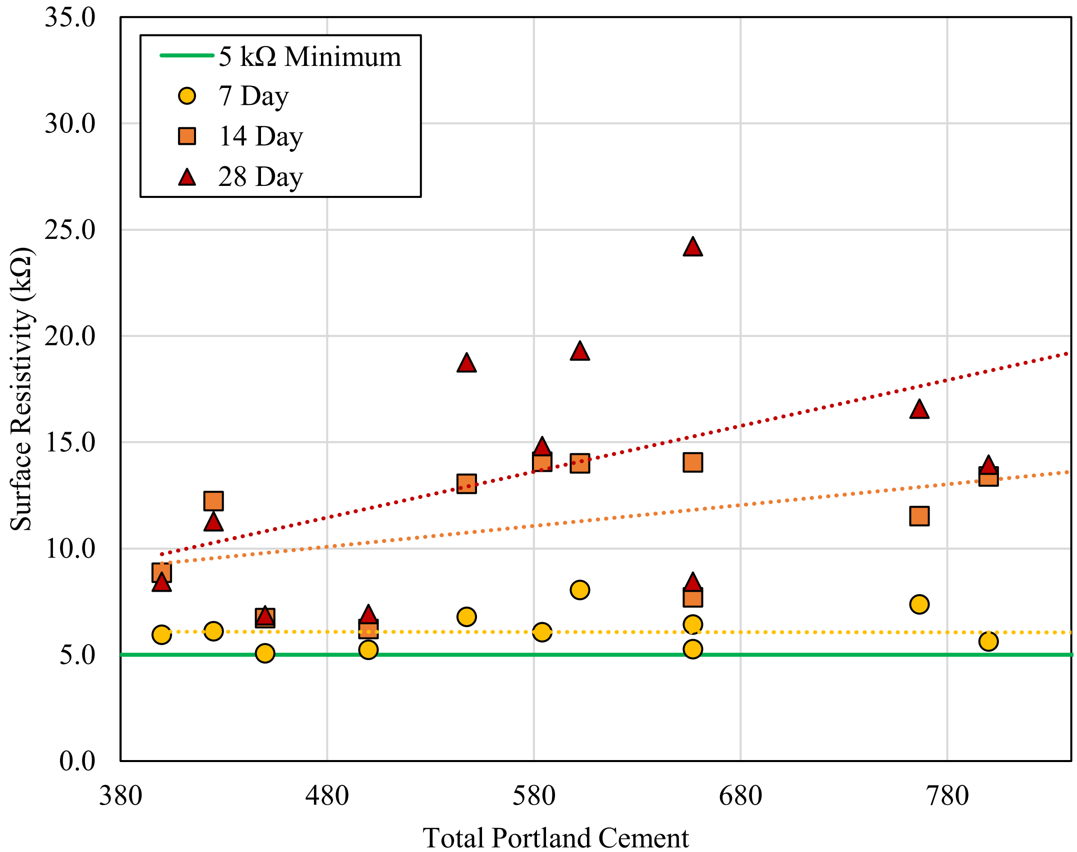

Figure 5-5: Correlation of Total Portland Cement and Surface Resistivity without Freeze Thaw Conditioning

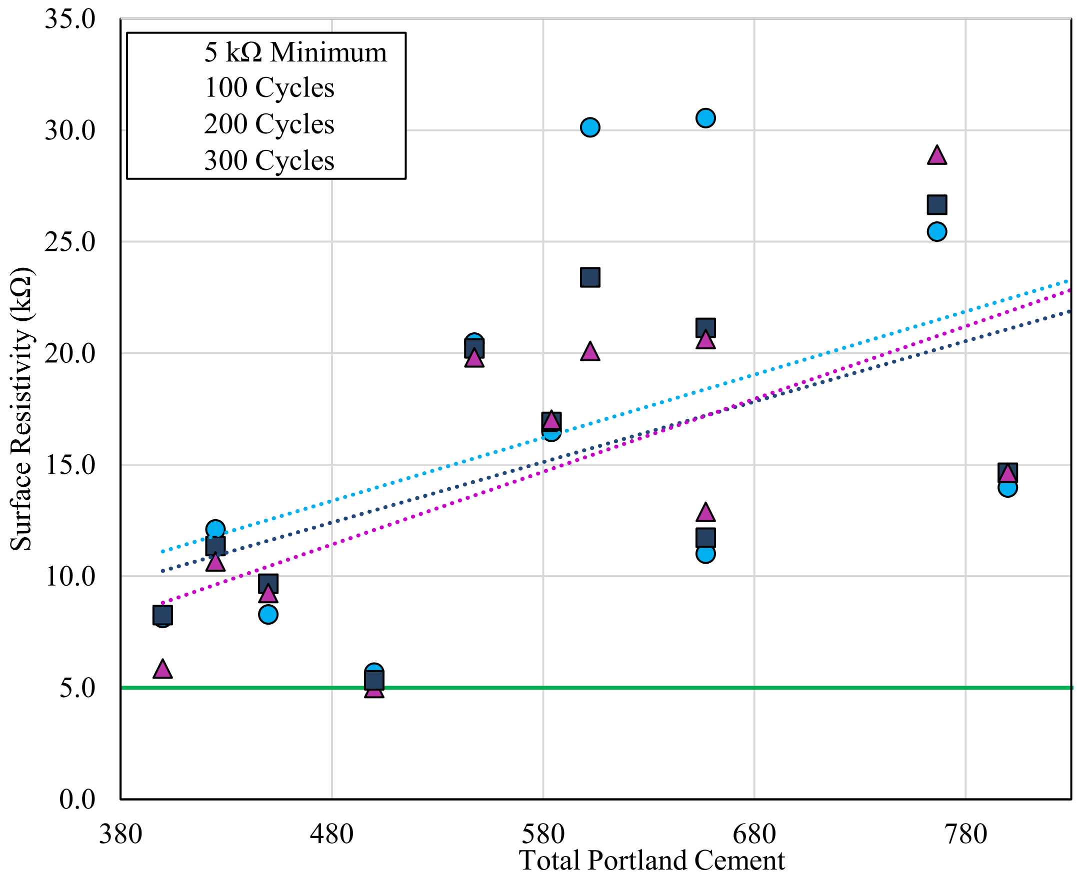

Figure 5-6: Correlation of Total Portland Cement and Surface Resistivity with Freeze Thaw Conditioning

CHAPTER 6: EXPERIMENTAL PLAN FOR PHASE-II LAB EVALUATION (TASK-3)

6.1 INTRODUCTION

To further assess the durability of field cast connections in VTrans' ABC projects, the data analysis conducted for Phase I (Task-2) was used to develop a Phase II (Task-3) experimental plan to better establish mix design limits for VTrans.

6.2 EXPERIMENTAL PLAN

On the basis of findings from Phase I (Task 2) and through feedback of project TAC, an experimental plan was prepared for Phase II (Task 3), as seen in Table 6-1, Table 6-2, and Table 6-3, and a sample testing calendar of scheduled laboratory assessments can be seen in Table 6-4.

Table 6-1: Task-3 Mix Design Attributes for Cementitious Quantities (blue shading indicates alterations to base mix design)

ID	*Total Cementitious Content (lbs./yd³)*	*Total Portland Cement (lbs./yd³)*	*% PC Replacement*	*Total Slag (lbs./yd³)*	*Total Class F Fly Ash (lbs./yd³)*	*Total Silica Fume (lbs./yd³)*
T3-M01	800 (P,F,FA)	450	44%	-	312	40
T3-M02	800 (P,F,S)	450	44%	312	-	40
T3-M03	900 (P,F, FA)	504	44%	-	351	45
T3-M04	800 (P,F,FA)	416	48%	-	344	40
T3-M05	800 (P,F,FA)	450	44%	-	312	40
T3-M06	800 (P,F,FA)	450	44%	-	312	40
T3-M07	800 (P,F,FA)	450	44%	-	312	40
T3-M08	800 (P,F,FA)	450	44%	-	312	40

P: Portland cement; S: Slag; F: Silica fume; FA: Fly Ash

Table 6-2: Task-3 Mix Design Attributes for w/cm Ratio, Workability, and Temperatures (blue shading indicates alterations to base mix design)

ID	*w/cm ratio*	*Target Workability (Slump)*	*Plastic Temperature (°F)*	*Curing Temperature (°F)*
T3-M01	0.325	7	70	77
T3-M02	0.325	7	70	77
T3-M03	0.325	7	70	77
T3-M04	0.325	7	70	77
T3-M05	0.325	9	70	77
T3-M06	0.30	7	70	77
T3-M07	0.35	7	70	77
T3-M08	0.325	7	85	92

Table 6-3: Phase II Mix Design Attributes for Admixtures (blue shading indicates alterations to base mix design)

ID	*Air Entrainer (oz/cy)*	*High Range Water Reducer (oz/cwt)*	*Workability Retainer (oz/cwt)*	*Shrinkage Reducing Admixture (oz/yd^3)*
T3-M01	40	8	6	128
T3-M02	40	8	6	128
T3-M03	40	9	6	128
T3-M04	40	8	6	128
T3-M05	40	9	6	128
T3-M06	40	8	6	128
T3-M07	40	8	6	128
T3-M08	40	8	6	128

Table 6-4: Task-3 Typical Testing Schedule

Week	*Laboratory Testing*
Week 1	Day 1: Compression test Day 2: Compression test
Week 2	Day 7: Compression test, surface resistivity test
Week 3	Day 14: Freeze Thaw conditioning begins
Week 4	Day 28: Compression test, bond shear strength test, surface resistivity test
Week 5-8	Freeze thaw mass-loss & surface resistivity measurements at 100 cycle intervals
Week 8	Day 49*: Freeze thaw conditioned/unconditioned samples durability compression test and shear bond strength test (* dependent on F/T chamber run time)

6.2.1 Cementitious Content

Cementitious content of any concrete is one of the most important variables since it directly impacts cost, strength, and durability. Between the eight Phase II (Task-3) mix designs, the experiment evaluated the use of Portland cement with SCMs (slag and silica fume). The baseline mixture had a total of 800 lbs./yd^3 of cementitious content and utilized Type I/II Portland cement (56%), along with fly ash (39%) and silica fume (5%). One variation increased the overall cementitious content to 900 lbs./yd^3.The slag corresponding to ASTM C989 class 100 and silica fume conforming to ASTM C1240 has been used in this study.

6.2.2 %PC Replacement and SCM

Phase I (Task-2) analysis indicated %PC replacement played a key role in bond shear strength after freeze thaw conditioning was complete, where lower amounts of %PC replacement (25%-40%) resulted in durability bond shear concerns. The %PC replacement that exceeded 50% resulted in surface resistivity values approaching the minimum threshold of 5 kΩ throughout the 28 day curing period and freeze thaw conditioning. As a result, a %PC replacement of 44% was chosen, with one iteration increasing to 48%.

6.2.3 Target Workability

Results from Phase I (Task-2) showed little issues with workability. Discussions with VTrans and results from Phase I (Task-2) dictated a baseline workability of 7 inch slump, and one variation increasing slump to 9 inch. Workability adjustments were mostly achieved through high-range water reducer, HRWR (ASTM C494 Type F) along with a commercially available workability retaining admixture.

6.2.4 w/cm Ratio

Phase I (Task-2) consisted of 3 distinct w/cm ratios between the 3 baselines and were not changed in their respective iterations. These w/cm ratios were 0.297 for SCC-1, 0.315 for PCC-2, and 0.35 for PCC-3. No significant correlations relating to w/cm ratio were found in the Phase I (Task-2) analysis, and through discussions between VTrans and the research team, a baseline w/cm ratio of 0.325 was decided upon, with one mix iteration increasing the w/cm ratio to 0.35, and another decreasing it to 0.30.

6.2.5 Plastic & Curing Temperatures

Through discussions between VTrans and the research team, VTrans expressed interest in seeing the results of a mix iteration being cast and cured at a higher temperature than typically seen in lab to reflect hotter construction days often seen during the summer months. A plastic temperature baseline of 70°F was chosen as it was the average temperature taken of plastic concrete mixes during Phase I (Task-2) experimentation. A baseline curing temperature of 77°F was chosen as it was the curing temperature for all mixes during Phase I (Task-2). Both curing and plastic temperature were increased by 15°F for one mix iteration, to 85°F and 92°F respectively.

A higher plastic temperature was achieved by pre-heating all aggregate prior to batch creation for T3-M08. A higher curing temperature was achieved by submerging specimens into water within plastic containers and curing them inside an oven at the desired curing temperature for the duration of the experiment. It is important to note that companion specimens (unconditioned specimens) to those that were going be conditioned were removed from the oven at 14 days and placed into the standard curing room.

6.3 LABORATORY EXPERIMENTATION PLAN

The laboratory experimentation plan that was used to assess eight materials discussed in the previous section is presented in this section. As with Phase I, laboratory experimentation in this phase was also conducted in two stages. In the first stage, designs were evaluated for some of the current requirements of the VTrans special provision for RSC. These included:

(1) Compressive Strength: Min. 5,000 psi at 28 days (additionally min. 3,000 psi at 2 days).
(2) Shrinkage: Max. 0.04%
(3) Workability and Air Content: According to the experimental design

Depending on the property that is not met, designs were altered prior to start of stage-2 evaluation. In stage-2 evaluation, the following testing was undertaken:

(1) Strength Evolution: Compressive evolution (1, 2, 7 and 28 day)
(2) Shrinkage
(3) Freeze-thaw (F-T) Conditioning Impacts: Conducted by making companion specimen and subjecting one set to rapid F-T cycling (ASTM C666) after 28 days of curing. The following tests were conducted:
    a. Surface resistivity prior to conditioning and at every 100 F-T cycles
    b. Mass-loss and visual observations at every 100 F-T cycles
    c. Compressive strength (conditioning and unconditioned specimen)
    d. Slant-shear bond tests (conditioned and unconditioned specimen)

Different lab test procedures for the experimentation used in this study are briefly described in the previous section (Section 3.3).

CHAPTER 7: LABORATORY TEST RESULTS FOR PHASE-II EXPERIMENT (TASK-3)

7.1 INTRODUCTION

This chapter presents the laboratory measured properties for all the testing conducted in Phase II (Task-3) of this study. This chapter presents the results with brief descriptions to make some comparative evaluations between different mixtures evaluated in this task. However, next chapter presents a more detailed analysis with respect to mix constituents and its effects on fresh and hardened RSC properties, including use of statistical testing to identify most influential constituents and their proportions with respect to their effects on the properties. Once again, comprehensive results from all laboratory evaluations are included in the appendix accompanying this report.

7.2 TEST RESULTS

7.2.1 Fresh Properties

Fresh property results were consistently close to their target values for air content as well as slump. T3-M08 had an increased plastic temperature target, and its measured value was only 1°F off. In general, a maximum variation of 1% for air content and 1 inch for slump workability was determined to be acceptable. These results can be seen in Table 7-1.

Table 7-1: Fresh Properties of All Mix Iterations

Mix Design	*Target Air Content*	*Measured Air Content*	*Target Slump (in)*	*Measured Slump (in)*	*Target Plastic Temperature (°F)*	*Measured Plastic Temperature (°F)*
T3-M01	6.0%	6.5%	7	7	77	70
T3-M02	6.0%	6.5%	7	6.75	77	67
T3-M03	6.0%	5.7%	7	7.25	77	70
T3-M04	6.0%	5.7%	7	8	77	71
T3-M05	6.0%	5.5%	9	10	77	69
T3-M06	6.0%	5.6%	7	7	77	70
T3-M07	6.0%	6.4%	7	6.25	77	66
T3-M08	6.0%	5.7%	7	6.5	92	91

7.2.2 Compressive Strength

Compressive strength results are seen in Figure 7-1. Variations from replicates tests were low for compressive strength, with a maximum variation of 800 psi. This indicates that the lab batches were well-mixed and homogenous, and testing procedures were repeatable. The minimum 2 day requirement of 3500 psi and 28 day requirement of 5000 psi are also indicted on the plots. A majority of the mix iterations met and exceeded these requirements, with only T3-M01 failing to meet the 3500 psi 2 day recommended target. The failing mix still exceeded 3000 psi and thus was deemed to be acceptable for conducting durability testing and for use of their results in the subsequent statistical analyses.

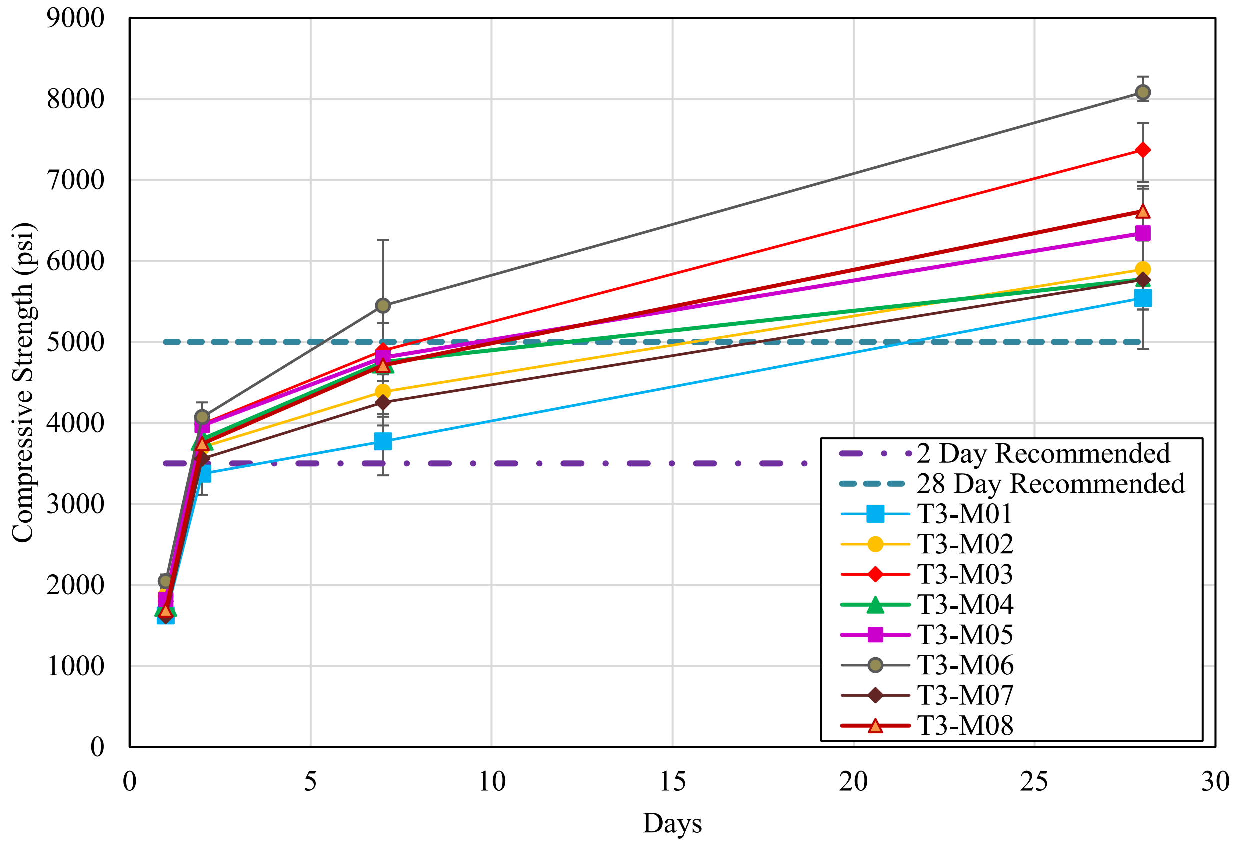

Figure 7-1: Compressive Strengths for All Mix Iterations (error bars indicate maximum and minimum values of replicate tests)

7.2.3 Bond Shear Strength

The ACI repair manual recommends a minimum bond strength of 2900 psi using the slant shear bond test after 28 days for repairs conducted on structural concrete. Results of mix iterations for Phase II bond shear strength meet or exceed these recommendations on average as shown in Figure 7-2**.** One replicate for T3-M02 fell below the 28 day value, but overall values exceeded recommendations. These results indicate that there would be little concern about debonding for the evaluated materials.

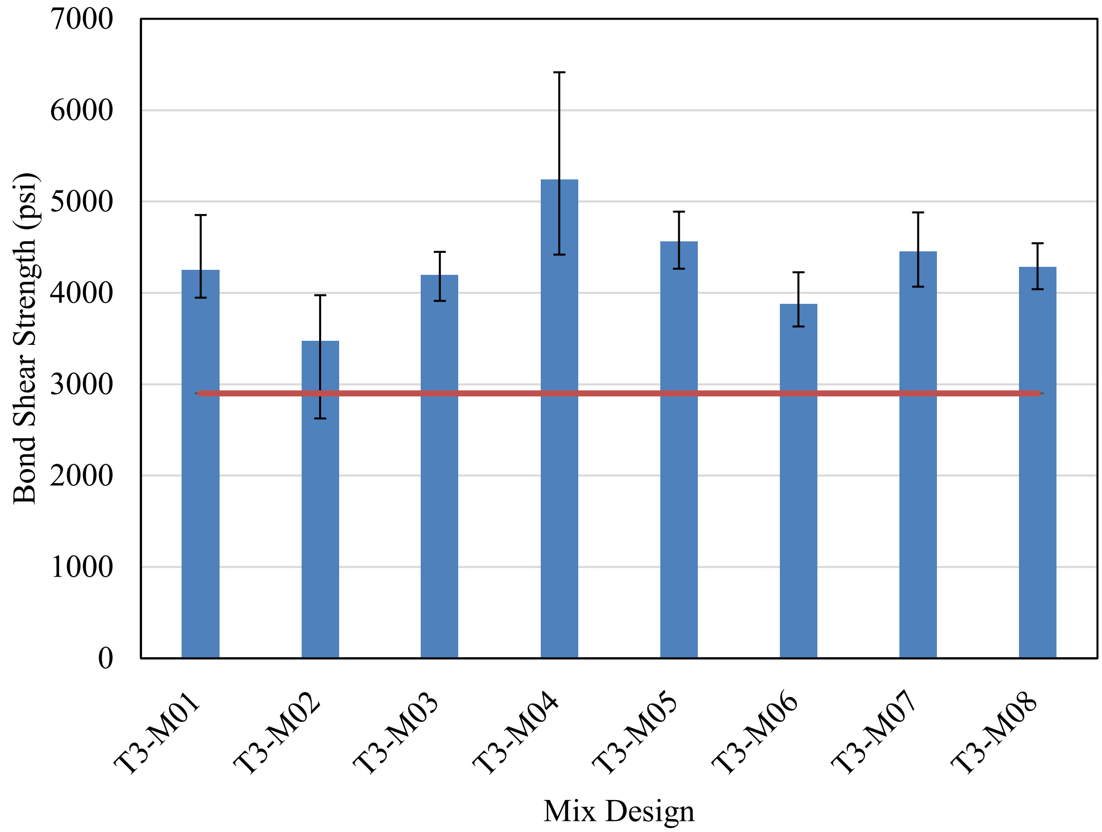

Figure 7-2: Bond Shear Strengths for All Mix Iterations (red line indicates 28 day recommended value)

7.2.4 Durability

Mass loss results from the freeze-thaw conditioning during Phase II (Task-3) generally showed 1%-3% mass loss for cylindrical compression samples at 100 cycles, 3%-6% at 200 cycles, and 4%-8% at 300 cycles as seen in Figure 7-3. T3-M04 and T3-M05 had the highest mass loss overall, likely due to higher slump values, with M04 having a 9 inch measured slump (7 inch target) and M05 having a 10 inch slump (9 inch target).

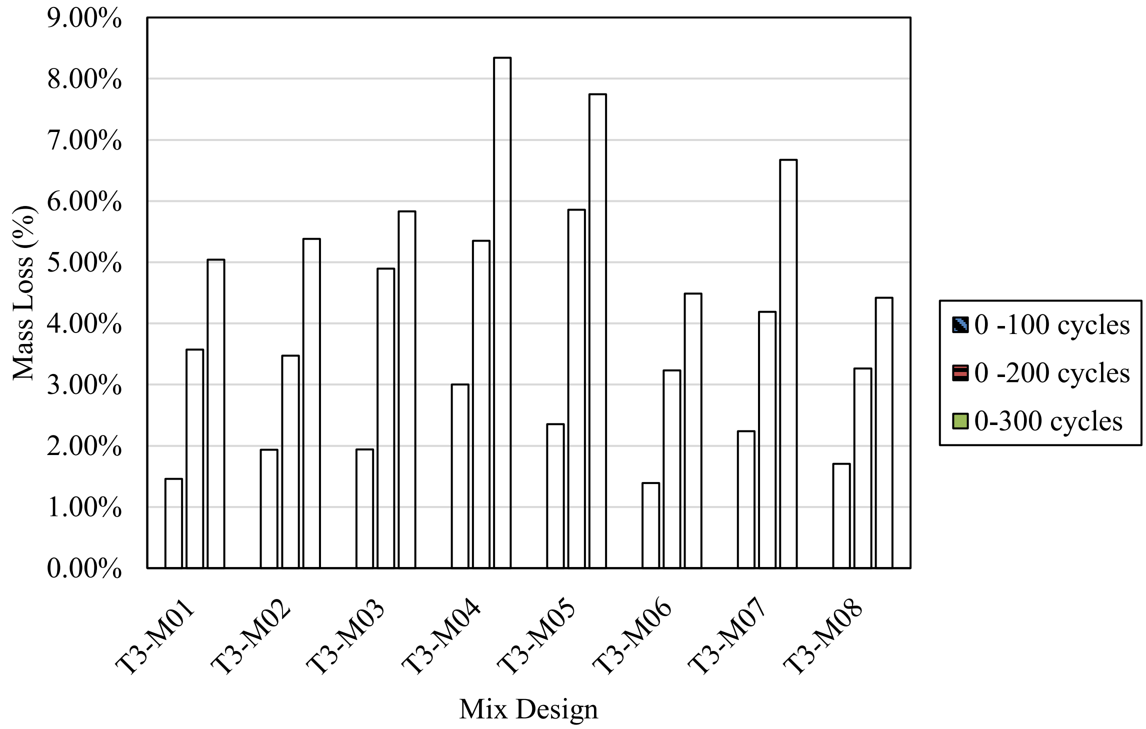

Figure 7-3: Mass Loss Measurements for All Compressive Strengths Specimens After Freeze-Thaw Conditioning

Durability results for compressive strength specimens can be seen in Figure 7-4. Specimens put through conditioning have shown specimens retained on average 90% strength compared to unconditioned specimens, with the lowest being 86%. Indicating the conditioning of specimens has not had a large effect on compressive strength, indicating durability is not a large concern for RSC.

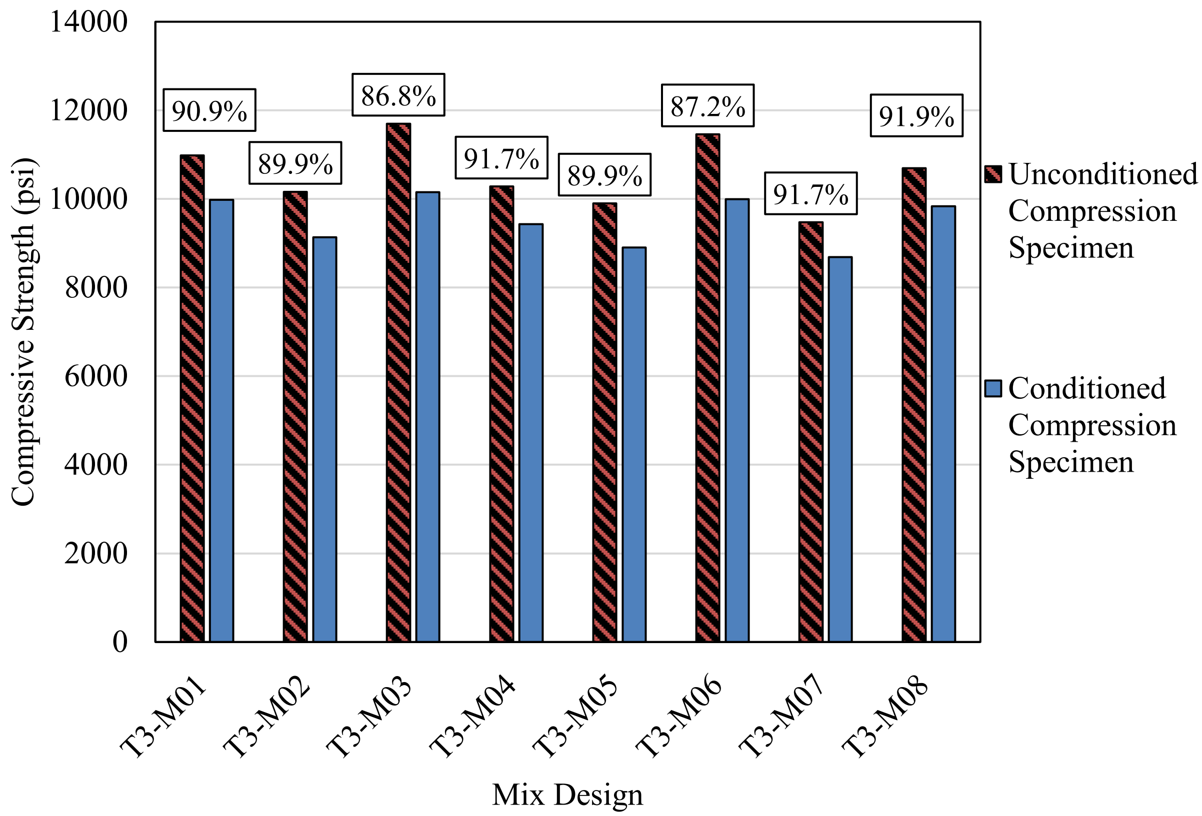

Figure 7-4: Durability Results for Compressive Strength Specimens (numbers on top of bars indicate the value of conditioned compressive strengths as percent of unconditioned compressive strengths)

Durability results for bond shear strength specimens can be seen in Figure 7-5. Specimens put through freeze thaw conditioning have seen an average of 77% bond shear strength retention when compared to unconditioned specimens. T3-M03 conditioned samples were not tested due to the bond connection breaking during the conditioning process. These breaks were identical to ones seen in PCC-2 mix iterations during Phase I (Task-2), where the breaks were directly on the bond shear connection and a result of the degradation of the bond shear connections over the course of freeze thaw conditioning without any external stress. Overall, these results indicate that there is not a concern with durability in RSC connections with relation to bond shear connections, indicating durability is not a large concern for RSC.

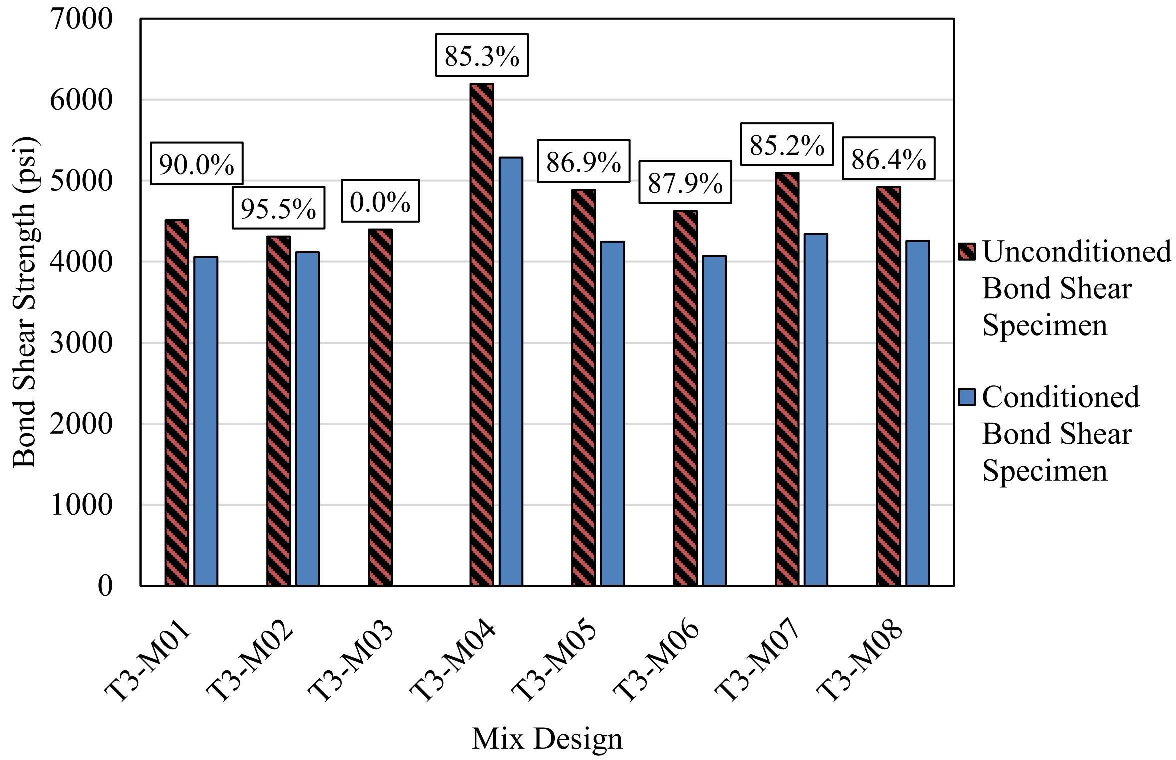

Figure 7-5: Durability Results for Bond Shear Strength Specimens (numbers on top of bars indicate the value of conditioned bond shear strengths as percent of unconditioned bond shear strengths)

7.2.5 Surface Resistivity

Results for surface resistivity can be seen in Figure 7-6**.** Results are plotted for surface resistivity measurements for control samples at 7, 14, and 28 days and companion freeze-thaw conditioned samples after 100, 200 and 300 cycles. Surface resistivity values increased throughout curing time, as well as 0-100 cycles, indicating continued C-S-H growth and reduction in chloride ion penetration potential. After 100cycles, the values level off or decrease, and continue through 300 cycles. Almost all measurements exceeded 5 kΩ (very low permeability category). A minimum value of 5 kΩ is used by several DOTs in United States, for example the New Hampshire Department of Transportation (2015) uses this threshold for concrete exposed to severe freeze-thaw conditions along with use of deicing chemicals, and as a result this value was used for this study. Overall, these results indicate that there is not a concern with surface resistivity in RSC connections, indicating durability is not a large concern for RSC.

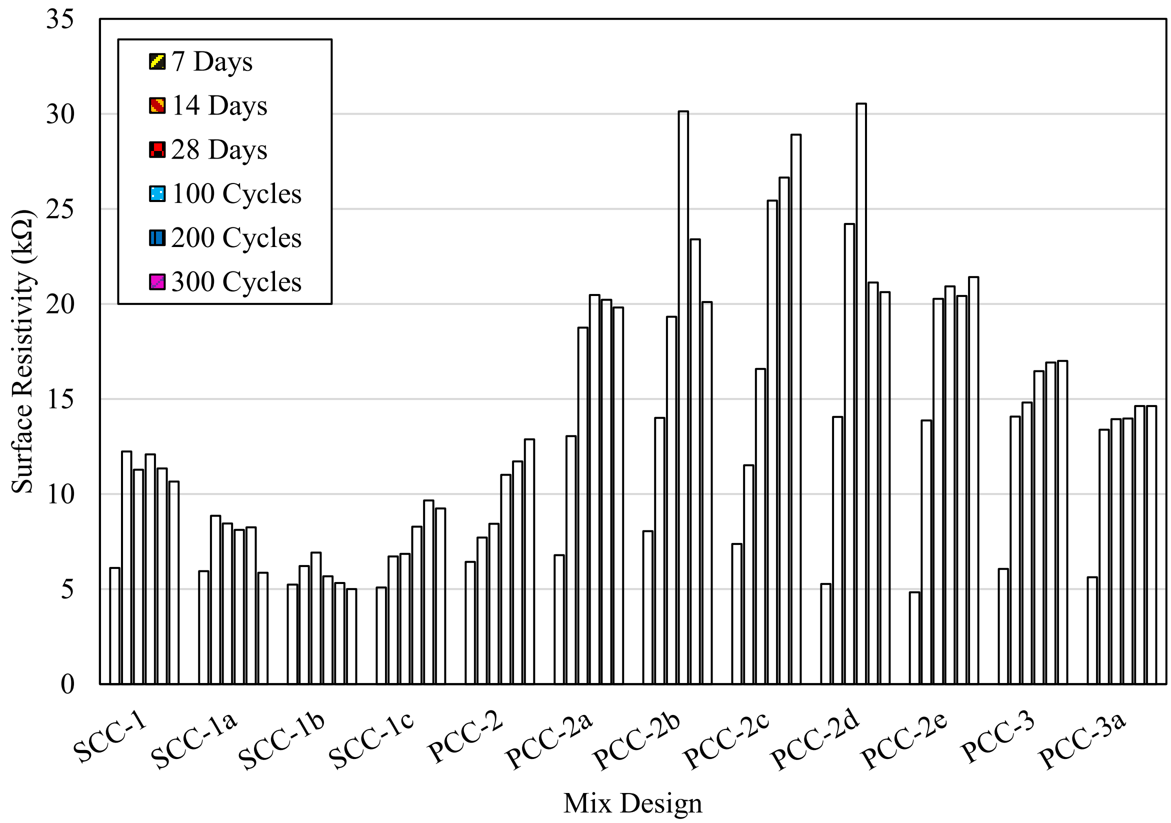

Figure 7-6: Surface Resistivity for All Mix Iterations

CHAPTER 8: DATA ANALYSIS FOR PHASE-II EXPERIMENT (TASK-3)

8.1 INTRODUCTION

This chapter presents outcomes of data analysis from all experimentally measured results frm Phase I (Task-2) and Phase II (Task-3).

8.2 MULTIVARIATE ANALYSIS INPUTS

Using mix design variables incorporated into the Phase I (Task-2) and Phase II (Task-3) experimental plans and laboratory experimentation results, a multivariate analysis was conducted to assess which variables were significant and how they affected certain results. A Pearson's correlation matrix was generated to find significant relationships between variables, a subset of which (not fully shown due to its size) can be found in Table 8-1. This allowed the research team to assess the mix design attributes that may significantly have affected the laboratory measured parameters, in doing so, effects of mix design on material properties can be assessed. Direct laboratory results were used, along with multiple regression fit models applied to the data, such as a logarithmic model for early age (1,2, and 7 day) compressive strength evolution, and a linear fit to 3 and 28 day bond strength data. This allowed analysis of the growth rate of compressive and bond shear strength. A table of the lab results used in the analysis can be seen in Table 8-2**.**

Table 8-1: Sample of Pearson's Correlation Matrix Generated for Phase I (shading indicates strength of correlation, with darker shading indicating a greater strength of correlation)

Parameter	*Cement Content*	*SCM Content*	*% PC Replacement*	*w/cm ratio*	*Plastic Temperature (°F)*	*Curing Temperature (°F)*
Compressive Strength – 2-Day	0.360	0.340	0.044	-0.584	0.020	-0.054
Compressive Strength – 28-Day	0.428	0.182	-0.294	-0.692	0.153	0.086
Early Age Comp. Strength- A value	0.234	0.300	0.153	-0.537	0.247	0.174
Early Age Comp. Strength– C value	0.196	0.116	-0.085	-0.745	-0.223	-0.282
Bond Shear 28-Days	-0.077	0.409	0.744	0.298	0.080	-0.007
Surface Resistivity - 7-Day	-0.478	-0.578	-0.257	0.049	0.382	0.515
Surface Resistivity - 14-Day	-0.486	-0.477	-0.087	0.000	0.436	0.544
Surface Resistivity - 28-Day	-0.221	-0.400	-0.327	0.035	0.371	0.504
Surface Resistivity - 100 Cycles	0.158	0.009	-0.200	-0.012	0.151	0.252
Surface Resistivity - 200 Cycles	0.398	0.122	-0.348	-0.120	-0.118	-0.039
Surface Resistivity - 300 Cycles	0.547	0.248	-0.352	-0.188	-0.395	-0.352
Durability - Avg Compressive Strength - % Difference	-0.646	-0.337	0.348	0.588	0.325	0.390
Durability - Avg Bond Shear Strength - % Difference	-0.994	-0.793	0.105	-0.023	0.061	0.119
Mass Loss 0-100 Cycles	-0.049	0.447	0.765	0.429	-0.217	-0.230
Mass Loss 100-200 Cycles	0.428	0.416	0.071	0.043	-0.311	-0.390
Mass Loss 200-300 Cycles	-0.475	0.041	0.706	0.467	-0.383	-0.349

Table 8-2: Multivariate Analysis Lab Result Inputs

Laboratory Testing Properties	
Lab Test	***Parameters***
Temperature	• Plastic Temperature (°F) Curing Temperature (°F)
Compressive Strength	• 2- & 28-day measurements • Early age strength gain rate: A and C parameters from logarithmic model (f'c=A*ln(t)+C) for 1-, 2-, and 7-days
Bond Shear Strength	• Strength gain rate: • M and B parameters from linear model (fbs=M*x+B) for 3 and 28 days • 28-day measurements
Surface Resistivity	• 7, 14, 28-days • 100, 200, 300 freeze-thaw cycles
Durability	• Average compressive strength & bond shear strength • Conditioned (300 freeze-thaw cycles) and unconditioned specimens • Change between conditioned (300 freeze-thaw cycles) and unconditioned samples
Mass Loss	• 0, 100, 200, 300 freeze-thaw cycles

Through data analysis, key mix variables that played significant roles in desired and undesired outcomes were determined. Primary variables were total cementitious content, total Portland cement content, total SCMs, percent of Portland cement replacement with SCMs (% PC replacement), and curing temperature as these were the variables used to develop the mix designs.

8.3 ANALYSIS RESULTS

8.3.1 Portland Cement & Compressive Strength

Figure 8-1 shows how the compressive strength changes with cementitious content. Data analysis from Phase I (Task-2) showed that approximately 800lbs./yd^3 of cementitious content achieved desired compressive strength of 3500 psi at 2 days and ensured that strength exceeds 5000 psi at 28 days. In Task-3, 800 lbs./yd^3 achieved the 2 day desired strength for 7 out of 8 mix iterations. Overall, greater amounts of cementitious content led to a higher compressive strength, which was expected as cementitious contents are the key factor for strength gain in concrete. Both Tasks indicated that for every 100 lbs./yd^3 of cementitious content added, compressive strength increased by approximately 500 psi.

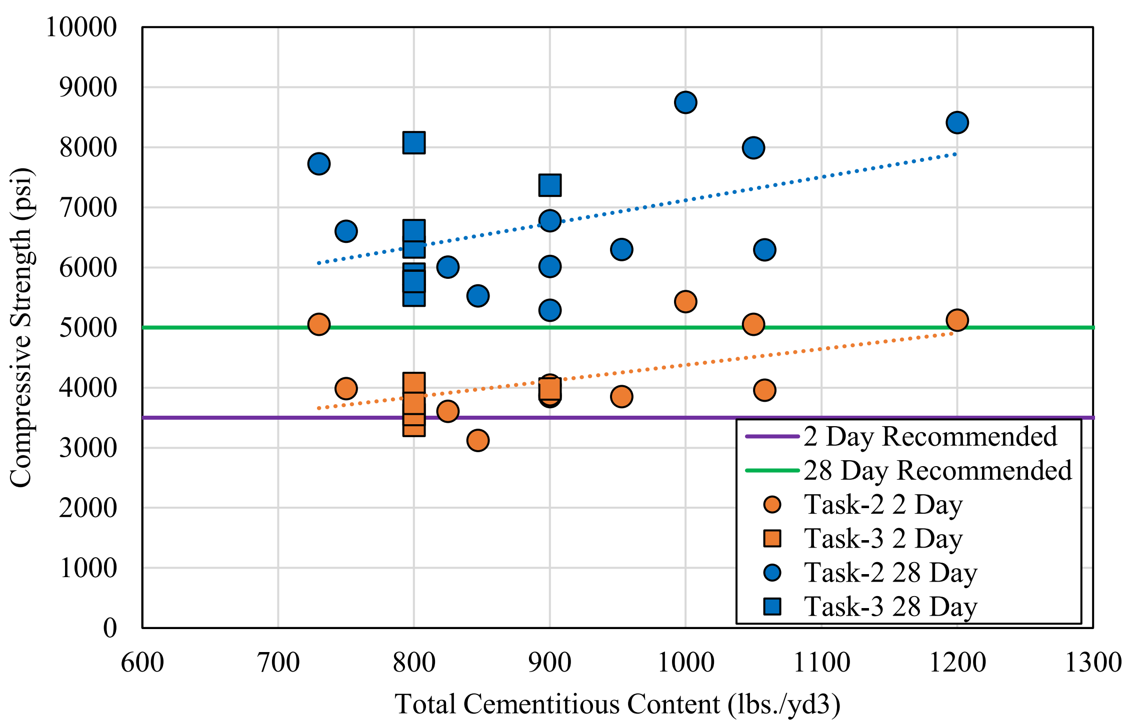

Figure 8-1: Correlation of Total Cementitious Content & 2 & 28 Day Compressive Strength

8.3.2 %PC Replacement & Bond Shear Strength

Analysis showed that % PC replacement had a major effect on bond shear strength with and without freeze thaw conditioning as seen in Figure 8-2. When samples were unconditioned, the majority specimens resulted in bond shear strength values exceeding the 2900 psi ACI repair manual recommendation. With freeze thaw conditioning, multiple PCC-2 mix iterations in Phase I (Task-2) had lower durability bond shear values due to breakage of specimens in the chamber as a result of degradation to their bond connections during conditioning. In Phase II (Task-3), T3-M03 had both specimens break in same manner between 200 and 300 cycles. The results for T3-M03 were not included in the trend evaluation and are represented in the graph using a non-filled blue box. Overall correlation results appear to indicate a quadratic correlation, where very little %PC replacement or high amounts of replacement generate favorable bond shear durability, however around 25%-40% replacement can result in bond connection degradation.

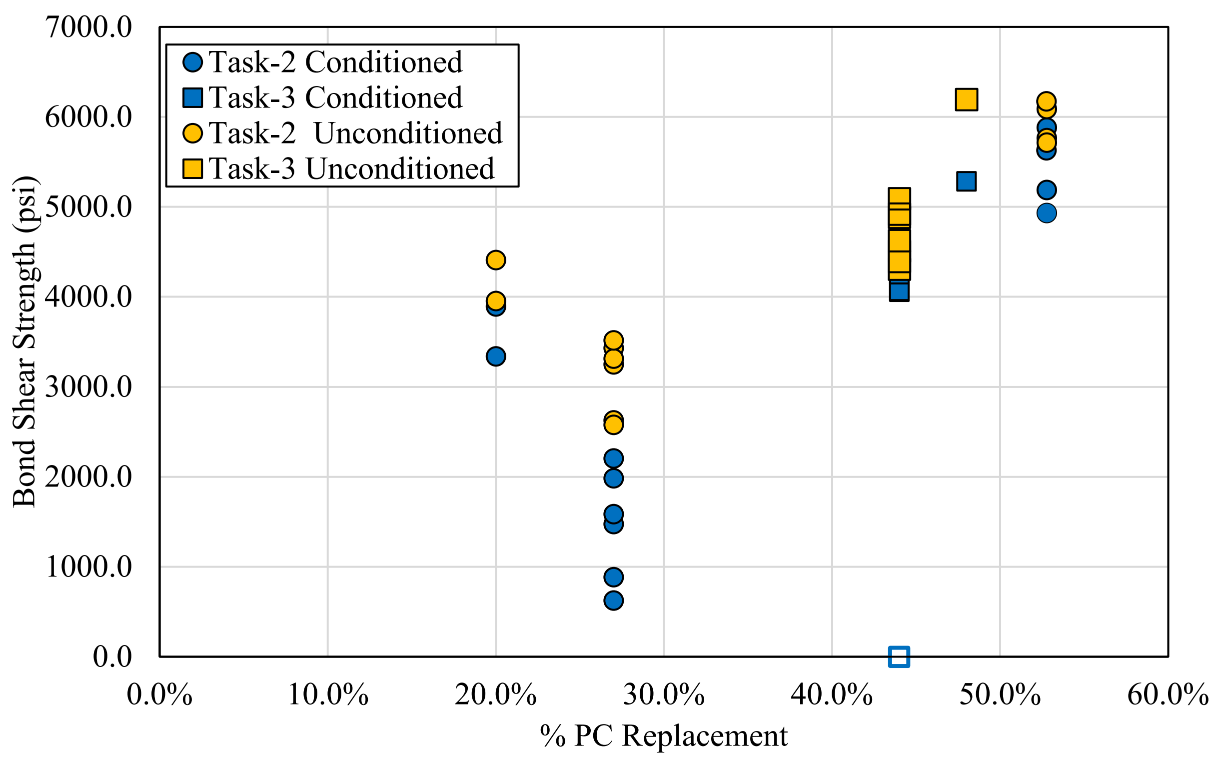

Figure 8-2: Correlation of %PC Replacement and Durability Bond Shear Strength

8.3.3 %PC Replacement & Surface Resistivity

Analysis of both experimentation phases indicated that increasing %PC Replacement in mix iterations in both phases of experimentation resulted in decreased surface resistivity values, as seen in Figure 8-3 and Figure 8-4. Mix iterations that saw 50% PC replacement or more had surface resistivity values approach 5 kΩ after extended conditioning. Limiting %PC replacement would result in better surface resistivity values, however nearly all measurements for mix iterations during both phases of experimentation remained above the 5 kΩ minimum requirement. As a result, higher %PC replacement can be utilized so long as values do not exceed a %PC replacement of greater than 50% to prevent surface resistivity concerns.

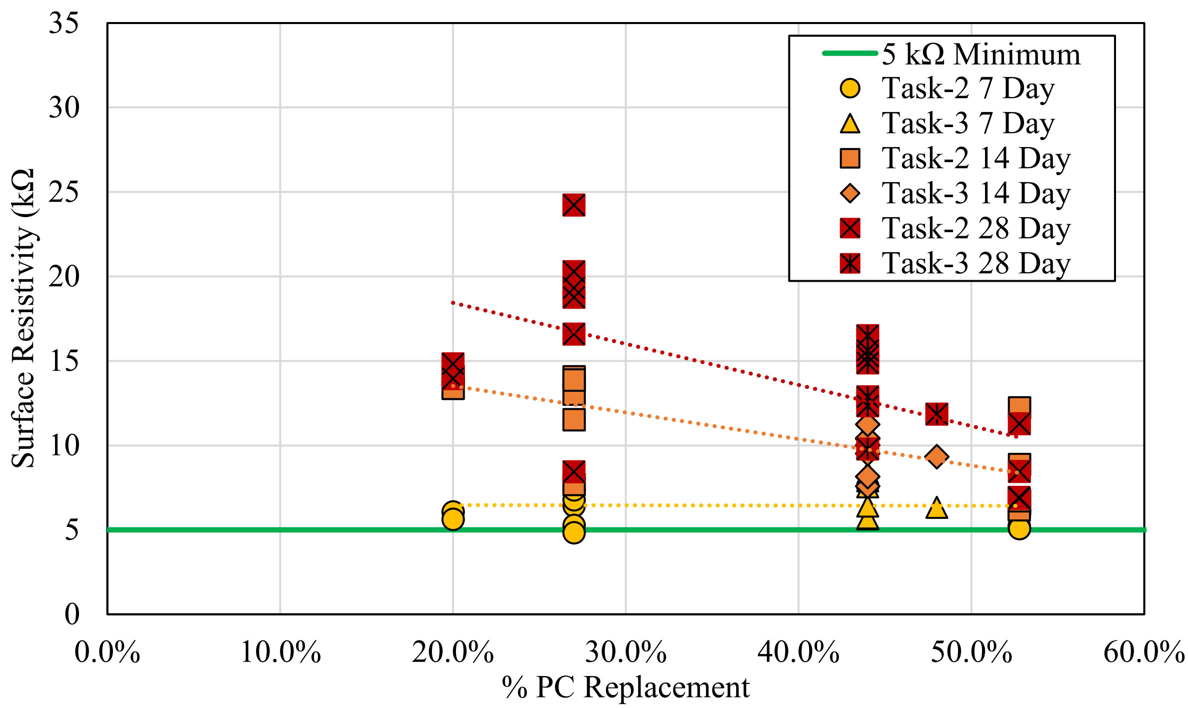

Figure 8-3: Correlation of %PC Replacement and Surface Resistivity without Freeze Thaw Conditioning

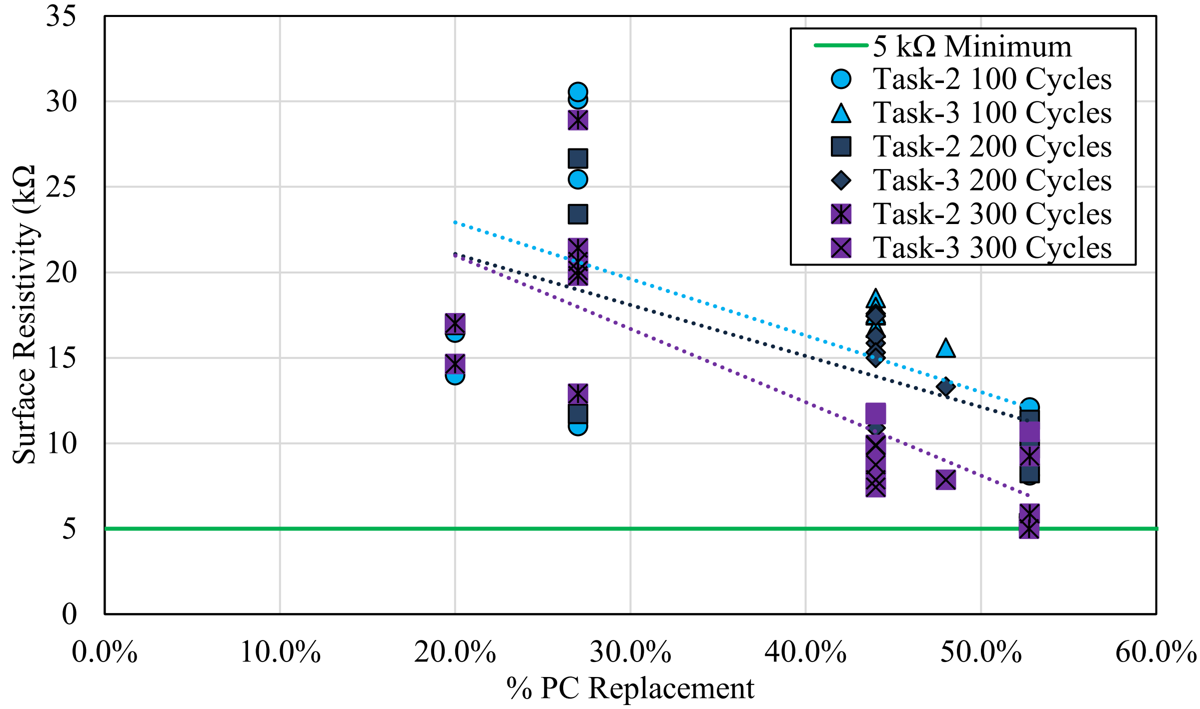

Figure 8-4: Correlation of %PC Replacement and Surface Resistivity with Freeze Thaw Conditioning

8.3.4 Total Portland Cement & Surface Resistivity

Figure 8-5 shows that greater amounts of Portland cement resulted in higher surface resistivity values as curing time increased for both Phase I and II. This effect increased throughout the freeze thaw conditioning process as seen in Figure 8-5 likely due to the specimen samples still curing while being submerged in the water bath of the freeze thaw chamber. Batches above 400lbs. of Portland cement exceeded this threshold throughout the evaluation period except for SCC-1b in Phase I, which was very close to 5kΩ after 300 cycles. During the conditioning process, the data begins to become more sporadic, likely due to many of the samples having various amount of scaling on the specimen and damage to them during the process as seen in Figure 8-6. This in turn results in more variance in the degree of resistivity as the surface resistivity meter indirectly measures permeability and the concrete’s ability to resist chloride ions, and the scaling seen over the course of conditioning results in a rougher surface which is harder for the meter to accurately assess.

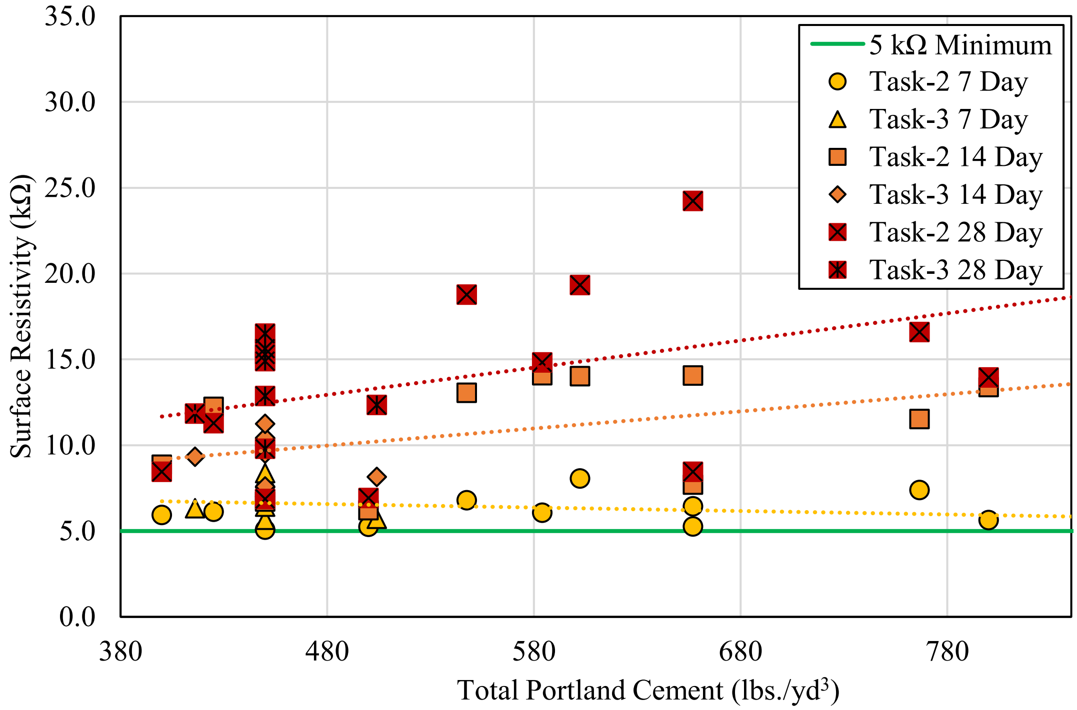

Figure 8-5: Correlation of Total Portland Cement and Surface Resistivity without Freeze Thaw Conditioning

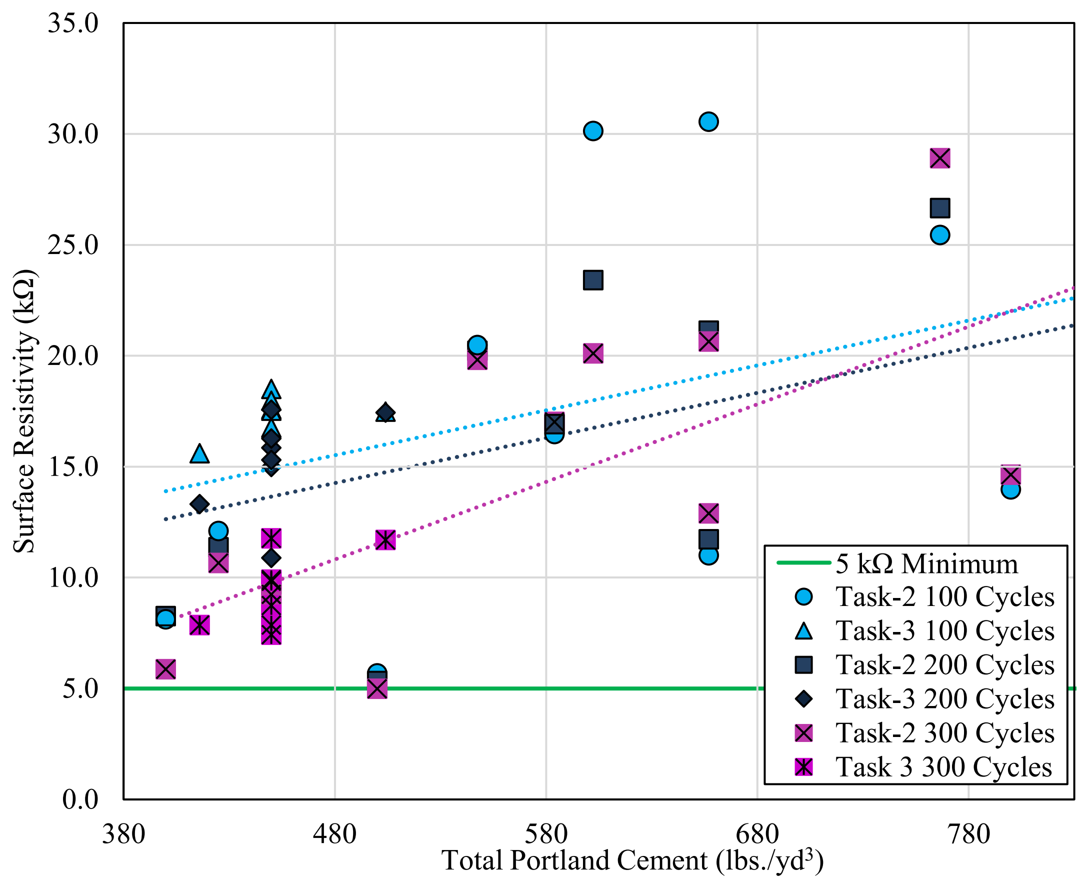

Figure 8-6: Correlation of Total Portland Cement and Surface Resistivity with Freeze Thaw Conditioning

8.3.5 Curing Temperature & Mass Loss

Analysis showed that higher curing temperature led to minor decreased mass loss over the course of freeze thaw conditioning, as seen in Figure 8-7. Initial mass loss after 100 cycles saw some increase with higher curing temperatures, however after 100 cycles the relationship inverted. This was likely due to faster and more thorough curing and C-S-H growth while curing at a higher temperature prior to conditioning. Overall curing temperature within the range evaluated during Phase II (Task-3) played a very minimal role in mass loss.

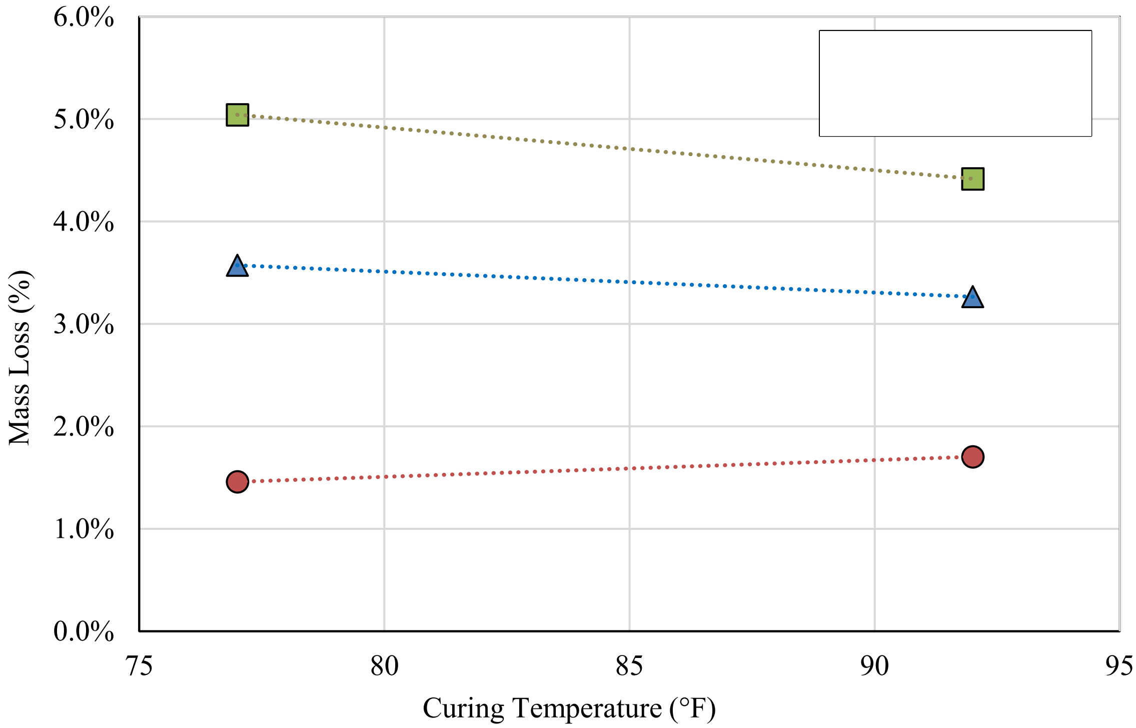

Figure 8-7: Correlation of Curing Temperature and Mass Loss for Task-3 Mix Iteration T3-M01 and T3-M08

8.3.6 Curing Temperature & Surface Resistivity

Analysis showed that during Phase II higher curing temperature led to increases in surface resistivity without freeze thaw conditioning, as seen in Figure 8-8. This is likely due to faster and more thorough curing and C-S-H growth while under hotter conditions. With freeze thaw conditioning, this relationship became negligible by 300 cycles, as seen in Figure 8-9**.** Further analysis would be required to better understand this relationship, however, is likely not needed for RSC compositions similar to those in this study as surface resistivity was consistently above the 5 kΩ target value.

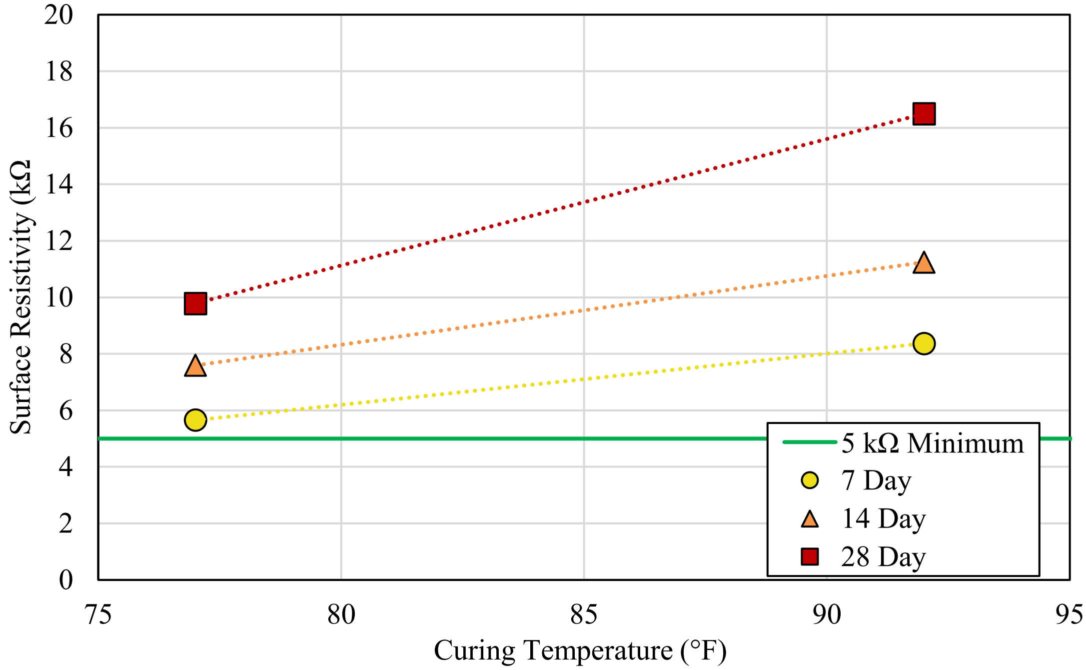

Figure 8-8: Correlation of Curing Temperature and Surface Resistivity without Freeze Thaw Conditioning for Task-3 Mix Iteration T3-M01 and T3-M08

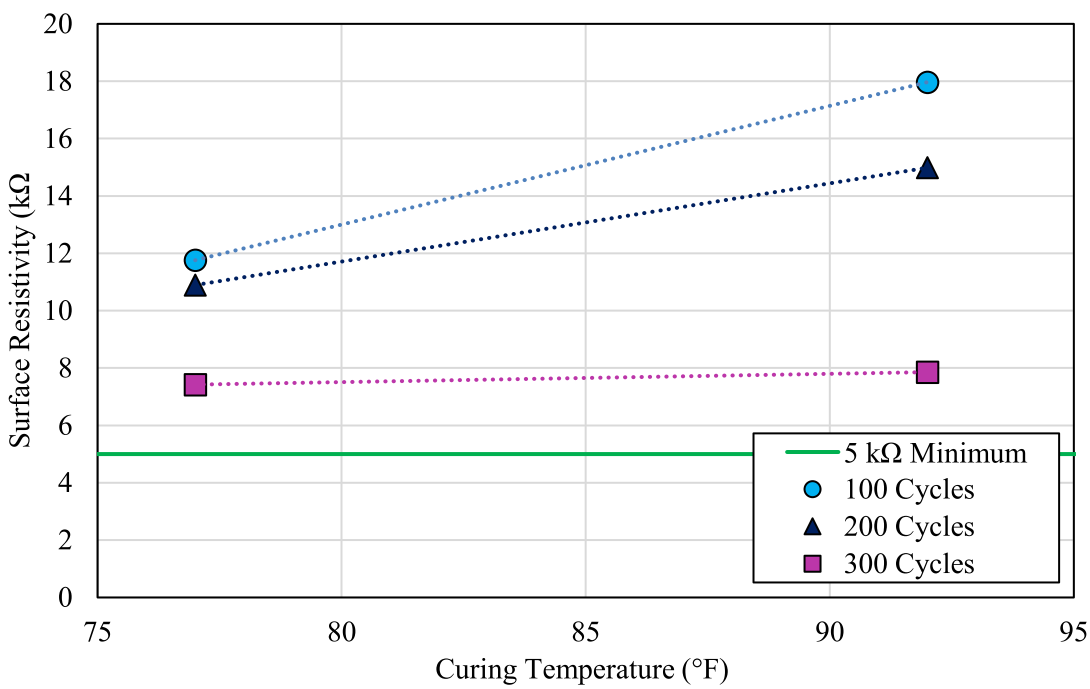

Figure 8-9: Correlation of Curing Temperature and Surface Resistivity with Freeze Thaw Conditioning for Task-3 Mix Iteration T3-M01 and T3-M08

CHAPTER 9: SUMMARY, RECOMMENDATIONS AND FUTURE EXTENSIONS

9.1 INTRODUCTION

This chapter summarizes this research study and presents recommendations that were developed through a two phased laboratory evaluation effort. The recommendations are made with respect to mix design compositions for RSC used in ABC projects as well as in terms of the expected durability performance of such materials.

9.2 SUMMARY

This report provides a summary of research efforts that were undertaken to evaluate the durability and mechanical properties of rapid setting concretes (RSC) that are commonly used in field placed connections during an accelerated bridge construction (ABC). The research discussed in this report also undertook efforts to propose an hybrid proportion and performance based mix design specification that can be adopted by VTrans to lower the costs and testing requirements associated with use of RSC. The research study was organized in three tasks. First task of this study conducted a state of the art and practice review on RSC used in ABC projects and laboratory evaluations methods to determine their durability and to conduct material designs. This first task yielded an experimental matrix for task-2 which evaluated recently used RSC by VTrans on ABC projects to determine their durability and mechanical properties as well as to conduct a first level assessment (partial factorial design) on effects of mix composition on RSC properties. Based on data analysis from task-2, a second level experimental design (full-factorial design) was developed to further validate findings of task-2 on RSC durability as well as to propose mix proportion limits that can be used in future VTrans ABC project RSC materials. The primary findings as well as recommendations on the basis of the two phases of laboratory testing are discussed next, this followed by a summary of key findings with respect to durability of RSC materials.

9.3 MIX DESIGN COMPOSITION

The outcome of the experimental effort was to develop mix composition recommendations based upon correlations found between mix design attributes and laboratory results. Using correlations discussed in the previous chapter, observations of results and mix design composition recommendations are as follows:

- Total Cementitious Content
  - Approximately 750 lbs./yd^3 of total cementitious content with 40-45% Portland cement replacement with supplementary cementitious materials (SCM) produced a consistent 3500 psi at 2 days, while approximately 850 lbs./yd^3 of content produced 4000 psi at the 2 day testing interval.
  - A 28 day 5000 psi compressive strength can be achieved with as low as 550 lbs./yd^3 of cementitious material.
  - Approximately 800 lbs./yd^3 kept the surface resistivity values above 5kΩ (very low permeability category) throughout testing, including after 300 freeze-thaw cycles.
  - Higher amounts resulted in faster compressive strength growth, which is expected. A 28 day strength gain of approximately 500 psi per 100 lbs./yd^3 was observed in this study.
  - <u>A total cementitious content of 850 lbs./yd^3 is recommended for an optimal RSC mix composition.</u>
- Percent Portland Cement (%PC) Replacement
  - 20% or less replacement had little to no issues with bond shear strength or surface resistivity.

- 25%-40% replacement resulted in bond shear issues after durability conditioning was completed, with some samples breaking in half during the cycling process. This breakage was not due to external stress, but physical degradation of the specimen's bond shear connection to the point of failure.
- Over 50% resulted in measured surface resistivity values approaching the 5kΩ minimum requirement.
- <u>A %PC replacement of 44% is recommended with 39% slag and 5% silica fume for an optimal RSC mix composition. When using fly ash as supplementary cementitious material, a 39% replacement using class F fly ash is recommended with 5% silica fume.</u>

- Aggregate Source
  - No significant correlations were found in the analysis between different aggregate sources from Vermont.
  - <u>Aggregate did not play a significant role and should not be limited in RSC mix designs as long as it is coming from an approved VTrans source.</u>

- Water to cementitious materials (w/cm) Ratio
  - All mix iterations consisted of a w/cm ratio in the range of 0.297-0.35, and no significant correlations were found relating directly to w/cm ratio. Most likely due to the narrow range of w/cm evaluated in this effort.
  - <u>A w/cm ratio of 0.33 is recommended to err on the safer side for an optimal RSC mix composition.</u>

- Air Content
    - Air content did not appear to play a significant role in any analysis, including mass loss. The experiment used 6% as a baseline and did not observe durability concerns.
    - <u>A minimum 6% air content is recommended for an optimal RSC mix composition.</u>
- Workability
    - Higher slump/spread lead to minor losses in surface resistivity, however this was attributed to higher paste volumes, and all measurements taken after 7 days exceeded the 5kΩ minimum requirement.
    - <u>A 7 inch slump and 20 inch spread is recommended for an optimal RSC mix composition.</u>

9.4 DURABILITY OF RSC USED FOR CONNECTIONS

This study sought to determine if there was any concern with durability of RSC connections. Through experimentation, it was seen that with correct mix design composition, durability would not be of concern and acceptable based on established thresholds and criteria for durability. The key findings with respect to durability are:

- Durability assessment of compressive strength showed 90% strength retention after freeze thaw conditioning was completed when compared to unconditioned samples of the same age, all of which remained above the 5000 psi recommendation for RSC.
- Durability assessment of bond shear strength during Phase I (Task-2) showed an average strength retention of 68%. This was due to some mixes, specifically PCC-2 and its mix iterations, having low amounts of total SCM and %PC replacement. Correlations discovered during analysis showed total SCM and %PC Replacement

having an inversely proportional relationship to conditioned bond shear strength. Separating PCC-2 iterations out, SCC-1 and PCC-3 iterations showed a 90% bond shear strength rendition, while PCC-2 showed just 40%. During Phase II (Task-3), average bond shear strength retention was 77% due to one mix iteration experiencing breakage to both its samples during conditioning. Ensuring proper %PC replacement is critical to ensuring proper bond shear strength post conditioning.

- The 12 mix iterations of Phase I (Task-2), and the 8 mix iterations of Phase II (Task-3) saw surface resistivity measurements stayed above the 5 kΩ minimum value set forth for most mixes for all measurements both before and after freeze-thaw conditioning, with only 1 mix iteration in Phase I being below 5 kΩ at 7 days, the remainder of its measurements were above, including post conditioning.

Therefore, durability is not a concern for RSC connections as post conditioning compressive strength and surface resistivity were of little concern as shown through laboratory analysis, and bond shear strength post conditioning is of little concern when proper %PC replacement, as highlighted in the previous section.

In addition to these mix design recommendations, it appears the RSC placed in-situ can withstand freeze thaw conditioning and deicing agents often used on roadways, therefore it is recommended that ABC projects built by VTrans in future can utilize “bare deck” approach without need for membranes and asphalt overlays.

9.5 RSC SPECIAL PROVISION

The current VTrans RSC special provision dictates that RSC used in the field must have specimens created to be tested for freeze thaw durability to ensure they have proper durability. This research showed that durability was of little concern for RSC when manufactured with mix composition proposed through this research, and therefore it is the research team's recommendation that freeze thaw conditioning no longer be required for contractor testing. Further, shrinkage testing results also did not show concerns, thus the shrinkage measurements can also be relaxed.

9.6 RECOMMENDATIONS FOR FUTURE EFFORTS

While this research study evaluated a range of materials in different proportions using a comprehensive laboratory experimentation, however, the types of evaluated materials should still be considered narrow and not all-encompassing range of materials that may be encountered by VTrans in their projects. Further, the types of laboratory evaluations were also limited to those possible within the resources available for this research study. In light of this, following future efforts are recommended to be undertaken as next steps during the pilot implementation of recommendations from this research study:

- Additional brands of chemical admixtures (products from different vendors that are on VTrans' approved/qualified product lists) should be evaluated to ensure that proportion-based RSC made using those products still meet and exceed performance criteria used in this study.
- Due to potential for a delayed curing and hydration product development in mixes with high fly ash contents, it is imperative that a substantially hydrated specimen is used for freeze-thaw assessment. Thus, for RSC using fly ash as Portland cement replacement, a longer curing duration of 56 days should be considered prior to freeze-thaw durability test initiation. Current research conducted freeze-thaw conditioning of test specimens after 14 days of curing.
- The chloride ingress in RSC was assessed in this research through estimation of the permeability of concrete as measured in terms of its surface resistivity. While this approach has been well vetted and already adopted by large number of public transportation agencies, an independent validation of the chloride ingress potential would be beneficial and will provide added confidence.

- This research clearly demonstrated a very high mechanical performance of previously used RSC by VTrans on ABC projects as well as those that may be used on the basis of this project's recommendations. The flexural strengths (or modulus of rupture) measurements during phase-I experimentation substantially exceeded values that are often measured for normal structural concrete. Thus, capacity of field placed RSC connections used in ABC projects to provide moment transfer should be explored and evaluated.
- While phase-II experimentation provided validation of lab measured durability and mechanical properties for RSC, a field validation effort is essential to full validate the findings and recommendations of this research study and to deploy them for routine usage.

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APPENDIX A: LABORATORY RESULTS FROM TASK-2

Table A 1: Batch Components for SCC-1 and PCC-3 Mix Iterations

Batch Material	*SCC-1*	*SCC-1a*	*SCC-1b*	*SCC-1c*	*PCC-3*	*PCC-3a*
Water (lbs.)	38.0	28.4	40.4	34.6	42.5	44.4
Portland Cement Content (lbs.)	63.8	51.9	66.7	60.0	114.9	136.7
Blended Cement (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Slag (lbs.)	63.8	51.9	66.7	60.0	n.a.	n.a.
Fly Ash (lbs.)	n.a.	n.a.	n.a.	n.a.	23.0	27.3
Silica Fume (lbs.)	7.5	6.1	7.8	7.1	n.a.	n.a.
Coarse Aggregate (lbs.)	221.4	193.5	197.6	199.6	232.7	227.5
Fine Aggregate (lbs.)	190.1	176.1	132.2	155.5	201.8	146.7
Air Entrainer (mL)	22.18	19.17	19.72	19.72	5.59	5.39
High Range Water Reducer (mL)	150.83	115.46	185.56	150.30	394.19	578.02
Workability Retainer (mL)	94.27	72.16	115.97	93.94	1087.43	1594.54
Shrinkage Reducer (lbs.)	1.88	1.62	1.67	1.67	0.66	0.63

n.a.: not applicable

Table A 2: Batch Components for PCC-2 Mix Iterations

Batch Material	*PCC-2*	*PCC-2a*	*PCC-2b*	*PCC-2c*	*PCC-2d*	*PCC-2e*
Water (lbs.)	48.4	38.9	22.1	48.4	42.0	57.1
Portland Cement Content (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Blended Cement (lbs.)	150.0	125.0	160.4	163.3	140.0	186.7
Slag (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fly Ash (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Silica Fume (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Coarse Aggregate (lbs.)	247.8	248.8	297.3	234.0	232.1	232.1
Fine Aggregate (lbs.)	206.7	249.7	300.6	144.2	195.3	115.8
Air Entrainer (mL)	197.16	197.16	230.02	184.01	184.01	184.01
High Range Water Reducer (mL)	354.88	246.45	347.90	450.83	331.22	588.84
Workability Retainer (mL)	266.16	184.83	260.92	338.12	248.42	441.63
Shrinkage Reducer (lbs.)	1.39	1.39	1.62	1.30	1.30	1.30

n.a.: not applicable

Table A 3: 28 Day Shrinkage Values

Mix Design	*28 Day % Length Change*
SCC-1	0.390%
SCC-1a	0.301%
SCC-1b	0.398%
SCC-1c	0.360%
PCC-2	0.356%
PCC-2a	0.334%
PCC-2b	0.380%
PCC-2c	0.324%
PCC-2d	0.314%
PCC-2e	0.417%
PCC-3	0.320%
PCC-3a	0.389%

Table A 4: Flexural Strength at 3 and 28 days

Mix Design	*3 Day Modulus of Rupture - Specimen 01 (psi)*	*3 Day Modulus of Rupture - Specimen 02 (psi)*	*3 Day Modulus of Rupture - Average (psi)*	*28 Day Modulus of Rupture - Specimen 01 (psi)*	*28 Day Modulus of Rupture - Specimen 02 (psi)*	*28 Day Modulus of Rupture - Average (psi)*
SCC-1	1024	947	507	1323	1211	1390
SCC-1a	815	829	822	1207	1276	1241
SCC-1b	808	800	804	1165	1168	1166
SCC-1c	853	924	889	1165	1185	1175
PCC-2	1331	1196	1263	1402	1277	1340
PCC-2a	859	729	794	1121	1286	1204
PCC-2b	1164	1029	1096	1102	1176	1139
PCC-2c	990	1004	997	1331	1196	1263
PCC-2d	899	863	881	1058	1209	1133
PCC-2e	1010	1093	1051	1349	1476	1413
PCC-3	672	632	652	823	805	814
PCC-3a	834	769	801	1289	1211	1250

Table A 5: Compressive Strengths at 1 Day

Mix Design	*1 Day Compressive Strength - Specimen 01 (psi)*	*1 Day Compressive Strength - Specimen 02 (psi)*	*1 Day Compressive Strength - Specimen 03 (psi)*	*1 Day Compressive Strength - Specimen 04 (psi)*	*1 Day Compressive Strength - Average (psi)*
SCC-1	1816	1830	1848	n.a.	1831
SCC-1a	1379	1399	1329	n.a.	1369
SCC-1b	1286	1485	1588	n.a.	1453
SCC-1c	1381	1709	1588	n.a.	1559
PCC-2	2570	2740	2522	n.a.	2611
PCC-2a	2590	2768	2546	n.a.	2635
PCC-2b	2767	2831	2888	n.a.	2829
PCC-2c	3507	3635	3748	n.a.	3630
PCC-2d	3048	3328	3143	n.a.	3173
PCC-2e	3925	4304	4379	n.a.	4202
PCC-3	2063	2215	2056	n.a.	2112
PCC-3a	2115	2026	2109	n.a.	2083

n.a.: not applicable

Table A 6: Compressive Strengths at 2 Days

Mix Design	*2 Day Compressive Strength - Specimen 01 (psi)*	*2 Day Compressive Strength - Specimen 02 (psi)*	*2 Day Compressive Strength - Specimen 03 (psi)*	*2 Day Compressive Strength - Specimen 04 (psi)*	*1 Day Compressive Strength - Average (psi)*
SCC-1	4319	3725	4093	n.a.	4045
SCC-1a	3253	2809	3311	n.a.	3124
SCC-1b	3355	4171	4354	n.a.	3960
SCC-1c	2899	2603	3306	n.a.	2936
PCC-2	3951	3796	3814	n.a.	3854
PCC-2a	3951	3796	3814	n.a.	3854
PCC-2b	3645	3725	3454	n.a.	3608
PCC-2c	5033	5395	4744	n.a.	5058
PCC-2d	4013	3959	3689	n.a.	3887

PCC-2e	4757	4836	5788	n.a.	5127
PCC-3	4580	4015	4572	n.a.	4389
PCC-3a	5373	5690	5238	n.a.	5434

n.a.: not applicable

Table A 7: Compressive Strengths at 7 Days

Mix Design	*7 Day Compressive Strength - Specimen 01 (psi)*	*7 Day Compressive Strength - Specimen 02 (psi)*	*7 Day Compressive Strength - Specimen 03 (psi)*	*7 Day Compressive Strength - Specimen 04 (psi)*	*7 Day Compressive Strength - Average (psi)*
SCC-1	3836	4131	3715	n.a.	3894
SCC-1a	3773	3895	4590	n.a.	4086
SCC-1b	4988	4915	4784	n.a.	4896
SCC-1c	4988	4915	4784	n.a.	4896
PCC-2	5013	5511	5219	n.a.	5248
PCC-2a	6073	5705	5490	6213	5870
PCC-2b	4269	4940	4213	n.a.	4474
PCC-2c	6751	6858	6139	n.a.	6583
PCC-2d	5855	5588	5302	n.a.	5582
PCC-2e	5757	5931	6252	n.a.	5980
PCC-3	6008	5825	5557	n.a.	5797
PCC-3a	6091	5846	6250	n.a.	6062

n.a.: not applicable

Table A 8: Compressive Strengths at 28 Days

Mix Design	*28 Day Compressive Strength - Specimen 01 (psi)*	*28 Day Compressive Strength - Specimen 02 (psi)*	*28 Day Compressive Strength - Specimen 03 (psi)*	*28 Day Compressive Strength - Specimen 04 (psi)*	*28 Day Compressive Strength - Average (psi)*
SCC-1	4966	5482	5424	n.a.	5291
SCC-1a	6091	5375	5118	n.a.	5528
SCC-1b	6284	6164	6439	n.a.	6296
SCC-1c	6279	6521	6112	n.a.	6304
PCC-2	5840	6540	6260	n.a.	6213
PCC-2a	6543	6712	6365	n.a.	6540
PCC-2b	6390	5831	5802	n.a.	6008

PCC-2c	7604	8419	7964	n.a.	7995
PCC-2d	6999	6962	6389	n.a.	6783
PCC-2e	9464	8008	7779	8656	8477
PCC-3	6799	8424	7970	n.a.	7731
PCC-3a	9498	8368	8389	8687	8735

n.a.: not applicable

Table A 9: Bond Shear Strengths at 1 Day

Mix Design	***1 Day Bond Shear Strength - Specimen 01 (psi)***	***1 Day Bond Shear Strength - Specimen 02 (psi)***	***1 Day Bond Shear Strength - Specimen 03 (psi)***	***1 Day Bond Shear Strength - Specimen 04 (psi)***	***1 Day Bond Shear Strength - Average (psi)***
SCC-1	1816	1879	1865	n.a.	1854
SCC-1a	1124	1011	1516	n.a.	1217
SCC-1b	1066	1052	1381	n.a.	1166
SCC-1c	1115	1021	1350	n.a.	1162
PCC-2	3374	2380	2643	n.a.	2799
PCC-2a	1877	1714	1797	n.a.	1796
PCC-2b	2276	1904	1591	n.a.	1924
PCC-2c	1646	1838	2702	n.a.	2062
PCC-2d	1966	1916	1964	n.a.	1949
PCC-2e	2898	2469	2392	n.a.	2586
PCC-3	1654	1474	1400	n.a.	1509
PCC-3a	2187	2654	2341	n.a.	2394

n.a.: not applicable

Table A 10: Bond Shear Strengths at 3 Days

Mix Design	***3 Day Bond Shear Strength - Specimen 01 (psi)***	***3 Day Bond Shear Strength - Specimen 02 (psi)***	***3 Day Bond Shear Strength - Specimen 03 (psi)***	***3 Day Bond Shear Strength - Specimen 04 (psi)***	***3 Day Bond Shear Strength - Average (psi)***
SCC-1	1543	1606	1535	n.a.	1561
SCC-1a	3960	2718	3303	n.a.	3327
SCC-1b	3147	2619	2850	n.a.	2872
SCC-1c	3632	3410	4209	n.a.	3750
PCC-2	2154	2259	1795	n.a.	2069

PCC-2a	2325	2106	2378	n.a.	2270
PCC-2b	2135	2461	3405	n.a.	2667
PCC-2c	1879	2346	2548	n.a.	2257
PCC-2d	2955	2242	2506	n.a.	2567
PCC-2e	2688	2564	3176	1105	2809
PCC-3	2798	2070	2005	n.a.	2291
PCC-3a	4765	5887	5228	n.a.	5293

n.a.: not applicable

Table A 11: Bond Shear Strengths at 28 Days

Mix Design	*28 Day Bond Shear Strength - Specimen 01 (psi)*	*28 Day Bond Shear Strength - Specimen 02 (psi)*	*28 Day Bond Shear Strength - Specimen 03 (psi)*	*28 Day Bond Shear Strength - Specimen 04 (psi)*	*28 Day Bond Shear Strength - Average (psi)*
SCC-1	2111	2131	2273	n.a.	2171
SCC-1a	4109	4480	4209	n.a.	4266
SCC-1b	4455	4067	3487	n.a.	4003
SCC-1c	3632	3410	4209	n.a.	3750
PCC-2	2455	3653	3828	n.a.	3312
PCC-2a	2940	3093	3161	n.a.	3065
PCC-2b	3912	3755	2623	n.a.	3430
PCC-2c	2921	2807	3129	n.a.	2952
PCC-2d	3759	2810	3028	n.a.	3199
PCC-2e	4374	4984	5760	n.a.	5039
PCC-3	3441	2883	3591	3088	3251
PCC-3a	6482	7284	7641	n.a.	7136

n.a.: not applicable

Table A 12: Mass Loss for Specimens 1 & 2

Mix Design	*Mass Loss Specimen 1*			*Mass Loss Specimen 2*		
	0-100 cycles	*100-200 cycles*	*200-300 cycles*	*0-100 cycles*	*100-200 cycles*	*200-300 cycles*
SCC-1	1.72%	0.62%	1.14%	1.69%	0.19%	0.54%
SCC-1a	2.82%	1.98%	1.46%	-1.04%	1.92%	1.49%
SCC-1b	1.53%	1.00%	1.83%	1.38%	1.35%	1.35%
SCC-1c	1.38%	0.74%	2.16%	1.27%	1.67%	1.88%
PCC-2	1.32%	1.25%	2.25%	0.98%	1.49%	1.38%

PCC-2a	0.99%	1.40%	1.20%	1.12%	1.91%	1.81%
PCC-2b	1.71%	3.76%	0.89%	1.46%	3.11%	0.86%
PCC-2c	0.59%	4.04%	4.06%	0.90%	5.96%	10.24%
PCC-2d	1.23%	3.35%	2.50%	0.31%	1.34%	1.39%
PCC-2e	0.89%	0.46%	1.27%	0.59%	0.70%	1.20%
PCC-3	1.48%	1.31%	1.16%	1.89%	1.81%	1.67%
PCC-3a	1.57%	3.57%	2.06%	2.86%	2.99%	0.57%

Table A 13: Mass Loss for Specimens 3 & 4

Mix Design	Mass Loss Specimen 3			Mass Loss Specimen 4		
	0-100 cycles	100-200 cycles	200-300 cycles	0-100 cycles	100-200 cycles	200-300 cycles
SCC-1	1.95%	0.66%	1.33%	1.28%	1.06%	0.80%
SCC-1a	4.81%	2.32%	2.04%	2.90%	2.62%	2.70%
SCC-1b	3.12%	1.48%	3.50%	2.53%	1.62%	3.56%
SCC-1c	1.88%	1.27%	1.23%	0.63%	1.40%	2.14%
PCC-2	1.77%	2.21%	2.06%	1.90%	1.59%	2.07%
PCC-2a	1.39%	1.98%	2.45%	1.95%	1.34%	1.32%
PCC-2b	2.17%	2.69%	0.98%	1.31%	4.10%	0.89%
PCC-2c	0.57%	3.01%	6.50%	3.80%	2.87%	2.44%
PCC-2d	1.30%	2.03%	1.55%	0.57%	0.80%	0.72%
PCC-2e	0.97%	1.11%	1.75%	1.37%	1.11%	1.37%
PCC-3	2.21%	0.87%	1.98%	0.69%	0.86%	1.06%
PCC-3a	2.22%	10.42%	2.11%	0.72%	5.67%	2.50%

Table A 14: Durability Compressive Strength for Unconditioned Specimens

Mix Design	Unconditioned Compressive Strength (psi)			
	Specimen 01	Specimen 02	Specimen 03	Average
SCC-1	8820	8470	8313	8534
SCC-1a	8470	8662	8186	8439
SCC-1b	9732	9917	8820	9490
SCC-1c	8663	8790	8028	8494
PCC-2	8679	8458	8826	8654
PCC-2a	5677	5455	5641	5591
PCC-2b	5886	5345	7413	6215
PCC-2c	9592	9276	10076	9648
PCC-2d	8088	8638	7978	8235
PCC-2e	9921	10901	9187	10003

PCC-3	8313	7248	6614	7392
PCC-3a	8329	8178	8470	8326

Table A 15: Durability Compressive Strength for Conditioned Specimens

Mix Design	***Conditioned Compressive Strength (psi)***				
	Specimen 01	***Specimen 02***	***Specimen 03***	***Specimen 04***	***Average***
SCC-1	8663	7451	8315	8313	8186
SCC-1a	8031	7055	8223	7690	7750
SCC-1b	9135	8820	9542	8457	8989
SCC-1c	8522	8157	7091	8458	8057
PCC-2	6461	7533	7055	8156	7301
PCC-2a	4664	5641	4591	5171	5017
PCC-2b	5570	5298	5797	6015	5670
PCC-2c	9377	8512	9408	8065	8840
PCC-2d	8490	6964	7204	8302	7740
PCC-2e	10281	9929	8490	8623	9331
PCC-3	6461	7043	7405	6883	6948
PCC-3a	8440	7910	8770	8120	8310

Table A 16: Durability Bond Shear Strength for Unconditioned Specimens

Mix Design	***Unconditioned Bond Shear Strength (psi)***			
	Specimen 01	***Specimen 02***	***Specimen 03***	***Average***
SCC-1	6422	6118	5727	6089
SCC-1a	5641	5991	5662	5765
SCC-1b	6461	6897	5164	6174
SCC-1c	5678	5990	5483	5717
PCC-2	3632	3160	3502	3431
PCC-2a	3317	3605	2832	3251
PCC-2b	2691	2629	2571	2630
PCC-2c	3035	4238	2670	3314
PCC-2d	3102	1983	2655	2580
PCC-2e	2906	3469	4179	3518
PCC-3	3784	3475	4606	3955
PCC-3a	4548	4619	4067	4411

Table A 17: Phase I Durability Bond Shear Strength for Unconditioned Specimens (red shading indicates result where bond shear connection broke in chamber)

Mix Design	*Conditioned Bond Shear Strength (psi)*				
	Specimen 01	*Specimen 02*	*Specimen 03*	*Specimen 04*	*Average*
SCC-1	5612	6871	5689	5356	5882
SCC-1a	4889	4650	5566	4622	4932
SCC-1b	5677	5552	5169	6119	5629
SCC-1c	5482	5046	5625	4606	5190
PCC-2	2721	3177	0	0	1474
PCC-2a	2878	0	2780	3161	2205
PCC-2b	2498	0	0	0	624
PCC-2c	2728	0	2372	2842	1985
PCC-2d	1578	0	1965	0	886
PCC-2e	0	4434	1907	0	1585
PCC-3	3602	3192	3471	3098	3340
PCC-3a	3317	3912	4089	4262	3895

Table A 18: Phase I Surface Resistivity at 7 Days

MIX ID	*Surface Resistivity (kΩ) at 7 Days*								
	Specimen 01				*Specimen 02*				
	M1	*M2*	*M3*	*M4*	*M1*	*M2*	*M3*	*M4*	*Avg*
SCC-1	5.9	6.9	5.0	6.4	8.0	5.0	5.1	6.6	6.1
SCC-1a	6.1	8.0	8.5	5.0	5.1	3.9	5.8	5.0	5.9
SCC-1b	5.9	5.9	6.6	5.0	4.2	4.8	5.3	4.2	5.2
SCC-1c	4.8	3.1	5.3	6.0	4.4	5.3	6.6	5.1	5.1
PCC-2	5.9	6.9	6.3	8.6	7.0	6.4	5.2	5.2	6.4
PCC-2a	7.9	6.6	7.0	5.9	6.4	7.3	6.3	7.2	6.8
PCC-2b	8.9	7.2	8.6	7.6	10.0	7.6	6.1	8.6	8.1
PCC-2c	6.6	7.6	7.2	8.6	6.4	7.8	8.1	6.9	7.4
PCC-2d	5.9	4.7	7.4	4.7	3.9	5.6	5.2	5.0	5.3
PCC-2e	5.1	4.2	4.7	5.6	4.7	4.1	5.6	4.8	4.8
PCC-3	6.1	8.6	5.0	5.1	6.4	5.1	6.7	5.7	6.1
PCC-3a	6.0	5.8	6.8	4.9	4.7	5.7	6.1	5.0	5.6

Table A 19: Surface Resistivity at 14 Days

MIX ID	Surface Resistivity (kΩ) at 14 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	11.9	13.0	13.3	13.9	11.3	11.0	11.7	11.8	12.2
SCC-1a	8.9	10.5	9.3	9.5	8.0	8.2	8.3	8.3	8.9
SCC-1b	5.5	5.8	5.8	6.8	6.2	6.7	6.2	6.7	6.2
SCC-1c	5.9	6.6	7.2	6.1	6.4	6.9	7.4	7.5	6.7
PCC-2	6.9	8.1	8.5	7.0	7.5	7.8	8.0	7.9	7.7
PCC-2a	12.0	14.4	14.2	12.5	12.0	14.1	12.2	13.1	13.0
PCC-2b	14.9	10.0	16.8	13.9	14.9	15.2	12.6	13.9	14.0
PCC-2c	12.2	10.2	9.9	12.5	12.2	13.6	11.7	10.0	11.5
PCC-2d	15.0	11.4	14.9	15.0	11.4	12.5	15.6	16.8	14.1
PCC-2e	13.6	14.2	12.3	14.2	13.4	12.4	16.8	14.3	13.9
PCC-3	14.1	13.1	12.5	14.5	14.1	14.5	14.9	15.1	14.1
PCC-3a	11.3	13.4	13.7	13.8	11.8	13.1	14.8	15.5	13.4

Table A 20: Surface Resistivity at 28 Days

MIX ID	Surface Resistivity (kΩ) at 28 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	9.6	10.5	13.1	12.2	9.9	11.8	11.3	11.9	11.3
SCC-1a	8.7	8.0	9.1	7.5	8.6	9.3	8.0	8.6	8.5
SCC-1b	5.9	9.4	7.1	8.0	5.2	6.7	7.1	6.1	6.9
SCC-1c	6.6	6.4	7.2	6.9	7.3	6.1	7.2	7.4	6.9
PCC-2	10.8	5.9	8.6	8.0	9.1	11.1	7.4	6.6	8.4
PCC-2a	21.8	20.6	21.6	16.9	17.6	17.8	16.8	17.2	18.8
PCC-2b	17.6	21.4	19.6	16.8	21.9	16.9	20.1	20.3	19.3
PCC-2c	17.2	17.6	15.1	14.2	19.7	16.9	15.0	17.2	16.6
PCC-2d	25.1	22.3	26.0	22.3	28.3	22.4	22.1	25.4	24.2
PCC-2e	21.9	19.6	17.4	22.3	20.0	21.8	19.6	19.7	20.3
PCC-3	17.6	15.9	14.7	14.0	14.2	15.3	12.6	14.4	14.8
PCC-3a	14.5	13.5	12.3	14.1	15.7	15.0	12.5	14.0	13.9

Table A 21: Surface Resistivity at 100 Cycles

MIX ID	Surface Resistivity (kΩ) at 100 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	11.3	14.1	11.9	12.3	14.0	10.1	12.1	11.0	12.1
SCC-1a	6.0	7.1	8.4	8.1	7.8	9.6	9.0	9.2	8.1
SCC-1b	6.3	6.9	7.1	6.0	4.8	4.6	4.3	5.5	5.7
SCC-1c	8.1	8.8	7.9	7.3	8.6	8.7	8.9	8.0	8.3
PCC-2	11.3	11.9	12.3	10.0	10.8	11.2	10.6	10.0	11.0
PCC-2a	17.6	19.0	21.9	19.1	22.4	21.6	19.6	22.5	20.5
PCC-2b	28.1	32.6	32.5	30.0	28.9	28.4	30.9	29.8	30.1
PCC-2c	27.6	24.7	25.1	25.8	24.7	25.1	26.8	24.0	25.4
PCC-2d	31.0	28.1	33.2	31.7	28.3	31.4	32.0	28.8	30.5
PCC-2e	22.3	21.9	19.1	22.3	19.6	22.3	20.3	19.7	20.9
PCC-3	17.6	15.3	17.0	19.1	15.3	17.1	14.1	16.4	16.5
PCC-3a	14.3	12.3	11.6	13.3	16.3	15.5	14.3	14.4	14.0

Table A 22: Surface Resistivity at 200 Cycles

MIX ID	Surface Resistivity (kΩ) at 200 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	14.2	11.6	11.1	11.3	10.0	10.6	9.4	12.8	11.4
SCC-1a	8.0	7.5	8.0	9.0	6.9	9.1	9.8	7.8	8.3
SCC-1b	6.1	6.6	5.1	5.7	5.0	5.0	4.4	5.3	5.4
SCC-1c	10.8	9.1	9.6	10.0	9.9	10.5	8.9	8.6	9.7
PCC-2	12.0	11.6	12.3	11.4	11.9	12.1	11.2	11.4	11.7
PCC-2a	20.3	21.7	24.1	21.9	20.4	18.1	17.5	17.8	20.2
PCC-2b	21.9	24.7	21.9	23.4	23.9	21.9	24.4	25.4	23.4
PCC-2c	27.2	26.3	27.6	28.1	25.0	28.9	25.3	25.0	26.7
PCC-2d	22.7	24.1	17.6	21.3	22.5	20.3	20.6	20.0	21.1
PCC-2e	20.6	19.6	15.8	19.6	22.8	21.8	21.8	21.5	20.4
PCC-3	17.9	16.9	17.1	17.5	16.8	15.7	16.8	16.7	16.9
PCC-3a	12.2	16.8	14.1	13.6	14.1	15.3	16.3	14.8	14.6

Table A 23: Surface Resistivity at 300 Cycles

MIX ID	Surface Resistivity (kΩ) at 300 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	9.6	11.3	10.0	10.5	13.6	11.3	9.6	9.3	10.7
SCC-1a	7.5	5.6	6.4	5.8	5.0	5.3	5.9	5.6	5.9
SCC-1b	5.0	4.7	5.0	5.3	6.1	4.9	4.4	4.7	5.0
SCC-1c	9.7	8.0	8.0	10.0	10.3	8.6	9.1	10.2	9.2
PCC-2	12.8	12.3	12.2	12.8	12.6	13.9	14.1	12.4	12.9
PCC-2a	20.3	19.7	20.3	18.6	21.9	19.6	16.8	21.4	19.8
PCC-2b	20.4	21.7	20.5	20.0	18.6	20.0	20.8	19.1	20.1
PCC-2c	27.0	30.5	30.8	31.5	26.3	20.7	30.0	34.5	28.9
PCC-2d	17.6	16.4	22.1	20.4	19.6	20.7	21.3	26.9	20.6
PCC-2e	21.4	26.5	22.9	21.0	17.5	21.1	19.6	21.5	21.4
PCC-3	16.8	18.6	18.1	17.3	17.8	15.9	16.4	15.3	17.0
PCC-3a	16.3	14.2	13.6	14.2	12.3	14.0	17.0	15.6	14.6

APPENDIX B: LABORATORY RESULTS FROM TASK-3

Table A 24: Batch Components for Task-2 SCC-1 and PCC-3 Mix Iterations

Batch Material	*SCC-1*	*SCC-1a*	*SCC-1b*	*SCC-1c*	*PCC-3*	*PCC-3a*
Water (lbs.)	38.0	28.4	40.4	34.6	42.5	44.4
Portland Cement Content (lbs.)	63.8	51.9	66.7	60.0	114.9	136.7
Blended Cement (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Slag (lbs.)	63.8	51.9	66.7	60.0	n.a.	n.a.
Fly Ash (lbs.)	n.a.	n.a.	n.a.	n.a.	23.0	27.3
Silica Fume (lbs.)	7.5	6.1	7.8	7.1	n.a.	n.a.
Coarse Aggregate (lbs.)	221.4	193.5	197.6	199.6	232.7	227.5
Fine Aggregate (lbs.)	190.1	176.1	132.2	155.5	201.8	146.7
Air Entrainer (mL)	22.18	19.17	19.72	19.72	5.59	5.39
High Range Water Reducer (mL)	150.83	115.46	185.56	150.30	394.19	578.02
Workability Retainer (mL)	94.27	72.16	115.97	93.94	1087.43	1594.54
Shrinkage Reducer (lbs.)	1.88	1.62	1.67	1.67	0.66	0.63

n.a.: not applicable

Table A 25: Batch Components for Task-2 PCC-2 Mix Iterations

Batch Material	*PCC-2*	*PCC-2a*	*PCC-2b*	*PCC-2c*	*PCC-2d*	*PCC-2e*
Water (lbs.)	48.4	38.9	22.1	48.4	42.0	57.1
Portland Cement Content (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Blended Cement (lbs.)	150.0	125.0	160.4	163.3	140.0	186.7
Slag (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fly Ash (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Silica Fume (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Coarse Aggregate (lbs.)	247.8	248.8	297.3	234.0	232.1	232.1
Fine Aggregate (lbs.)	206.7	249.7	300.6	144.2	195.3	115.8
Air Entrainer (mL)	197.16	197.16	230.02	184.01	184.01	184.01
High Range Water Reducer (mL)	354.88	246.45	347.90	450.83	331.22	588.84
Workability Retainer (mL)	266.16	184.83	260.92	338.12	248.42	441.63
Shrinkage Reducer (lbs.)	1.39	1.39	1.62	1.30	1.30	1.30

n.a.: not applicable

Table A 26: Batch Components for Task-3 Mix iterations

Batch Material	***T3-M01***	***T3-M02***	***T3-M03***	***T3-M04***	***T3-M05***	***T3-M06***	***T3-M07***	***T3-M08***
Water (lbs.)	5.4	5.7	6.7	5.4	5.6	4.8	6.0	7.4
Portland Cement Content (lbs.)	12.4	12.4	14.0	11.3	11.6	12.4	12.4	11.5
Blended Cement (lbs.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Slag (lbs.)	n.a.	8.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fly Ash (lbs.)	8.7	n.a.	9.8	9.8	9.6	8.7	8.7	8.0
Silica Fume (lbs.)	1.1	1.1	1.3	1.1	1.1	1.1	1.1	1.0
Coarse Aggregate (lbs.)	41.6	41.4	41.4	41.6	41.4	41.6	41.6	37.8
Fine Aggregate (lbs.)	47.2	47.2	43.2	48.2	48.0	48.8	45.7	41.7
Air Entrainer (mL)	36.97	36.97	36.97	32.86	32.86	32.86	32.86	30.32
High Range Water Reducer (mL)	32.86	32.86	32.86	26.81	30.76	29.44	29.44	27.17
Workability Retainer (mL)	22.08	22.08	37.26	20.11	20.50	22.08	22.08	20.37
Shrinkage Reducer (lbs.)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.21

Table A 27: 28 Day Shrinkage Values for Task-2

Mix Design	28 Day % Length Change
SCC-1	0.390%
SCC-1a	0.301%
SCC-1b	0.398%
SCC-1c	0.360%
PCC-2	0.356%
PCC-2a	0.334%
PCC-2b	0.380%
PCC-2c	0.324%
PCC-2d	0.314%
PCC-2e	0.417%
PCC-3	0.320%
PCC-3a	0.389%

Table A 28: Flexural Strength at 3 and 28 days for Task-2

Mix Design	3 Day Modulus of Rupture - Specimen 01 (psi)	3 Day Modulus of Rupture - Specimen 02 (psi)	3 Day Modulus of Rupture - Average (psi)	28 Day Modulus of Rupture - Specimen 01 (psi)	28 Day Modulus of Rupture - Specimen 02 (psi)	28 Day Modulus of Rupture - Average (psi)
SCC-1	1024	947	507	1323	1211	1390
SCC-1a	815	829	822	1207	1276	1241
SCC-1b	808	800	804	1165	1168	1166
SCC-1c	853	924	889	1165	1185	1175
PCC-2	1331	1196	1263	1402	1277	1340
PCC-2a	859	729	794	1121	1286	1204
PCC-2b	1164	1029	1096	1102	1176	1139
PCC-2c	990	1004	997	1331	1196	1263
PCC-2d	899	863	881	1058	1209	1133
PCC-2e	1010	1093	1051	1349	1476	1413
PCC-3	672	632	652	823	805	814
PCC-3a	834	769	801	1289	1211	1250

Table A 29: Compressive Strengths at 1 Day for Task-2

Mix Design	*1 Day Compressive Strength - Specimen 01 (psi)*	*1 Day Compressive Strength - Specimen 02 (psi)*	*1 Day Compressive Strength - Specimen 03 (psi)*	*1 Day Compressive Strength - Specimen 04 (psi)*	*1 Day Compressive Strength - Average (psi)*
SCC-1	1816	1830	1848	n.a.	1831
SCC-1a	1379	1399	1329	n.a.	1369
SCC-1b	1286	1485	1588	n.a.	1453
SCC-1c	1381	1709	1588	n.a.	1559
PCC-2	2570	2740	2522	n.a.	2611
PCC-2a	2590	2768	2546	n.a.	2635
PCC-2b	2767	2831	2888	n.a.	2829
PCC-2c	3507	3635	3748	n.a.	3630
PCC-2d	3048	3328	3143	n.a.	3173
PCC-2e	3925	4304	4379	n.a.	4202
PCC-3	2063	2215	2056	n.a.	2112
PCC-3a	2115	2026	2109	n.a.	2083

n.a.: not applicable

Table A 30: Compressive Strengths at 2 Days for Task-2

Mix Design	*2 Day Compressive Strength - Specimen 01 (psi)*	*2 Day Compressive Strength - Specimen 02 (psi)*	*2 Day Compressive Strength - Specimen 03 (psi)*	*2 Day Compressive Strength - Specimen 04 (psi)*	*1 Day Compressive Strength - Average (psi)*
SCC-1	4319	3725	4093	n.a.	4045
SCC-1a	3253	2809	3311	n.a.	3124
SCC-1b	3355	4171	4354	n.a.	3960
SCC-1c	2899	2603	3306	n.a.	2936
PCC-2	3951	3796	3814	n.a.	3854
PCC-2a	3951	3796	3814	n.a.	3854
PCC-2b	3645	3725	3454	n.a.	3608
PCC-2c	5033	5395	4744	n.a.	5058
PCC-2d	4013	3959	3689	n.a.	3887
PCC-2e	4757	4836	5788	n.a.	5127
PCC-3	4580	4015	4572	n.a.	4389
PCC-3a	5373	5690	5238	n.a.	5434

n.a.: not applicable

Table A 31: Compressive Strengths at 7 Days for Task-2

Mix Design	***7 Day Compressive Strength - Specimen 01 (psi)***	***7 Day Compressive Strength - Specimen 02 (psi)***	***7 Day Compressive Strength - Specimen 03 (psi)***	***7 Day Compressive Strength - Specimen 04 (psi)***	***7 Day Compressive Strength - Average (psi)***
SCC-1	3836	4131	3715	n.a.	3894
SCC-1a	3773	3895	4590	n.a.	4086
SCC-1b	4988	4915	4784	n.a.	4896
SCC-1c	4988	4915	4784	n.a.	4896
PCC-2	5013	5511	5219	n.a.	5248
PCC-2a	6073	5705	5490	6213	5870
PCC-2b	4269	4940	4213	n.a.	4474
PCC-2c	6751	6858	6139	n.a.	6583
PCC-2d	5855	5588	5302	n.a.	5582
PCC-2e	5757	5931	6252	n.a.	5980
PCC-3	6008	5825	5557	n.a.	5797
PCC-3a	6091	5846	6250	n.a.	6062

n.a.: not applicable

Table A 32: Compressive Strengths at 28 Days for Task-2

Mix Design	***28 Day Compressive Strength - Specimen 01 (psi)***	***28 Day Compressive Strength - Specimen 02 (psi)***	***28 Day Compressive Strength - Specimen 03 (psi)***	***28 Day Compressive Strength - Specimen 04 (psi)***	***28 Day Compressive Strength - Average (psi)***
SCC-1	4966	5482	5424	n.a.	5291
SCC-1a	6091	5375	5118	n.a.	5528
SCC-1b	6284	6164	6439	n.a.	6296
SCC-1c	6279	6521	6112	n.a.	6304
PCC-2	5840	6540	6260	n.a.	6213
PCC-2a	6543	6712	6365	n.a.	6540
PCC-2b	6390	5831	5802	n.a.	6008
PCC-2c	7604	8419	7964	n.a.	7995
PCC-2d	6999	6962	6389	n.a.	6783
PCC-2e	9464	8008	7779	8656	8477
PCC-3	6799	8424	7970	n.a.	7731
PCC-3a	9498	8368	8389	8687	8735

n.a.: not applicable

Table A 33: Bond Shear Strengths at 1 Day for Task-2

Mix Design	*1 Day Bond Shear Strength - Specimen 01 (psi)*	*1 Day Bond Shear Strength - Specimen 02 (psi)*	*1 Day Bond Shear Strength - Specimen 03 (psi)*	*1 Day Bond Shear Strength - Specimen 04 (psi)*	*1 Day Bond Shear Strength - Average (psi)*
SCC-1	1816	1879	1865	n.a.	1854
SCC-1a	1124	1011	1516	n.a.	1217
SCC-1b	1066	1052	1381	n.a.	1166
SCC-1c	1115	1021	1350	n.a.	1162
PCC-2	3374	2380	2643	n.a.	2799
PCC-2a	1877	1714	1797	n.a.	1796
PCC-2b	2276	1904	1591	n.a.	1924
PCC-2c	1646	1838	2702	n.a.	2062
PCC-2d	1966	1916	1964	n.a.	1949
PCC-2e	2898	2469	2392	n.a.	2586
PCC-3	1654	1474	1400	n.a.	1509
PCC-3a	2187	2654	2341	n.a.	2394

n.a.: not applicable

Table A 34: Bond Shear Strengths at 3 Days for Task-2

Mix Design	*3 Day Bond Shear Strength - Specimen 01 (psi)*	*3 Day Bond Shear Strength - Specimen 02 (psi)*	*3 Day Bond Shear Strength - Specimen 03 (psi)*	*3 Day Bond Shear Strength - Specimen 04 (psi)*	*3 Day Bond Shear Strength - Average (psi)*
SCC-1	1543	1606	1535	n.a.	1561
SCC-1a	3960	2718	3303	n.a.	3327
SCC-1b	3147	2619	2850	n.a.	2872
SCC-1c	3632	3410	4209	n.a.	3750
PCC-2	2154	2259	1795	n.a.	2069
PCC-2a	2325	2106	2378	n.a.	2270
PCC-2b	2135	2461	3405	n.a.	2667
PCC-2c	1879	2346	2548	n.a.	2257
PCC-2d	2955	2242	2506	n.a.	2567
PCC-2e	2688	2564	3176	1105	2809
PCC-3	2798	2070	2005	n.a.	2291
PCC-3a	4765	5887	5228	n.a.	5293

n.a.: not applicable

Table A 35: Bond Shear Strengths at 28 Days for Task-2

Mix Design	*28 Day Bond Shear Strength - Specimen 01 (psi)*	*28 Day Bond Shear Strength - Specimen 02 (psi)*	*28 Day Bond Shear Strength - Specimen 03 (psi)*	*28 Day Bond Shear Strength - Specimen 04 (psi)*	*28 Day Bond Shear Strength - Average (psi)*
SCC-1	2111	2131	2273	n.a.	2171
SCC-1a	4109	4480	4209	n.a.	4266
SCC-1b	4455	4067	3487	n.a.	4003
SCC-1c	3632	3410	4209	n.a.	3750
PCC-2	2455	3653	3828	n.a.	3312
PCC-2a	2940	3093	3161	n.a.	3065
PCC-2b	3912	3755	2623	n.a.	3430
PCC-2c	2921	2807	3129	n.a.	2952
PCC-2d	3759	2810	3028	n.a.	3199
PCC-2e	4374	4984	5760	n.a.	5039
PCC-3	3441	2883	3591	3088	3251
PCC-3a	6482	7284	7641	n.a.	7136

n.a.: not applicable

Table A 36: Mass Loss for Specimens 1 & 2 for Task-2

Mix Design	*Mass Loss Specimen 1*			*Mass Loss Specimen 2*		
	0-100 cycles	*100-200 cycles*	*200-300 cycles*	*0-100 cycles*	*100-200 cycles*	*200-300 cycles*
SCC-1	1.72%	0.62%	1.14%	1.69%	0.19%	0.54%
SCC-1a	2.82%	1.98%	1.46%	-1.04%	1.92%	1.49%
SCC-1b	1.53%	1.00%	1.83%	1.38%	1.35%	1.35%
SCC-1c	1.38%	0.74%	2.16%	1.27%	1.67%	1.88%
PCC-2	1.32%	1.25%	2.25%	0.98%	1.49%	1.38%
PCC-2a	0.99%	1.40%	1.20%	1.12%	1.91%	1.81%
PCC-2b	1.71%	3.76%	0.89%	1.46%	3.11%	0.86%
PCC-2c	0.59%	4.04%	4.06%	0.90%	5.96%	10.24%
PCC-2d	1.23%	3.35%	2.50%	0.31%	1.34%	1.39%
PCC-2e	0.89%	0.46%	1.27%	0.59%	0.70%	1.20%
PCC-3	1.48%	1.31%	1.16%	1.89%	1.81%	1.67%
PCC-3a	1.57%	3.57%	2.06%	2.86%	2.99%	0.57%

Table A 37: Mass Loss for Specimens 3 & 4 for Task-2

Mix Design	Mass Loss Specimen 3			Mass Loss Specimen 4		
	0-100 cycles	100-200 cycles	200-300 cycles	0-100 cycles	100-200 cycles	200-300 cycles
SCC-1	1.95%	0.66%	1.33%	1.28%	1.06%	0.80%
SCC-1a	4.81%	2.32%	2.04%	2.90%	2.62%	2.70%
SCC-1b	3.12%	1.48%	3.50%	2.53%	1.62%	3.56%
SCC-1c	1.88%	1.27%	1.23%	0.63%	1.40%	2.14%
PCC-2	1.77%	2.21%	2.06%	1.90%	1.59%	2.07%
PCC-2a	1.39%	1.98%	2.45%	1.95%	1.34%	1.32%
PCC-2b	2.17%	2.69%	0.98%	1.31%	4.10%	0.89%
PCC-2c	0.57%	3.01%	6.50%	3.80%	2.87%	2.44%
PCC-2d	1.30%	2.03%	1.55%	0.57%	0.80%	0.72%
PCC-2e	0.97%	1.11%	1.75%	1.37%	1.11%	1.37%
PCC-3	2.21%	0.87%	1.98%	0.69%	0.86%	1.06%
PCC-3a	2.22%	10.42%	2.11%	0.72%	5.67%	2.50%

Table A 38: Durability Compressive Strength for Unconditioned Specimens for Task-2

Mix Design	Unconditioned Compressive Strength (psi)			
	Specimen 01	Specimen 02	Specimen 03	Average
SCC-1	8820	8470	8313	8534
SCC-1a	8470	8662	8186	8439
SCC-1b	9732	9917	8820	9490
SCC-1c	8663	8790	8028	8494
PCC-2	8679	8458	8826	8654
PCC-2a	5677	5455	5641	5591
PCC-2b	5886	5345	7413	6215
PCC-2c	9592	9276	10076	9648
PCC-2d	8088	8638	7978	8235
PCC-2e	9921	10901	9187	10003
PCC-3	8313	7248	6614	7392
PCC-3a	8329	8178	8470	8326

Table A 39: Durability Compressive Strength for Conditioned Specimens for Task-2

Mix Design	*Conditioned Compressive Strength (psi)*				
	Specimen 01	*Specimen 02*	*Specimen 03*	*Specimen 04*	*Average*
SCC-1	8663	7451	8315	8313	8186
SCC-1a	8031	7055	8223	7690	7750
SCC-1b	9135	8820	9542	8457	8989
SCC-1c	8522	8157	7091	8458	8057
PCC-2	6461	7533	7055	8156	7301
PCC-2a	4664	5641	4591	5171	5017
PCC-2b	5570	5298	5797	6015	5670
PCC-2c	9377	8512	9408	8065	8840
PCC-2d	8490	6964	7204	8302	7740
PCC-2e	10281	9929	8490	8623	9331
PCC-3	6461	7043	7405	6883	6948
PCC-3a	8440	7910	8770	8120	8310

Table A 40: Durability Bond Shear Strength for Unconditioned Specimens for Task-2

Mix Design	*Unconditioned Bond Shear Strength (psi)*			
	Specimen 01	*Specimen 02*	*Specimen 03*	*Average*
SCC-1	6422	6118	5727	6089
SCC-1a	5641	5991	5662	5765
SCC-1b	6461	6897	5164	6174
SCC-1c	5678	5990	5483	5717
PCC-2	3632	3160	3502	3431
PCC-2a	3317	3605	2832	3251
PCC-2b	2691	2629	2571	2630
PCC-2c	3035	4238	2670	3314
PCC-2d	3102	1983	2655	2580
PCC-2e	2906	3469	4179	3518
PCC-3	3784	3475	4606	3955
PCC-3a	4548	4619	4067	4411

Table A 41: Phase I Durability Bond Shear Strength for Unconditioned Specimens for Task-2 (red shading indicates result where bond shear connection broke in chamber)

Mix Design	*Conditioned Bond Shear Strength (psi)*				
	Specimen 01	*Specimen 02*	*Specimen 03*	*Specimen 04*	*Average*
SCC-1	5612	6871	5689	5356	5882
SCC-1a	4889	4650	5566	4622	4932
SCC-1b	5677	5552	5169	6119	5629
SCC-1c	5482	5046	5625	4606	5190
PCC-2	2721	3177	0	0	1474
PCC-2a	2878	0	2780	3161	2205
PCC-2b	2498	0	0	0	624
PCC-2c	2728	0	2372	2842	1985
PCC-2d	1578	0	1965	0	886
PCC-2e	0	4434	1907	0	1585
PCC-3	3602	3192	3471	3098	3340
PCC-3a	3317	3912	4089	4262	3895

Table A 42: Phase I Surface Resistivity at 7 Days for Task-2

MIX ID	*Surface Resistivity (kΩ) at 7 Days*								
	Specimen 01				*Specimen 02*				
	M1	*M2*	*M3*	*M4*	*M1*	*M2*	*M3*	*M4*	*Avg*
SCC-1	5.9	6.9	5.0	6.4	8.0	5.0	5.1	6.6	6.1
SCC-1a	6.1	8.0	8.5	5.0	5.1	3.9	5.8	5.0	5.9
SCC-1b	5.9	5.9	6.6	5.0	4.2	4.8	5.3	4.2	5.2
SCC-1c	4.8	3.1	5.3	6.0	4.4	5.3	6.6	5.1	5.1
PCC-2	5.9	6.9	6.3	8.6	7.0	6.4	5.2	5.2	6.4
PCC-2a	7.9	6.6	7.0	5.9	6.4	7.3	6.3	7.2	6.8
PCC-2b	8.9	7.2	8.6	7.6	10.0	7.6	6.1	8.6	8.1
PCC-2c	6.6	7.6	7.2	8.6	6.4	7.8	8.1	6.9	7.4
PCC-2d	5.9	4.7	7.4	4.7	3.9	5.6	5.2	5.0	5.3
PCC-2e	5.1	4.2	4.7	5.6	4.7	4.1	5.6	4.8	4.8
PCC-3	6.1	8.6	5.0	5.1	6.4	5.1	6.7	5.7	6.1
PCC-3a	6.0	5.8	6.8	4.9	4.7	5.7	6.1	5.0	5.6

Table A 43: Surface Resistivity at 14 Days for Task-2

MIX ID	Surface Resistivity (kΩ) at 14 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	11.9	13.0	13.3	13.9	11.3	11.0	11.7	11.8	12.2
SCC-1a	8.9	10.5	9.3	9.5	8.0	8.2	8.3	8.3	8.9
SCC-1b	5.5	5.8	5.8	6.8	6.2	6.7	6.2	6.7	6.2
SCC-1c	5.9	6.6	7.2	6.1	6.4	6.9	7.4	7.5	6.7
PCC-2	6.9	8.1	8.5	7.0	7.5	7.8	8.0	7.9	7.7
PCC-2a	12.0	14.4	14.2	12.5	12.0	14.1	12.2	13.1	13.0
PCC-2b	14.9	10.0	16.8	13.9	14.9	15.2	12.6	13.9	14.0
PCC-2c	12.2	10.2	9.9	12.5	12.2	13.6	11.7	10.0	11.5
PCC-2d	15.0	11.4	14.9	15.0	11.4	12.5	15.6	16.8	14.1
PCC-2e	13.6	14.2	12.3	14.2	13.4	12.4	16.8	14.3	13.9
PCC-3	14.1	13.1	12.5	14.5	14.1	14.5	14.9	15.1	14.1
PCC-3a	11.3	13.4	13.7	13.8	11.8	13.1	14.8	15.5	13.4

Table A 44: Surface Resistivity at 28 Days for Task-2

MIX ID	Surface Resistivity (kΩ) at 28 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	9.6	10.5	13.1	12.2	9.9	11.8	11.3	11.9	11.3
SCC-1a	8.7	8.0	9.1	7.5	8.6	9.3	8.0	8.6	8.5
SCC-1b	5.9	9.4	7.1	8.0	5.2	6.7	7.1	6.1	6.9
SCC-1c	6.6	6.4	7.2	6.9	7.3	6.1	7.2	7.4	6.9
PCC-2	10.8	5.9	8.6	8.0	9.1	11.1	7.4	6.6	8.4
PCC-2a	21.8	20.6	21.6	16.9	17.6	17.8	16.8	17.2	18.8
PCC-2b	17.6	21.4	19.6	16.8	21.9	16.9	20.1	20.3	19.3
PCC-2c	17.2	17.6	15.1	14.2	19.7	16.9	15.0	17.2	16.6
PCC-2d	25.1	22.3	26.0	22.3	28.3	22.4	22.1	25.4	24.2
PCC-2e	21.9	19.6	17.4	22.3	20.0	21.8	19.6	19.7	20.3
PCC-3	17.6	15.9	14.7	14.0	14.2	15.3	12.6	14.4	14.8
PCC-3a	14.5	13.5	12.3	14.1	15.7	15.0	12.5	14.0	13.9

Table A 45: Surface Resistivity at 100 Cycles for Task-2

MIX ID	Surface Resistivity (kΩ) at 100 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	11.3	14.1	11.9	12.3	14.0	10.1	12.1	11.0	12.1
SCC-1a	6.0	7.1	8.4	8.1	7.8	9.6	9.0	9.2	8.1
SCC-1b	6.3	6.9	7.1	6.0	4.8	4.6	4.3	5.5	5.7
SCC-1c	8.1	8.8	7.9	7.3	8.6	8.7	8.9	8.0	8.3
PCC-2	11.3	11.9	12.3	10.0	10.8	11.2	10.6	10.0	11.0
PCC-2a	17.6	19.0	21.9	19.1	22.4	21.6	19.6	22.5	20.5
PCC-2b	28.1	32.6	32.5	30.0	28.9	28.4	30.9	29.8	30.1
PCC-2c	27.6	24.7	25.1	25.8	24.7	25.1	26.8	24.0	25.4
PCC-2d	31.0	28.1	33.2	31.7	28.3	31.4	32.0	28.8	30.5
PCC-2e	22.3	21.9	19.1	22.3	19.6	22.3	20.3	19.7	20.9
PCC-3	17.6	15.3	17.0	19.1	15.3	17.1	14.1	16.4	16.5
PCC-3a	14.3	12.3	11.6	13.3	16.3	15.5	14.3	14.4	14.0

Table A 46: Surface Resistivity at 200 Cycles for Task-2

MIX ID	Surface Resistivity (kΩ) at 200 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	14.2	11.6	11.1	11.3	10.0	10.6	9.4	12.8	11.4
SCC-1a	8.0	7.5	8.0	9.0	6.9	9.1	9.8	7.8	8.3
SCC-1b	6.1	6.6	5.1	5.7	5.0	5.0	4.4	5.3	5.4
SCC-1c	10.8	9.1	9.6	10.0	9.9	10.5	8.9	8.6	9.7
PCC-2	12.0	11.6	12.3	11.4	11.9	12.1	11.2	11.4	11.7
PCC-2a	20.3	21.7	24.1	21.9	20.4	18.1	17.5	17.8	20.2
PCC-2b	21.9	24.7	21.9	23.4	23.9	21.9	24.4	25.4	23.4
PCC-2c	27.2	26.3	27.6	28.1	25.0	28.9	25.3	25.0	26.7
PCC-2d	22.7	24.1	17.6	21.3	22.5	20.3	20.6	20.0	21.1
PCC-2e	20.6	19.6	15.8	19.6	22.8	21.8	21.8	21.5	20.4
PCC-3	17.9	16.9	17.1	17.5	16.8	15.7	16.8	16.7	16.9
PCC-3a	12.2	16.8	14.1	13.6	14.1	15.3	16.3	14.8	14.6

Table A 47: Surface Resistivity at 300 Cycles for Task-2

MIX ID	Surface Resistivity (kΩ) at 300 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
SCC-1	9.6	11.3	10.0	10.5	13.6	11.3	9.6	9.3	10.7
SCC-1a	7.5	5.6	6.4	5.8	5.0	5.3	5.9	5.6	5.9
SCC-1b	5.0	4.7	5.0	5.3	6.1	4.9	4.4	4.7	5.0
SCC-1c	9.7	8.0	8.0	10.0	10.3	8.6	9.1	10.2	9.2
PCC-2	12.8	12.3	12.2	12.8	12.6	13.9	14.1	12.4	12.9
PCC-2a	20.3	19.7	20.3	18.6	21.9	19.6	16.8	21.4	19.8
PCC-2b	20.4	21.7	20.5	20.0	18.6	20.0	20.8	19.1	20.1
PCC-2c	27.0	30.5	30.8	31.5	26.3	20.7	30.0	34.5	28.9
PCC-2d	17.6	16.4	22.1	20.4	19.6	20.7	21.3	26.9	20.6
PCC-2e	21.4	26.5	22.9	21.0	17.5	21.1	19.6	21.5	21.4
PCC-3	16.8	18.6	18.1	17.3	17.8	15.9	16.4	15.3	17.0
PCC-3a	16.3	14.2	13.6	14.2	12.3	14.0	17.0	15.6	14.6

Table A 48: Task-3 Compressive Strengths at 1 Day

Mix Design	1 Day Compressive Strength - Specimen 01 (psi)	1 Day Compressive Strength - Specimen 02 (psi)	1 Day Compressive Strength - Specimen 03 (psi)	1 Day Compressive Strength - Specimen 04 (psi)	1 Day Compressive Strength - Average (psi)
T3-M01	1579	1699	1592	n.a.	1623
T3-M02	1866	1699	2043	n.a.	1869
T3-M03	2043	1699	1645	n.a.	1796
T3-M04	1707	1955	1591	n.a.	1751
T3-M05	1866	1699	1901	n.a.	1822
T3-M06	2043	1964	2129	n.a.	2045
T3-M07	1574	1603	1667	n.a.	1615
T3-M08	1699	1778	1597	n.a.	1691

Table A 49: Task-3 Compressive Strengths at 2 Days

Mix Design	*2 Day Compressive Strength - Specimen 01 (psi)*	*2 Day Compressive Strength - Specimen 02 (psi)*	*2 Day Compressive Strength - Specimen 03 (psi)*	*2 Day Compressive Strength - Specimen 04 (psi)*	*1 Day Compressive Strength - Average (psi)*
T3-M01	3113	3634	3371	n.a.	3373
T3-M02	3634	4086	3387	n.a.	3702
T3-M03	3880	3969	4103	n.a.	3984
T3-M04	3721	3963	3720	n.a.	3801
T3-M05	3792	3982	4137	n.a.	3970
T3-M06	4253	3879	4077	n.a.	4070
T3-M07	3466	3466	3740	n.a.	3558
T3-M08	3632	3720	3880	n.a.	3744

Table A 50: Task-3 Compressive Strengths at 7 Days

Mix Design	*7 Day Compressive Strength - Specimen 01 (psi)*	*7 Day Compressive Strength - Specimen 02 (psi)*	*7 Day Compressive Strength - Specimen 03 (psi)*	*7 Day Compressive Strength - Specimen 04 (psi)*	*7 Day Compressive Strength - Average (psi)*
T3-M01	3880	3353	4077	n.a.	3770
T3-M02	4512	4676	3969	n.a.	4386
T3-M03	4777	5233	4676	n.a.	4895
T3-M04	4600	4882	4776	n.a.	4752
T3-M05	4757	4873	4790	n.a.	4807
T3-M06	4958	6259	5120	n.a.	5445
T3-M07	4271	4112	4375	n.a.	4253
T3-M08	4516	4660	4961	n.a.	4712

Table A 51: Task-3 Compressive Strengths at 28 Days

Mix Design	*28 Day Compressive Strength - Specimen 01 (psi)*	*28 Day Compressive Strength - Specimen 02 (psi)*	*28 Day Compressive Strength - Specimen 03 (psi)*	*28 Day Compressive Strength - Specimen 04 (psi)*	*28 Day Compressive Strength - Average (psi)*
T3-M01	1579	1699	3414 (excluded)	5471	5011
T3-M02	6363	5537	5786	n.a.	5895
T3-M03	7437	6975	7699	n.a.	7370
T3-M04	6252	5400	5669	n.a.	5773
T3-M05	6892	6624	5510	n.a.	6342
T3-M06	7996	7973	8275	n.a.	8081
T3-M07	4914	6611	5779	n.a.	5768
T3-M08	6663	6254	6926	n.a.	6614

Table A 52: Task-3 Bond Shear Strength at 28 Days

Mix Design	*28 Day Bond Shear Strength - Specimen 01 (psi)*	*28 Day Bond Shear Strength - Specimen 02 (psi)*	*28 Day Bond Shear Strength - Specimen 03 (psi)*	*28 Day Bond Shear Strength - Specimen 04 (psi)*	*28 Day Bond Shear Strength - Average (psi)*
T3-M01	4852	3948	3960	n.a.	4254
T3-M02	2626	3975	3823	n.a.	3474
T3-M03	4226	4449	3912	n.a.	4196
T3-M04	4419	6415	4889	n.a.	5241
T3-M05	4889	4265	4541	n.a.	4565
T3-M06	4226	3789	3632	n.a.	3882
T3-M07	4420	4881	4068	n.a.	4456
T3-M08	4040	4543	4272	n.a.	4285

Table A 53: Task-3 Mass Loss for Specimens 1 & 2

Mix Design	Mass Loss Specimen 1				Mass Loss Specimen 2			
	0-100 cycles	100-200 cycles	200-300 cycles	0-300 cycles	0-100 cycles	100-200 cycles	200-300 cycles	0-300 cycles
T3-M01	1.54%	2.24%	0.84%	4.55%	1.73%	2.42%	1.15%	5.22%
T3-M02	1.84%	1.33%	2.08%	5.15%	2.31%	1.57%	2.55%	6.29%
T3-M03	1.53%	2.60%	2.52%	6.50%	1.93%	2.79%	-0.72%	3.98%
T3-M04	1.99%	2.39%	2.76%	6.97%	3.24%	2.39%	3.48%	8.84%
T3-M05	2.06%	3.42%	2.03%	7.33%	3.28%	3.90%	2.49%	9.37%
T3-M06	1.52%	2.00%	1.53%	4.97%	0.97%	1.95%	1.64%	4.49%
T3-M07	3.04%	1.94%	1.41%	6.27%	1.99%	2.05%	2.94%	6.81%
T3-M08	2.01%	1.88%	1.20%	5.01%	1.36%	1.36%	0.84%	3.52%

Table A 54: Task-3 Mass Loss for Specimens 1 & 2

Mix Design	Mass Loss Specimen 3				Mass Loss Specimen 4			
	0-100 cycles	100-200 cycles	200-300 cycles	0-300 cycles	0-100 cycles	100-200 cycles	200-300 cycles	200-300 cycles
T3-M01	0.97%	2.72%	1.25%	1.59%	1.59%	1.07%	2.63%	5.21%
T3-M02	1.52%	1.69%	0.03%	2.08%	2.08%	1.56%	2.99%	6.49%
T3-M03	1.95%	3.52%	-1.00%	2.36%	2.36%	2.93%	2.92%	7.98%
T3-M04	4.09%	2.69%	2.64%	2.68%	2.68%	1.93%	3.08%	7.49%
T3-M05	2.66%	3.58%	1.99%	1.42%	1.42%	3.10%	1.04%	5.47%
T3-M06	1.96%	2.11%	0.97%	1.12%	1.12%	1.31%	0.87%	3.26%
T3-M07	1.38%	2.12%	3.04%	2.54%	2.54%	1.71%	2.54%	6.64%
T3-M08	2.10%	1.50%	0.78%	1.34%	1.34%	1.51%	1.79%	4.56%

Table A 55: Task-3 Durability Compressive Strength for Unconditioned Specimens

Mix Design	Unconditioned Compressive Strength (psi)			
	Specimen 01	Specimen 02	Specimen 03	Average
T3-M01	10832	10823	11299	10985
T3-M02	10391	10540	9558	10163
T3-M03	11963	11492	11649	11702
T3-M04	10093	9920	10834	10282
T3-M05	9870	9920	9904	9898
T3-M06	11130	11649	11600	11460
T3-M07	9728	9409	9290	9476

T3-M08	10831	10548	10705	10695

Table A 56: Task-3 Durability Compressive Strength for Conditioned Specimens

Mix Design	***Conditioned Compressive Strength (psi)***		
	Specimen 01	***Specimen 02***	***Average***
T3-M01	9885	10078	9981
T3-M02	9133	9133	9133
T3-M03	10235	10077	10156
T3-M04	9558	9306	9432
T3-M05	8820	8983	8901
T3-M06	9921	10073	9997
T3-M07	8506	8864	8685
T3-M08	9757	9908	9833

Table A 57: Task-3 Durability Bond Shear Strength for Unconditioned Specimens

Mix Design	***Unconditioned Bond Shear Strength (psi)***			
	Specimen 01	***Specimen 02***	***Specimen 03***	***Average***
T3-M01	4419	4889	4226	4512
T3-M02	4546	4124	4262	4311
T3-M03	3912	4889	4386	4396
T3-M04	5849	5996	6741	6195
T3-M05	5199	4591	4872	4887
T3-M06	4889	4732	4261	4628
T3-M07	5037	4891	5356	5095
T3-M08	4893	5204	4666	4921

Table A 58: Task-3 Durability Bond Shear Strength for Conditioned Specimens

Mix Design	***Conditioned Bond Shear Strength (psi)***		
	Specimen 01	***Specimen 02***	***Average***
T3-M01	3890	4226	4058
T3-M02	4323	3912	4118
T3-M03	0	0	0
T3-M04	4891	5682	5287
T3-M05	4449	4045	4247
T3-M06	4228	3912	4070

T3-M07	4263	4419	4341
T3-M08	4081	4426	4254

Table A 59: Task-3 Surface Resistivity at 7 Days

MIX ID	Surface Resistivity (kΩ) at 7 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
T3-M01	4.9	5.3	4.5	6.4	5.8	5.6	6.4	6.4	5.7
T3-M02	7.8	6.9	7.2	7.3	7.4	8.6	7.5	7.9	7.5
T3-M03	6.1	5.6	5.0	5.9	6.1	5.4	6.0	5.6	5.7
T3-M04	6.9	5.9	6.6	6.4	6.4	6.8	5.6	6.1	6.3
T3-M05	6.6	6.4	7.1	6.1	6.4	6.6	6.4	5.8	6.4
T3-M06	8.1	8.4	7.9	7.5	7.8	7.6	8.6	7.5	7.9
T3-M07	7.5	8.6	7.9	8.2	7.5	8.7	8.6	7.8	8.1
T3-M08	8.0	9.1	8.6	8.0	8.1	7.8	8.4	8.9	8.4

Table A 60: Task-3 Surface Resistivity at 14 Days

MIX ID	Surface Resistivity (kΩ) at 14 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
T3-M01	7.1	7.2	7.8	7.5	8.3	7.4	7.7	7.9	7.6
T3-M02	10.3	9.5	9.9	10.0	10.5	9.7	10.2	10.1	10.0
T3-M03	8.5	9.1	8.3	7.6	7.9	7.8	8.2	7.9	8.1
T3-M04	8.5	9.6	8.7	8.7	9.2	10.5	9.4	10.1	9.3
T3-M05	8.6	9.4	8.9	9.0	10.3	10.1	9.9	9.8	9.5
T3-M06	10.8	10.7	10.1	10.6	10.0	10.2	10.3	10.5	10.4
T3-M07	10.3	10.2	10.3	11.3	10.3	10.2	10.4	10.5	10.4
T3-M08	11.4	10.5	11.7	10.0	10.8	12.5	11.9	11.2	11.2

Table A 61: Task-3 Surface Resistivity at 28 Days

MIX ID	Surface Resistivity (kΩ) at 28 Days								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
T3-M01	8.6	9.5	10.0	10.3	10.1	10.3	9.9	9.7	9.8
T3-M02	14.5	15.3	15.0	14.4	15.3	15.1	14.7	15.0	14.9
T3-M03	11.7	12.8	12.5	12.2	13.6	12.8	12.5	10.9	12.4
T3-M04	11.4	12.8	12.0	12.5	11.7	11.4	12.4	10.6	11.8
T3-M05	12.8	14.2	12.8	11.9	12.5	12.8	12.9	13.2	12.9
T3-M06	15.3	14.7	14.9	15.6	16.1	15.3	15.6	14.9	15.3
T3-M07	16.1	15.4	15.9	16.1	15.1	15.5	15.8	15.3	15.6
T3-M08	17.0	16.4	16.1	17.1	16.1	16.4	16.2	16.7	16.5

Table A 62: Task-3 Surface Resistivity at 100 Cycles

MIX ID	Surface Resistivity (kΩ) at 100 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
T3-M01	11.7	10.9	12.2	10.4	10.9	11.7	13.6	12.8	11.8
T3-M02	19.1	18.9	17.5	18.1	18.4	18.1	19.6	18.4	18.5
T3-M03	16.4	17.0	17.1	17.5	17.5	18.9	18.4	17.2	17.5
T3-M04	15.3	15.8	15.4	15.0	15.0	15.9	15.9	16.6	15.6
T3-M05	17.8	18.4	17.3	17.0	16.4	15.8	16.1	15.3	16.8
T3-M06	18.1	17.8	17.5	18.1	17.8	17.6	16.9	17.1	17.6
T3-M07	17.0	17.3	17.5	17.4	18.0	17.6	17.9	17.4	17.5
T3-M08	18.1	17.6	18.9	18.6	16.8	17.2	18.6	18.1	18.0

Table A 63: Task-3 Surface Resistivity at 200 Cycles

MIX ID	Surface Resistivity (kΩ) at 200 Cycles								
	Specimen 01				Specimen 02				
	M1	M2	M3	M4	M1	M2	M3	M4	Avg
T3-M01	11.7	11.4	10.0	10.8	11.6	11.2	10.0	10.4	10.9
T3-M02	19.6	16.8	20.0	16.4	16.4	16.4	17.5	17.6	17.6
T3-M03	17.0	17.4	17.8	17.1	17.5	16.4	18.4	18.1	17.4
T3-M04	12.0	12.8	11.9	14.2	15.0	12.8	13.7	14.1	13.3
T3-M05	16.9	16.5	16.2	16.9	15.3	14.5	15.6	15.0	15.9
T3-M06	17.8	15.9	16.9	15.3	16.4	16.4	15.8	15.8	16.3
T3-M07	15.3	14.5	14.9	15.1	15.4	15.6	16.1	15.7	15.3
T3-M08	15.1	15.3	16.1	14.1	14.7	14.2	15.3	15.1	15.0

Table A 64: Task-3 Surface Resistivity at 300 Cycles

MIX ID	*Surface Resistivity (kΩ) at 300 Cycles*								
	Specimen 01				*Specimen 02*				
	M1	*M2*	*M3*	*M4*	*M1*	*M2*	*M3*	*M4*	*Avg*
T3-M01	7.9	6.9	8.7	6.6	7.1	7.1	7.3	7.8	7.4
T3-M02	10.8	13.6	11.8	11.3	10.8	11.7	11.4	12.8	11.8
T3-M03	11.7	12.1	10.4	11.6	12.8	11.9	11.4	11.7	11.7
T3-M04	7.8	7.0	7.5	7.8	7.6	8.6	8.5	8.1	7.9
T3-M05	10.0	10.0	10.9	9.2	10.0	9.7	9.8	9.2	9.8
T3-M06	10.3	9.7	10.6	10.1	10.3	9.6	9.2	9.5	9.9
T3-M07	7.5	8.6	8.2	8.4	9.1	9.4	9.7	9.1	8.7
T3-M08	7.0	7.4	7.8	7.1	7.8	8.2	8.9	8.7	7.9