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Developing a Low Shrinkage, High Creep Concrete for Infrastructure Repair

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Submitted by

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16. Abstract
Investigations to develop a durable concrete full depth pavement repair mixture with a four hour cure time and 4000 psi compressive strength that will minimize cracking were carried out. Current high early strength concrete mixtures have natural cracking and shrinkage problems due to the high content of cementitious material or their chemical components. Using IC allows for early strength, enhanced durability, reduced shrinkage and providing water that can be absorbed by the cement past after the final set. Different OPC and CSA mixtures were prepared, with and without IC. Mixtures with IC had reduced early strength and delayed hydration, however, when combined with CSA cement, were able to obtain about 4000 psi of compressive strength in 4 hours of curing. Significant improvements in volume stability were also noted in the IC mixtures. Drying and creep shrinkage were reduced by factors of up to 15% and 30%, respectively. A CSA mixture with IC is recommended by the authors.

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Executive Summary

Concrete is inherently a durable material, but its durability under any given set of exposure conditions varies with concrete mixture proportions; the presence and the localization of the reinforcement (flexural, shear, torsion, etc.); and the detailing, placing, finishing, curing, and protection it receives. In service, concrete may be subjected to conditions of abrasion, moisture cycles, freeze and thaw cycles, temperature fluctuations, reinforcement corrosion, and chemical attacks, resulting in deterioration and potential reduction of its service life (ACI 546, 2014).

In recent years, early opening of concrete pavements, roads, and pavement repairs to traffic has been given much emphasis for many reasons: efficiency, the population's comfort, political values, and others. Recent developments in materials and processes for concrete paving focus on early opening. As the concrete industry develops and grows, concrete repair is frequently required; however, with the increasing number and age of concrete structures, frequent deferral of maintenance, and increased public awareness of deterioration and maintenance needs, repair is becoming a major focus of design and construction activities.

The general objective of this project is to create a non-proprietary mixture that meets the requirements stipulated by UDOT for concrete repair mixtures. The results from various ASTM tests performed on the proprietary and non-proprietary mixtures are presented in this report. Several proprietary mixtures were tested and found to provide adequate strengths in excess of 4 ksi and also to have favorable dimensional stability. Non-proprietary mixtures are also presented as several trial batches were attempted and tested. The trial mixtures were subject only to compressive strength tests as they were iterated to increase strengths. The compressive strengths of the trial OPC mixtures were relatively low, nevertheless, trial CSA mixtures obtained compressive strengths higher than 7,500 psi in 4 hours.

Trial mixtures (both OPC and CSA) were selected according to their compressive strength (highest) and eight mixtures were developed. These eight mixtures were a combination of OPC, OPC and Silica Fume (SF) and CSA, with and without IC. Mixtures with OPC obtained low strengths (under 2,000 psi in 4 hours), however, had relatively good workability (higher than 27 minutes for initial setting). SF weight replacement increased the compressive strength of the OPC mixture by approximately 25%. CSA mixtures obtained high early compressive and split tensile strengths (around 8000 psi and 350 psi respectively).

Chapter 1: Introduction

Problem Statement

Rigid (concrete) pavements are generally more durable than flexible (asphalt) pavements. As a result, many of the highest volume roads in the United States are constructed using concrete pavements. However, repair of concrete pavements is expensive when compared to repair of asphalt pavements. The cost of pavement repair includes both material and construction costs, as well as the indirect cost of lane closure. Growing efforts to minimize the impact of construction on the public has led to an emphasis on minimizing the duration of lane closures. In response, a new classification of cement-based repair material has emerged: 4X4 concrete. 4X4 concrete is classified as a cement-based material that can achieve a compressive strength of at least 4,000 psi within 4 hours of placement. This is often considered the minimum performance standard for rapid concrete repair media. However, compressive strength is not the only property of interest. For the most effective repair, the fresh properties and durability of the repair media should also be taken into account. Thus, it is of interest to identify minimum performance specifications based on the fresh properties, mechanical properties, and durability of rapid concrete repair media. Since many existing 4X4 or similar rapid concrete repair media are proprietary, it is also of interest to develop a nonproprietary repair media that meets the 4X4 criterion as well as the other newly-identified performance specifications.

Cabrera and Al-Hassan (1997) explain that—in the past—engineers had a wide choice of materials to use for repair, but little guidance on the desired properties and performance. Repair media of similar composition to the substrate were preferred. At the time, engineers used OPC concrete, mortars, and grouts for repair media. In the 1960s, a variety of advanced repair media began to emerge, including polymer-modified portland cement, epoxy resin and polyurethane-based systems, and alternative cementitious materials like high-alumina cements, magnesium phosphate cements, and calcium sulfoaluminate cements (Morgan, 1996). Many of these products are proprietary in nature and are available only as pre-bagged "one-component" mixtures. As such, disclosure of their composition is not realistic. Instead, their suitability for use as repair media should be based on performance rather than composition (Cabrera & Al-Hassan, 1997).

Selection of the best or most applicable pavement repair media requires consideration of several performance attributes. First, the fresh properties (e.g., setting time and workability) should be adequate for placement. The rate of strength gain should be sufficient to meet the 4X4 requirement, but the mechanical properties (e.g., compressive strength, modulus of elasticity, coefficient of thermal expansion) should be compatible with the substrate. The volume stability (e.g., drying shrinkage, creep) must also be compatible with the substrate. Finally, the repair media should meet minimum durability specifications (e.g., chloride penetrability, freeze-thaw resistance).

Objectives

In response to the need for development of performance based acceptance criteria for rapid concrete pavement repair media, the following research objectives are identified:

- Describe the state of the art of rapid concrete pavement repair media;
- Conduct a survey of state Departments of Transportation (DOT) to identify current practices and future needs related to rapid concrete pavement repair media;

- Identify performance based acceptance criteria based on fresh properties, mechanical properties, and durability of existing proprietary rapid concrete pavement repair media; and
- Develop nonproprietary concrete pavement repair media that meet the identified acceptance criteria.

Chapter 2: Literature Review

General Overview

Mixture design for repair media typically relies on practitioner experience, who consider a relatively narrow range of performance parameters (e.g., compressive strength, bond performance, and early-age volume stability). These properties give a good idea of the mechanical performance of the repair medium, but give very little information about the long-term durability of the repair or its compatibility with the substrate. Enhanced technologies are approaching durability and dimensional compatibility of the repair media and have made advances regarding rapid repair media long term properties and the increase of the repair service life.

Repair Material Properties

Since concrete repair began, engineers have used OPC based concretes, mortars, and grouts to repair concrete. However, since 1960's, new enhanced concrete repair materials and systems have been introduced and widely used in civil engineering. These have ranged from polymer modifiers for Portland cement based products to epoxy resins, polyesters, polyurethane based systems, high alumina cement, and magnesium phosphate based repair products (Morgan, 1996).

In order to make an appropriate choice and also know the uses and limitations of repair materials, publications like Hewlett and Hurley (1985), Mays and Wilkinson (1987), and Heiman and Koerstz (1991) discuss issues such as stiffness and thermal and electrochemical compatibility of the repair systems.

Repair materials should be compatible or they will not act together as expected; the properties of one material could cancel the properties from the other. Compatibility is the balance of physical, chemical, and electrochemical properties and dimensions between a repair material and the existing substrate. Compatibility ensures that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designated period of time (Emmons, Vaysburd, & McDonald, 1993). . Figure 2.1 shows an adaptation from Emmons et al. of the factors that affect the durability of concrete repairs:

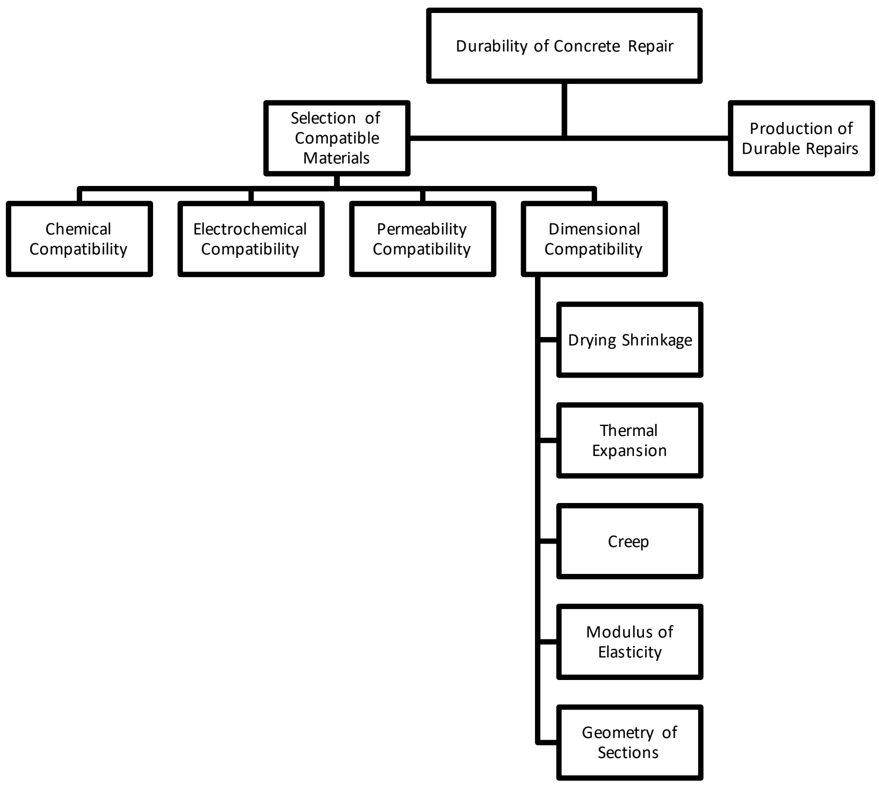

Figure 2.1 Factors affecting durability of concrete repairs (Adaptation from Emmons et al)

Of these considerations, the most important is the ability of the repaired area to withstand volume changes without bond loss and delamination; this is commonly referred to as "dimensional compatibility" and includes the ability of the repaired area to carry its share of the applied load without distress. Chemical compatibility involves selection of a repair material such that it does not have any adverse effects on the repaired component or structure. The electrochemical compatibility needs to be taken into consideration if corrosion-induced deterioration is to be avoided (Emmons, Vaysburd, & McDonald, 1993; Morgan, 1996).

Dimensional compatibility is a common issue in the repair industry. Parameters that influence dimensional compatibility are presented in Figure 2.1. The size, shape, and thickness of the area being repaired; the amount of reinforcing and anchorage; and strain capacity affect the dimensional compatibility (Emmons P., 1993). All too often, repairs become debonded as a result of:

- Excessive shrinkage strains in Portland cement and some polymer-modified concrete and polymer concrete systems (Emmons, Vaysburd, & McDonald, 1993; Plum, 1991).
- Excessive expansion in certain shrinkage compensated repair materials (Morgan, 1996).
- Excessively high thermal expansions followed by cooling and shrinkage occurring during early setting and hardening reactions (Plum, 1991).
- Very high thermal expansion in repair materials during diurnal or seasonal temperature changes (Woodson, 2011).

An ideal material would need to have a high strain capacity to be able to better resist imposed strains without cracking and disruption (Yuan & Marosszeky, 1991). Therefore, the material would be volumetrically stable; in other words, it would not undergo shrinkage or expansion once installed and would have similar modulus of elasticity and thermal expansion characteristics to the substrate concrete.

Bond Strength and Surface Preparation

Bond strength is one of the properties of repair concrete that has been studied the most. Good adhesion of a repair material to concrete is of vital importance in the application and performance of concrete patch repairs. The strength and integrity of the bond depends not only on the physical and chemical characteristics of the component but also on the workmanship involved, such as surface roughness and soundness. Tensile bond strength depends on the effect of surface preparation, modulus mismatch, and variation of specimen size. A wide range of test methods have been proposed to evaluate bond properties (Austin, Robins, & Pan, 1999).

Momayez et al. (2004) researched the difference between the pull-off, slant shear, and splitting prism tests and developed another test: the direct shear test or bi-surface shear test (Momayez, Ramezanianpour, Rajaie, & Ehsani, 2004). The measured bond strength is greatly dependent on the test method. Bond strength is strongly affected by adhesion between the repair material and the concrete interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Good adhesion depends on bonding agent, material compaction, cleanness, moisture content of repair surface, specimen age, and roughness of interface surface. Friction and aggregate interlock on an interface depends on aggregate size, aggregate shape, and surface preparation (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005).

In the field of rehabilitation and strengthening, the bond between new and old concrete is generally a vulnerability in repaired structures (Wall & Shrive, 1988). In order to evaluate bond strength, Tayeh et al. (2013) suggested that the following tests be performed: the slant shear test and the split test. The slant shear test is used to quantify the bond strength in shear, and the split test is used to evaluate the bond strength in indirect tension.

The performance of any concrete repair is highly dependent on the quality of the bond between the repair material and the substrate concrete. This is particularly true for repairs which are not anchored or tied back by encapsulating existing or new reinforcing steel or anchors, thus relying totally on the durability of the bond to the substrate concrete for long term success of the repair. Stresses on the bond interface of repairs in the field can be affected by factors like the ones listed below:

- Plastic and drying shrinkage strains in the repair material
- Heat generation from early heat of hydration or polymer reaction thermal stresses
- Time dependent volume changes
- Dead loads and changing live loads and dynamic loads (such as traffic)
- Frost build-up or salt crystallization pressures (Morgan, 1996)

Patch repair is one of the main processes used to repair concrete structures. The efficiency and durability of patch repairs depends highly on the bond properties. By increasing surface roughness, the surface treatment of concrete substrate can promote mechanical interlocking, which is one of the basic mechanisms of adhesion. Nonetheless, some problems may arise from the effects of the treatment, especially those due to the development of microcracks inside the substrate. Courard et al. (2014) investigated the effect of concrete substrate surface preparation for patch repairs and proposed bond strength estimation and a method for selecting a suitable surface treatment technique.

Structural and mechanical compatibility

Plum defined two different types of repairs: “Non-structural” or cosmetics repairs, in which stress-carrying is not a major consideration for the repair, and “structural” repairs, where the patch is required to carry the load originally carried by the removed concrete (Plum, 1991). Emberson and Mays (1990) laid out the general requirements of patch repair materials for structural compatibility, as shown in Table . The first requirement is that the strength in compression, flexure, and tension of the repair material exceed that of the substrate concrete. This requirement is commonly met with most repair materials; however, materials with excessively high stiffness (modulus of elasticity) should be avoided, as this may cause the repaired area to attract undue load (Saucier & Pigeon, 1991; Woodson, 2011).

Table 2.1 General requirements of patch repair materials for structural compatibility (Adapted from Emberson and Mays)

Property	Relationship of Repair (R) to Concrete Substrate (C)
Strength in Compression, Tension and Flexure	**R≥C**
Modulus in Compression, Tension and Flexure	**R~C**
Poisson's Ratio	**Dependent on modulus and type of repair**
Coefficient of Thermal Expansion	**R~C**
Adhesion in Tension and Shear	**R≥C**
Curing and long term shrinkage	**R≥C**
Strain Capacity	**R≥C**
Creep	**Dependent on whether creep causes desirable or undesirable effects**
Fatigue performance	**R≥C**

The second general requirement is that the repair material has approximately the same modulus of elasticity and coefficient of thermal expansion as the substrate concrete. While this requirement can be readily met with most Portland cement based repair materials and polymer modified repair materials, it has proven to be a problem with many polymer concretes (Emberson & Mays, 1990). Marosszeky (1991) demonstrated that designing repairs using repair materials with substantial property mismatch in terms of modulus of elasticity and coefficient of thermal expansion is fraught with dangers. The potential for success or failure of the repair will depend on factors such as:

- The magnitude and state of the stress field
- Whether load is left on the structure during the repair operations
- The creep capacity of the repair material
- The quality of tensile and shear bond strength of the repair material to the substrate concrete
- The temperature at which the repairs were carried out and subsequent range of temperatures during service life.

Rapid Full Depth Pavement Repair

Asphalt and concrete pavement infrastructures worldwide deteriorate with time, that's the main reason engineers search for innovative and creative ways to rehabilitate the infrastructure. When desired, a properly designed and constructed bonded overlay can add considerable life to an existing pavement by taking advantage of the remaining structural capacity of the original pavement. For patchwork and total rehabilitation, two types of thin concrete pavement overlays rely on a bond between the overlay and the existing pavement for performance. Concrete overlays bonded to existing concrete pavements are called Bonded Concrete Overlays (BCO). Concrete overlays bonded to existing asphalt pavements are called Ultra-Thin Whitetopping (UTW) (University of Maryland, 2005).

High early strength concrete was specified to have a minimum compressive strength of 2,000 psi (14 MPa) at 12 hours (Zia, Ahmad, & Leming, 1993). In the context of our research, however, the word "Early" is considered to be relative; the concrete mixes which have been researched will be termed "Early strength" without taking into consideration the time and place of strength gain.

These criteria were adopted after considering several factors pertinent to the construction and design of highway pavements and structures. The use of a time constraint of 4 to 6 hours for Very Early Strength (VES) concrete is intended for projects with very tight construction schedules involving full-depth pavement replacements in urban or heavily traveled areas. The strength requirement of 2,000 to 2,500 psi (14 to 17.5 MPa) is selected to provide a class of concrete that would meet the need for rapid replacement and construction of pavements. Since VES concrete is intended for pavement applications where exposure to frost must be expected, it is essential that the concrete be frost resistant. Thus, it is appropriate to select a maximum W/C ratio of 0.40, which is relatively low in comparison to conventional concrete. With a low W/C ratio, concrete durability is improved in all exposure conditions. Since VES concrete is expected to be in service for no more than 6 hours, the W/C ratio selected might provide a discontinuous capillary pore system at about that age (University of Maryland, 2005; Zia, Ahmad, & Leming, 1993).

High early strength concrete is one of the most versatile construction materials. It has applications in a wide variety of infrastructure types, such as new pavement, overlay pavement, full depth pavement repair, full bridge deck replacement, new bridge decks, bridge deck overlay, precast elements, prestressed piles, and columns and piers. With enhanced performance characteristics such as high early strength and increased durability, high early strength concrete would be extremely useful in situations where the speed of construction is important but not critical, even though the materials may be relatively more expensive (Cabrera & Al-Hassan, 1997).

DOT Survey

A survey was designed to capture DOT responses with the purpose of assessing the state of practice for methods of Full Depth Rapid Concrete Repair of roads. The 11-question survey was administered from September 2015 to January 2015, and 20 responses were received. A copy of the survey can be found in Appendix A of this report.

The survey was distributed to various DOTs in the United States. The following is a list of the agencies that participated in the survey:

- Alabama DOT
- Arizona DOT
- Illinois DOT
- Missouri DOT
- Montana DOT
- Nevada DOT
- Wisconsin DOT
- Texas DOT
- Maryland DOT
- North Carolina DOT
- Oregon DOT
- South Dakota DOT
- Washington DOT
- South Carolina DOT
- Alaska DOT
- Rhode Island DOT
- Vermont DOT
- New Hampshire DOT
- Massachusetts DOT
- Michigan DOT

Respondents from 15 states participated in the survey and provided feedback (Figure 2.2). In addition, 5 states participated and responded that they did not usually make use of concrete pavement (Figure 2.3). It is important to note that these responses came from all across the United States; some responses came from states that experience snow and other freeze-thaw conditions where salts and other de-icing chemicals are used on roadways and bridge decks, which can contribute to the decrease in durability of the concrete.

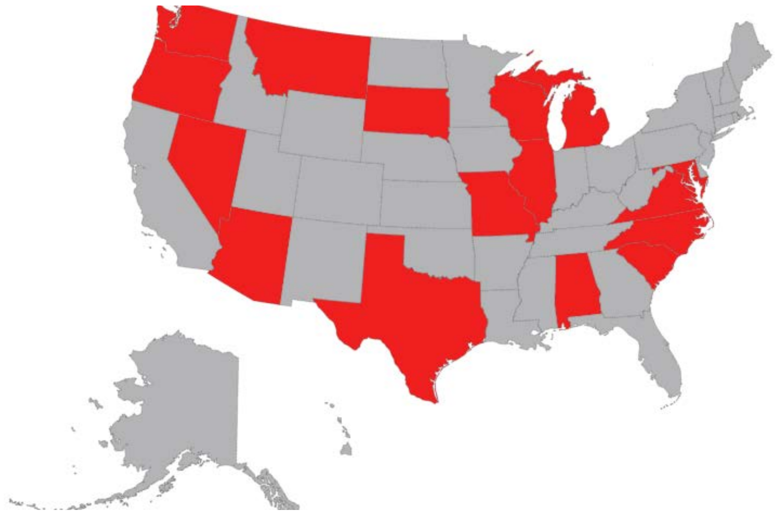

Figure 2.2 Representation of survey respondents by state with concrete pavement

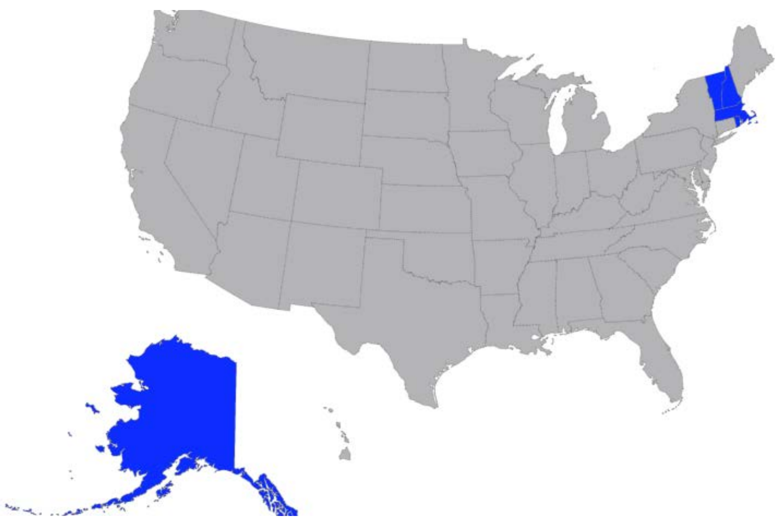

Figure 2.3 Representation of survey respondents by state without concrete pavement

Survey Results

Useful data was extracted from the responses. The questions asked general inquiries about concrete repair in the state as well as priorities, minimum strength, and minimum closure time. From the 20 responses received, a total of 5 states responded that they did not utilize concrete for their pavements.

A summary of the survey results is included below:

Figure 2.4 shows the DOT responses to Question 1 which asked the agencies what environmental zone, according to the dominant weather condition of the local area, the state DOT operated in.

Question 2 asked the agency to rank the DOT's current routine for Full Depth Pavement repair from 1 (being the worst) to 5 (being the best). Results are shown in Figure 2.5.

Question 3 asked the agency what the life expectancy of their full depth pavement repairs is. Responses are presented in Figure 2.6.

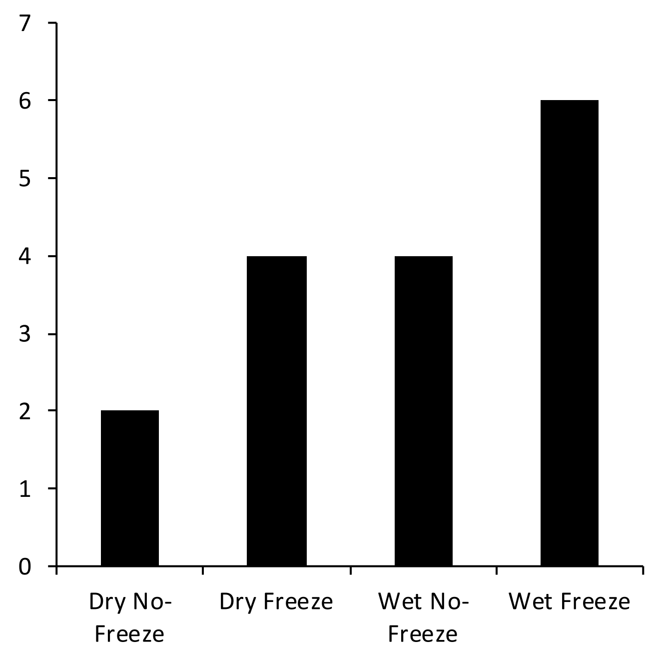

Figure 2.4 Results of survey question #1 (Environmental Zone)

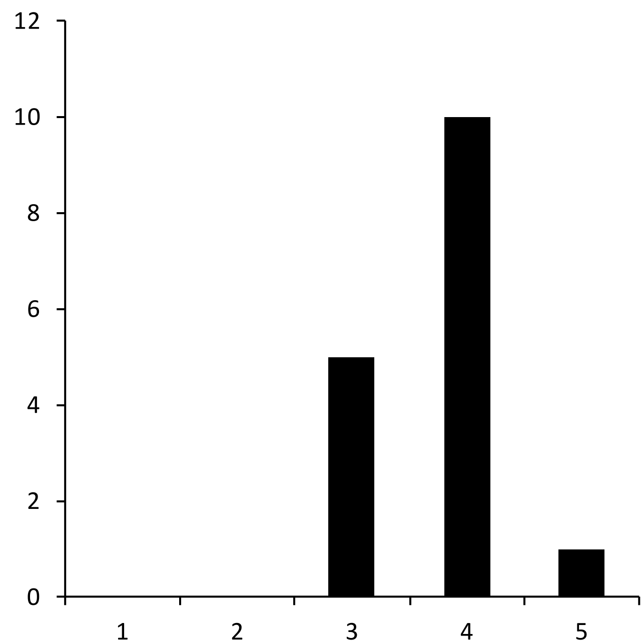

Figure 2.5 Results of survey question #2 (Repair Rating)

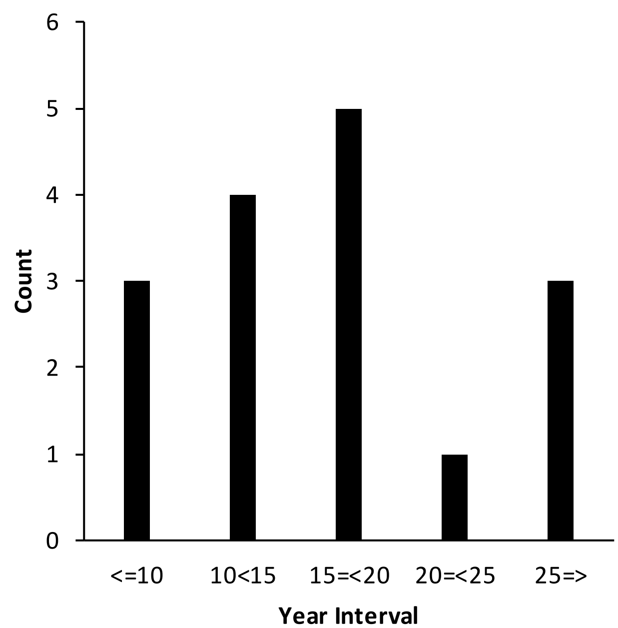

Figure 2.6 Results of survey question #3

Question 4 asked how long the agency's typical full depth pavement repair lasts (in years). Responses are shown in Figure 2.7.

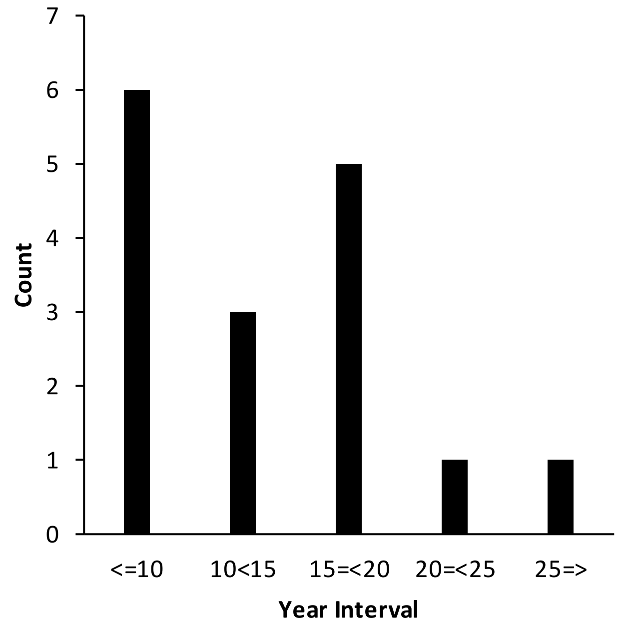

Figure 2.7 Results of survey question #4

Question 5 asked agency employees, contractors, or both if they utilized Full Depth Pavement Repair. Responses are presented in Figure 2.8.

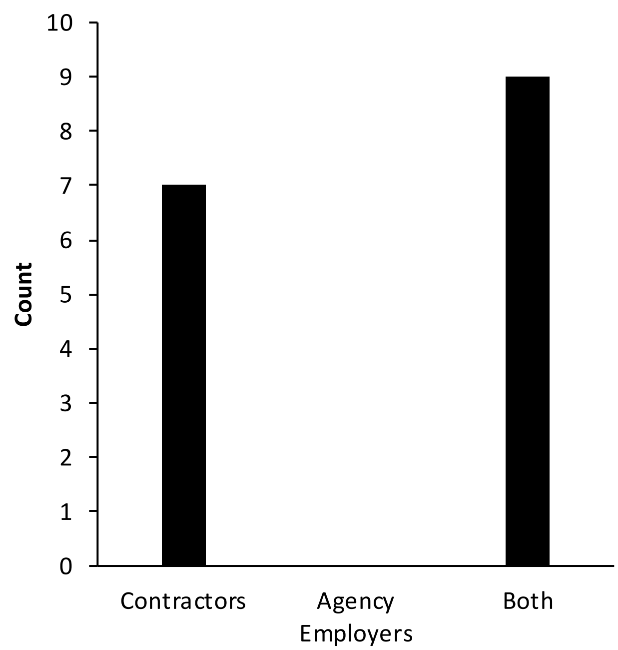

Figure 2.8 Results of survey question #5

Question 6 asked DOTs to specify how soon repaired areas re-opened to traffic. Answers obtained were mostly ranges of time, so two histograms were made, one with the earliest times and one with the latest times (see Figure 2.9 and Figure 2.10).

Question 7 asked what the criteria were for full depth pavement repairs to open to traffic (X strength, X time, etc.). Two histograms were plotted for this question. Figure 2.11 shows the minimum strength prior to opening and Figure 2.12 shows the minimum wait time before opening.

Question 8 asked what the material or practice was which performed the best for the DOT. The following answers were recorded and categorized as seen in Figure 2.13.

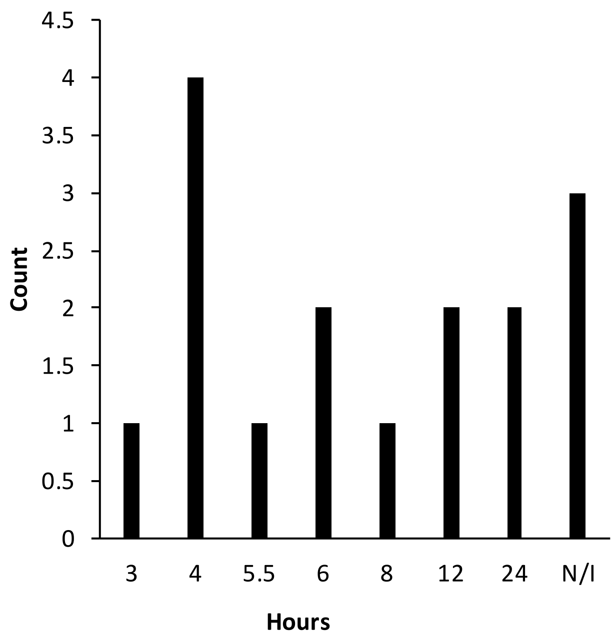

Figure 2.9 Results of survey question #6 Earliest Times (Note N/I means Not Important)

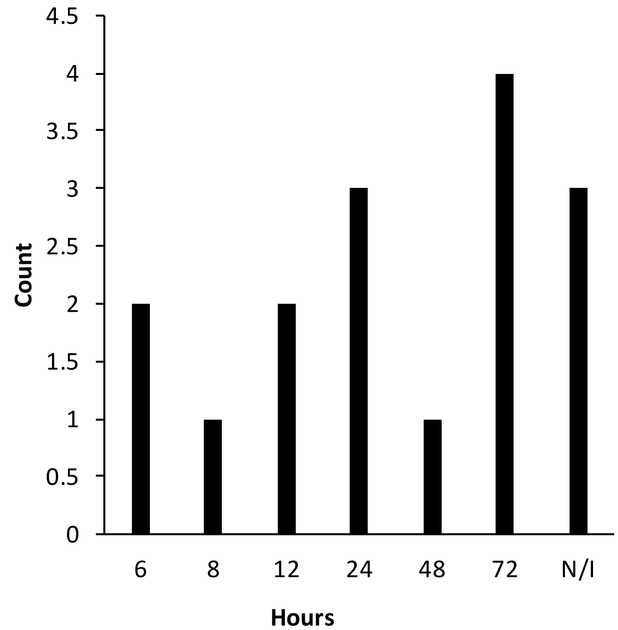

Figure 2.10 Results of survey question #6 Latest Times (Note N/I means Not Important)

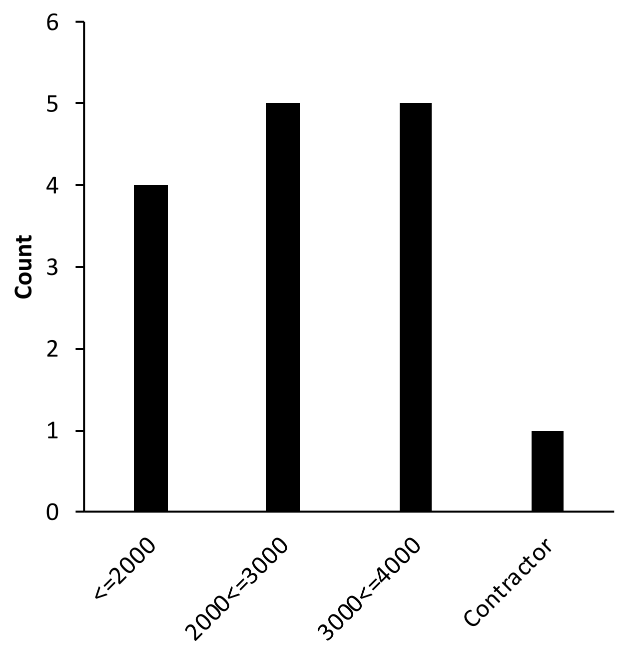

Figure 2.11 Results of survey question #7 Minimum Strength (Contractor means the Min. Strength is left to the Contractors decision)

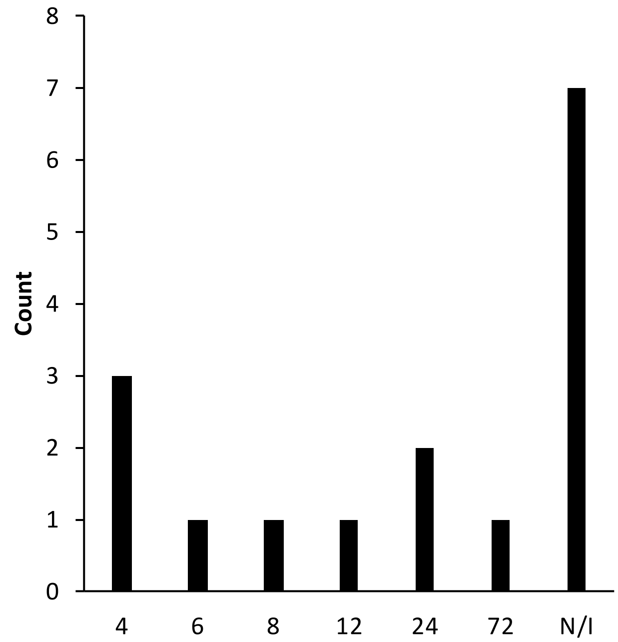

Figure 2.12 Results of survey question #7 Minimum Time before Opening

Table 2.1 Responses and Categories for Question #8

Response	Category	ID
Quartz-River Gravel	Concrete + Special Aggregate/Admixtures	1
Class "S" Concrete	Concrete + Special Aggregate/Admixtures	1
Type III Cement	Portland Cement Concrete	2
Type I/II with 2% CaCl	Concrete + Special Aggregate/Admixtures	1
Type III Cement	Portland Cement Concrete	2
N/A	N/A	5
Standard Concrete	Portland Cement Concrete	2
Portland Cement	Portland Cement Concrete	2
JPCP	Jointed Plain Concrete Pavement	3
Standard Concrete + Acc	Concrete + Special Aggregate/Admixtures	1
Portland Cement	Portland Cement Concrete	2
Lower Slump Slow Setting	Concrete + Special Aggregate/Admixtures	1
CTS Rapid Set	High Early Strength Concrete	4
High Early Strength Concrete	High Early Strength Concrete	4
Hydraulic Concrete with 20% Flyash	Concrete + Special Aggregate/Admixtures	1

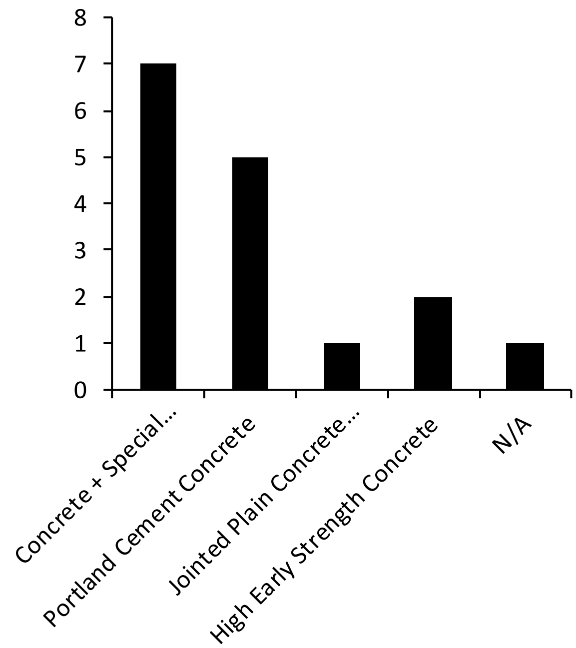

Figure 2.13 Results of survey question #8

Question 9 asked what material or practice performed the worst for the DOT. The following answers were recorded and categorized as seen in Table 2.2 and plotted in Figure 2.14 Results of survey question #9.

Table 2.2 Responses and Categories for Question #9

Response	Category	ID
Limestone	Concrete + Special Aggregate/Admixtures	1
N/A	N/A	6
Type III with 2% CaCl	Concrete + Special Aggregate/Admixtures	1
Repair Mixes with CaCl	Concrete + Special Aggregate/Admixtures	1
Portland Cement	Portland Cement Concrete	2
CRCP	Continuously Reinforced Concrete Pavement	3
Asphalt	Asphalt	5
Rapid Setting Products	Rapid Setting Products	4
Fast Setting PCC + ACC	Rapid Setting Products	4
Standard Concrete	Portland Cement Concrete	2
High Cement Content	Concrete + Special Aggregate/Admixtures	1

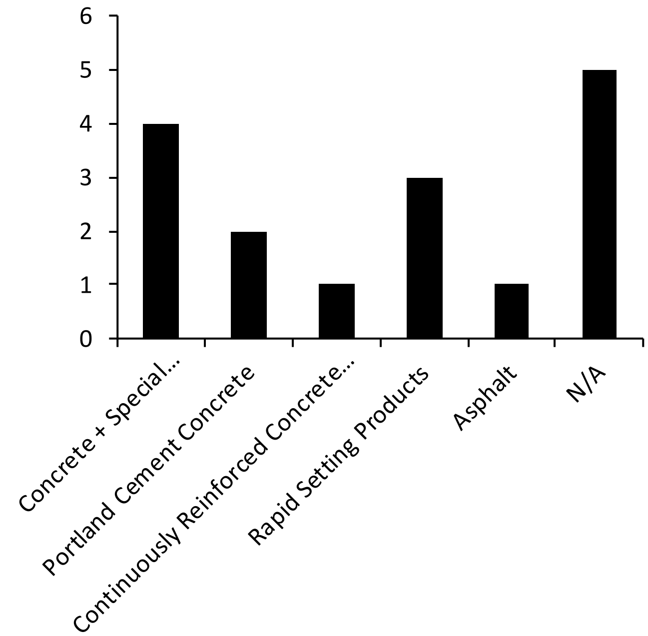

Figure 2.14 Results of survey question #9

Question 10 asked DOTs to select their top three criteria when performing a concrete repair mixture. The most selected criteria was Closure Time (see Figure 2.15)

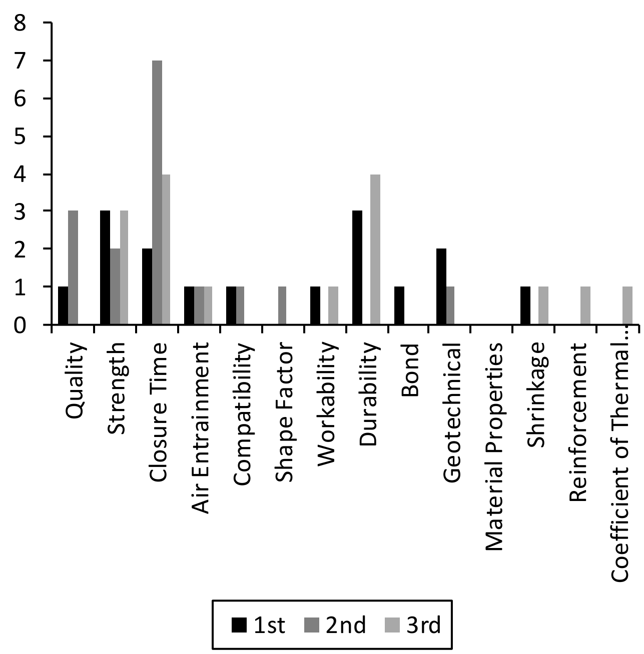

Figure 2.15 Results of survey question #10 (1st Priority, 2nd Priority and 3rd Priority)

Question 11 asked for the projected cost of a 12 ft. × 10 ft. × 10 in. concrete repair slab. This question was answered in different ways (approximate total cost, average total cost in the past and cost per cubic foot of repair concrete), however results were recorded in ranges of USD spent. Figure 2.16 shows the results of the survey.

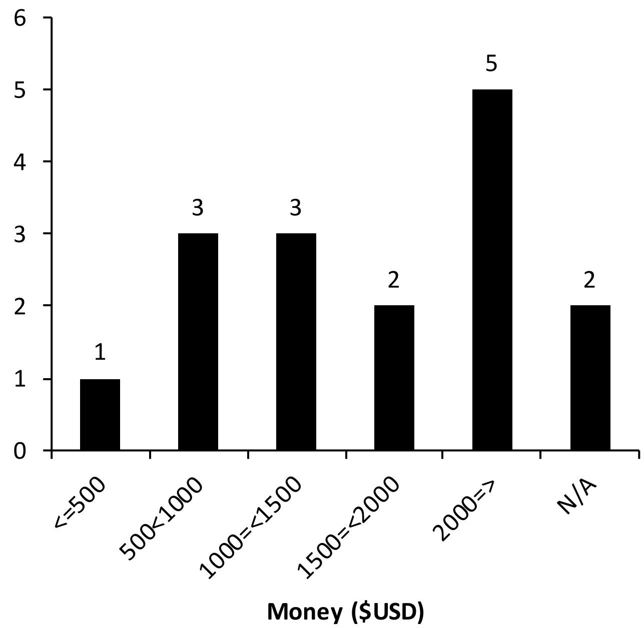

Figure 2.16 Results of survey question #11 (Total Cost of repair slab)

Results Analysis

The following tables and results were obtained via Statistical Analysis Software (SAS) University Edition.

Table 2.3 Pearson Correlation Matrix between the numerical variables obtained in the survey

Pearson Correlation Coefficients, N = 16

Prob > |r| under H0: Rho=0

	ID	rate	expect	actual	optime1	optime2	opstr	optimes	money
ID	1	-0.24254 0.3654	0.04624 0.865	0.04689 0.8631	0.29481 0.2677	-0.01537 0.9549	0.00703 0.9794	-0.1874 0.4871	-0.16083 0.5518
rate	-0.24254 0.3654	1	0.35842 0.1728	0.27281 0.3066	0.19705 0.4645	0.25804 0.3346	-0.11242 0.6785	0.24631 0.3578	-0.14715 0.5866
expect	0.04624 0.865	0.35842 0.1728	1	0.40748 0.1172	0.26551 0.3203	-0.01882 0.9449	-0.08519 0.7538	0.05262 0.8465	-0.11088 0.6827
actual	0.04689 0.8631	0.27281 0.3066	0.40748 0.1172	1	0.04986 0.8545	0.20672 0.4424	0.26707 0.3173	-0.00448 0.9869	0.13692 0.6131
optime1	0.29481 0.2677	0.19705 0.4645	0.26551 0.3203	0.04986 0.8545	1	0.25604 0.3385	0.34578 0.1896	-0.01617 0.9526	-0.19474 0.4698
optime2	-0.01537 0.9549	0.25804 0.3346	-0.01882 0.9449	0.20672 0.4424	0.25604 0.3385	1	-0.06348 0.8153	0.32482 0.2196	0.08064 0.7665
opstr	0.00703 0.9794	-0.11242 0.6785	-0.08519 0.7538	0.26707 0.3173	0.34578 0.1896	-0.06348 0.8153	1	-0.00073 0.9978	-0.17489 0.5171
optimes	-0.1874 0.4871	0.24631 0.3578	0.05262 0.8465	-0.00448 0.9869	-0.01617 0.9526	0.32482 0.2196	-0.00073 0.9978	1	0.54826 0.0279
money	-0.16083 0.5518	-0.14715 0.5866	-0.11088 0.6827	0.13692 0.6131	-0.19474 0.4698	0.08064 0.7665	-0.17489 0.5171	0.54826 0.0279	1

Numerical Variables:

- ID: represents each different state.
- Rate: represents answers to Question #2
- Expect: represents answers to Question #3 (in years)
- Actual: represents answers to Question #4 (in years)
- Optime1: represent answers to Question #6 (earliest time in hours)
- Optime2: represent answers to Question #6 (latest time in hours)
- Opstr: represents answers to Question #7 in psi
- Optimes: represents answers to Question #7 in hours
- Money: represents answers to Question #11 (in US dollars)

After analyzing the correlation table, it is safe to assume that there is not a significant relationship between opstr and optime1 (p-value =0.9978), meaning that one is not the predictor of the other. Therefore, those DOTs that indicated that time to opening is important not necessarily feel that high strength at the time of opening is important. Also, there is a significant relationship between money and optimes (p-value = 0.0279), which indicates that both variables are strongly correlated under the significance level of 5%.

The answers to question 2 (the rating a DOT gives to their repairs from 1 to 5) are not statistically related to the answers to question 3 (expected life for a repair, p-value = 0.1728) or question 4 (actual life for a repair, p-value = 0.3066). According to these results, the rating a DOT gives to their repairs has no relation with the expected life of a repair or the actual life of a repair. A DOT's quality assessment of their repairs in unrelated to the actual performance of their repairs. DOTs may need a more objective way to evaluate pavement performance.

Chapter 3: Experimental Procedure

This section introduces the materials evaluated in the experimental study and details the test methods used for their evaluation.

Aggregate Properties

Normalweight Aggregate

Normalweight coarse and fine aggregates were provided by Legrand Johnson Construction Co. Sieve analyses were performed by CMT Engineering Laboratories (Brigham City, UT) in accordance with the specifications of ASTM C136. The resulting coarse and fine aggregate gradations are shown in Figures 3.1 and 3.2, respectively. Select physical properties of the aggregates, also determined by CMT Engineering Laboratories, are given in Tables 3.1 and 3.2.

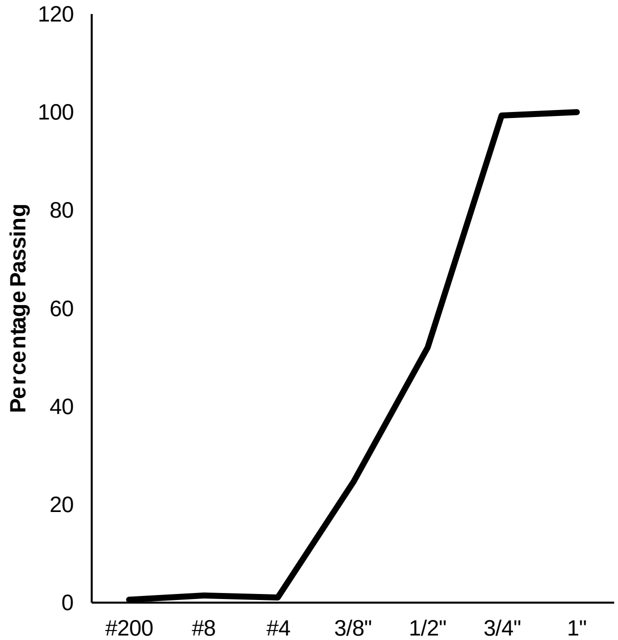

Figure 3.1 Normalweight coarse aggregate gradation

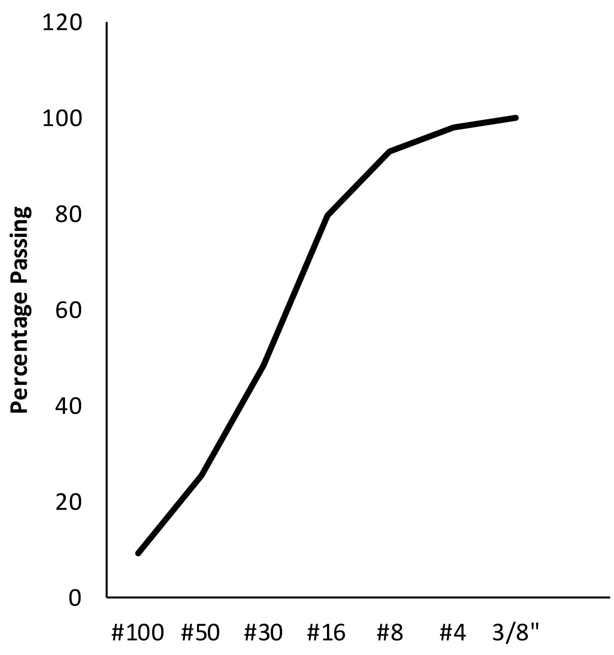

Figure 3.2 Normalweight fine aggregate gradation

Table 3.1 Specific Gravity & Absorption of the Coarse Aggregate

Coarse Aggregate	
Bulk Specific Gravity (OD) =	2.637
Bulk Specific Gravity (SSD) =	2.656
Apparent Specific Gravity =	2.688
Absorption =	0.7%

Table 3.2 Specific Gravity & Absorption of the Fine Aggregate

Fine Aggregate	
Bulk Specific Gravity (OD) =	2.63
Bulk Specific Gravity (SSD) =	2.646
Apparent Specific Gravity =	2.672
Absorption =	0.6%

Lightweight Aggregates

For the next round of experimental mixtures, lightweight aggregates (LWA) were used. Creating structural lightweight concrete (LWC) solves weight and durability problems while still having strengths comparable to normal weight concretes. LWC offers design flexibility and substantial cost savings by providing less dead loads, improved seismic structural response, longer spans, better fire ratings, thinner sections, decreased story height, smaller sized structural members, less reinforcing steel, and lower foundation costs. By using LWA, it is possible to include IC in concrete mixtures, which will maintain strength, reduce shrinkage and elastic modulus, and increase creep. In the case of repair concretes (i.e., this project), LWC allows for a lower modulus of elasticity and better dimensional stability. Figure 3.3, Figure 3.4, and Figure 3.5 show the gradation curve for each LWA.

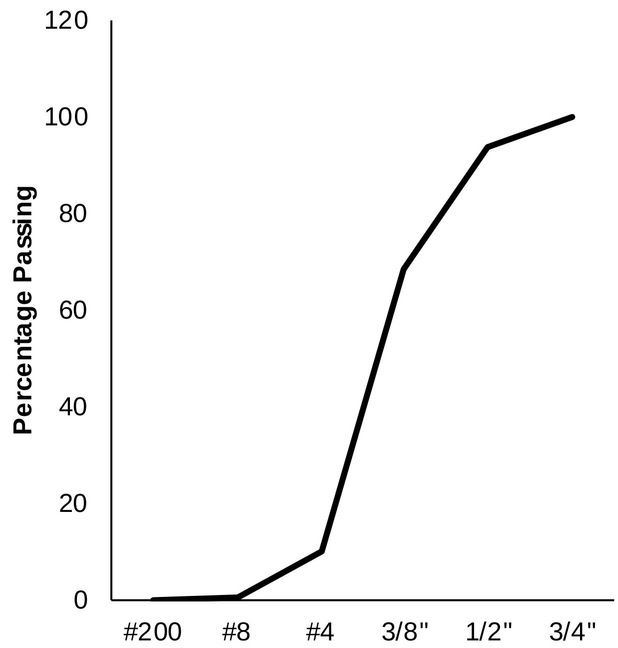

Figure 3.3 Lightweight coarse aggregate gradation

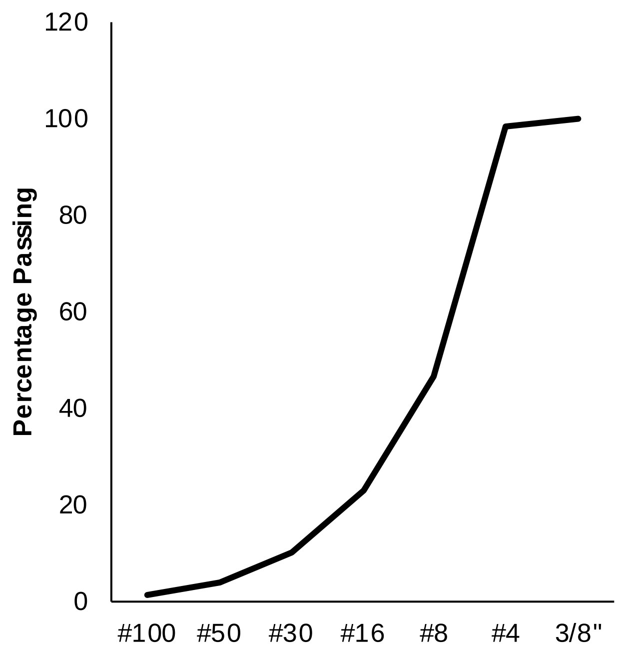

Figure 3.4 Lightweight fine aggregate gradation

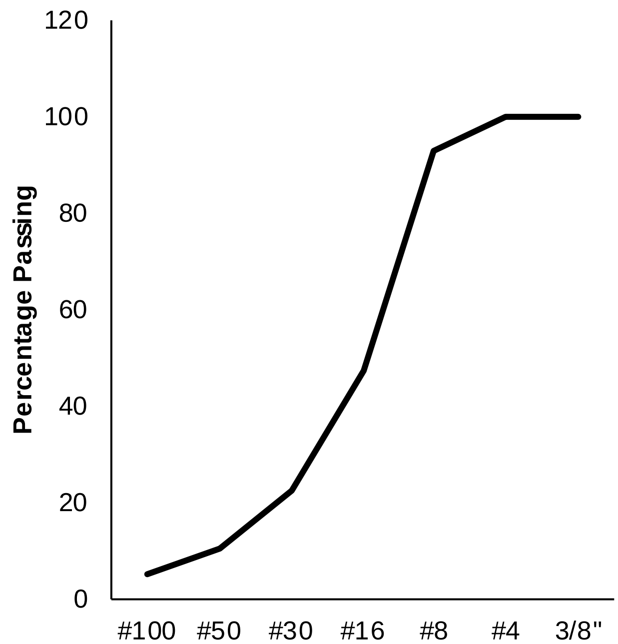

Figure 3.5 Lightweight crushed fines gradation

Proprietary Repair Media

Several proprietary rapid concrete pavement repair media were selected for evaluation. These materials are described below. The reported properties and characteristics are given in Table 3.3.

P1 (Sikacrete 321 FS) is a one-component portland cement concrete that contains factory blended coarse aggregate and is designed for quick turnaround patching and overlays. The best reported uses for this mixture are as a structural repair material for bridges, parking facilities, industrial plants, and walkways. P1 complies with ASTM C-928 specifications for very rapid and rapid hardening mortars.

P2 (BASF MasterEmaco T 1060) is a one-component (fine aggregates included in bag) shrinkage-compensated cement-based mortar with an extended working time. It is designed for repairing horizontal concrete surfaces. This mortar mixture has extra low permeability that helps minimize chloride intrusion, low residual moisture, can be coated in as little as 6 hours, has excellent resistance to freeze/thaw cycling, and can be extended up to 100% by weight using additional coarse aggregates (Pea Gravel aggregates). The extension of P2 (concrete mixture) was considered for the project and was named P2E.

P3 (Pavemend DOTLine) is a fiber reinforced, rapid setting, one-component structural repair concrete. The reported working time is 10–15 minutes and the reported compressive strength is a minimum of 2500 psi within 2 hours. P3 finishes like traditional portland cement concrete and cleans up easily with water. P3 rapid repair concrete offers high performance and ease of use in a pre-extended package.

Phase I Non-Proprietary Repair Media

In addition to the above proprietary mixtures, several non-proprietary high-early-strength concrete mixtures were also developed. These mixtures were based on Type II/V sulfate-resistant portland cement, type III high-early-strength portland cement, and calcium sulfoaluminate (CSA) cement. Mixture designs were determined by the absolute volume method with modifications based on supplier and practitioner experience. Where necessary, MasterSet AC 534 accelerating admixture was used to promote more rapid strength gain. Workability was controlled through the use of MasterGlenium7920 a high-range water reducing admixture. The Phase I non-proprietary repair media were evaluated based on compressive strength alone. Those that met or approached the 4X4 criterion (i.e., 4,000 psi within 4 hours) were selected for further evaluation in Phase II.

Table 3.3 Summary of proprietary repair media

	Product		
Property	P1	P2	P3
Base	Cement	Cement	Cementitious
One Component	Yes	Yes (Mortar)	Yes
Additional Materials	N/A	N/A	Fiber
Weight of Bag, lb	65	50	53.5
Yield, ft^3/unit	0.5	0.43	0.4
Yield - Extended, ft^3/unit	N/A	0.57-0.77	N/A
Required Water, L	2.365	2.6	1.89
Unit Weight, lb/ft^3	N/A	130	152
Min. Ambient Temp. for Mixture, °F	40	50	40
Max. Ambient Temp. for Mixture, °F	95	85	120
Compressive Strengths (ASTM C-39), psi			
2 Hours	2500	N/A	>2500
3 Hours	3000	3000	N/A
1 Day	5000	4000	>5000
7 Days	6000	N/A	>7000
28 Days	7500	7400-8000	>9000
Initial Set, min	40-50	50	20-25
Final Set, min	50-60	80	30-40
Splitting T. Strength (ASTM C496), psi			
1 Day	400	400	N/A
7 Days	600	N/A	N/A
28 days	N/A	450	>500
Shrinkage (ASTM C-157)	<0.06%	<0.05%	<0.045%
Freeze Thaw Factor (ASTM C-666)	>90%	100%	100%

Type II/V Portland Cement

ASTM C595 Type II OPC is classified as moderately resistant to sulfates due to low aluminate (C_3A) content (<8%). Type V OPC is classified as highly resistant to sulfates due to very low aluminate content (<5%). Type II/V OPC meets ASTM C595 criteria for both Types II and V. Despite its sulfate resistant classification, the cost of Type II/V cement is similar to that of Type I general use portland cement. For this reason, Type II/V cement is often used for general construction in areas where sulfate resistance is desirable. Mixture proportions for Phase I Type II/V OPC repair media are given in Table 3.4.

Type III Portland Cement

ASTM C595 Type III OPC is classified as high early strength cement due to its finer gradation and higher alite content. The 3-day compressive strength of Type III OPC is typically comparable to the 7-day compressive strength of Type I or Type II OPC, and the 7-day compressive strength is typically comparable to the 28-day compressive strength of Type I and II cements. However, the later age strength is typically lower than that of general purpose cements. The rapid strength gain in Type III OPC is expected to help achieve the 4X4 strength criterion. Mixture proportions for Phase I Type III OPC repair media are given in Table 3.4.

Calcium Sulfoaluminate (CSA) Cement

Calcium sulfoaluminate (CSA) cement is a rapidly hydrating non-portland hydraulic cement that was developed in the 1960s by Alexander Klein (Bescher, 2015). High early strength gain in CSA cements occurs as a result of rapid precipitation of ettringite (Glasser & Zhang, 2001). This type of cement is relatively new on the market but has been used in the United States since the 1980s. Its durability is excellent, but anecdotal evidence suggests problems with dimensional stability. CSA cement for this project was sourced from CTS Cement, Inc, which recommends its use as direct one-to-one replacement of portland cement. Mixture proportions for Phase I CSA cement repair media are given in Table 3.5.

Table 3.4 Mixture proportions for Phase I Type II/V and Type III OPC repair media

Components	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Cement (lb/yd^3)	790	850	850	850	850
Water (lb/yd^3)	264	280.5	280.5	280.5	280.5
Coarse Agg (lb/yd^3)	1700	1300	1400	1300	1400
Fine Agg (lb/yd^3)	1100	1300	1200	1300	1200
W/C	0.33	0.33	0.33	0.33	0.33
Accelerator (oz/cwt)	60	100	100	150	150
HRWR (oz/cwt)	15	15	15	15	15

Table 3.5 Mixture proportions for Phase I CSA cement repair media

Components	Mixture 1	Mixture 2	Mixture 3
Cement (lb/yd3)	850	850	850
Water (lb/yd3)	213	297.5	297.5
Coarse Agg (lb/yd3)	1787	1300	1400
Fine Agg (lb/yd3)	1015	1300	1200
W/C	0.35	0.35	0.35
Accelerator (oz/cwt)	0	0	0
HRWR (oz/cwt)	25.5	25.5	25.5

Phase II Non-Proprietary Repair Media

Eight mixtures were selected for further evaluation based on the results of Phase I limited testing of non-proprietary Type II/V, Type III, and CSA cement repair media. Mixture proportions from Phase I were selected according to their compressive strength results: around 4000 psi of strength in around 4 hours. Mixtures not close to meeting this criterion were not considered for Phase II Mixutre proportions of the selected mixtures were modified in order to increase strength gain, obtain better workability and include IC agents to observe their effects. Mixtures are coded to reflect their cement type (CSA or OPC Type III), if they are a control (denoted by the number 1), their silica fume weight replacement (SF%) and their IC agents (IC – full PSLWA, ICF- only fine PSLWA) Phase II mixture proportions are given in Table 3.6.

Mixing Procedure

The mixing procedure is given as follows:

1. Rinse the mixer with water;
2. Remove any excess (puddled) water from the mixer; the mixer should be damp, not wet;
3. Add coarse and fine aggregate to mixer and about ¼ of the mix water;
4. Mix for 1-2 minutes;
5. Start adding the cement and water to the mixer as it is mixing (cement is added using a scoop and some of the water is added after every 2 scoops of cement);
6. After all the cement and water has been added, add the air entrainment admixture (AEA);
7. Mix for 1-2 minutes;
8. If it the mixture has a low slump, add the HRWR and let it mix for about 1 minute;
9. Turn the mixer off for 3 minutes;
10. Restart the mixer, add the accelerator, and mix for 2 minutes;
11. Check slump, unit weight, air content, and temperature; and
12. Cast specimens

Mixing time requires approximately 4-8 minutes . Mixtures with OPC followed all the mixing procedure (around 8 minutes) because accelerator was added. Mixtures with CSA did not have a need for step 9 and 10, because accelerator was not used in them. Time to set was measured from the end of Step 5.

Testing Procedures

Repair media were mixed and prepared at Utah State University in Logan, UT. Once mixed, specimens were cast in cylindrical or prismatic molds (as listed below) and stored in a moist curing room at 23±2 ˚C. Specimens were demolded 4 hours after water was added to the mixture, at which point testing commenced. In some cases, rapid setting of the repair media precluded casting enough specimens for every test. In these cases, either multiple batches were cast or set dependent tests (slump, air content) were forgone in favor of non-set dependent tests (e.g., compressive strength, modulus of elasticity, freeze-thaw). The tests and relevant standardized methods are described below.

Table 3.6 Phase II Mixture Proportions

Material	Units	CSA	CSAIC	CSAICF	OPC1	OPCIC	OPCSF20	OPCSF30IC	OPCSF30ICF
Cement Type III	lb/yd^3				950	950	735	630	630
Cement CTS	lb/yd^3	800	800	800					
Silica Fume	lb/yd^3						185	270	270
Water	lb/yd^3	240	240	240	290	290	275	270	270
NW Coarse Agg	lb/yd^3	1700		1700	1600		1600		1600
NW Fine Agg	lb/yd^3	1450			1400		1400		
LW Coarse Agg	lb/yd^3		1095			1030		1030	
LW Fine Agg	lb/yd^3		940	940		905		905	905
W/C	lb/yd^3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Accelerator	oz/cwt				150	150	150	150	150
HRWR	oz/cwt	25.5	25.5	25.5	15	15	15	15	15

Compressive Strength

Compressive strength was evaluated in accordance with the specifications of ASTM C39. Three replicate 4×8 in cylindrical specimens were tested for each mixture at 4 and 24 hours. Cylinders were capped with neoprene caps in accordance with the specifications of ASTM C1231 prior to testing, as seen in Figure 3.6.

Modulus of Elasticity

The static modulus of elasticity was evaluated in accordance with the specifications of ASTM C469. Two or three replicate 4×8 in cylindrical specimens were tested for each mixture. The age at testing was 4 hours. Each cylinder was fitted with an axial compressometer (Figure 3.7) and loaded in uniaxial compression to a stress of approximately 40% the compressive strength. The modulus of elasticity was calculated as the chord modulus according to ASTM C469 Equation 3.

Figure 3.6 Cylinder in the compression test with neoprene caps

Splitting Tensile Strength

Splitting tensile strength was evaluated in accordance with the specifications of ASTM C496. Two or three replicate 4×8 in cylindrical specimens were tested for each mixture. The age at testing was 4 hours. The test setup is shown in Figure 3.8. Splitting tensile strength is known to underestimate the tensile strength of concrete compared to direct tension or flexural testing (Metha & Monteiro, 2006) (Olufunke, 2014).

Drying Shrinkage

Drying shrinkage of two 3×3×16-in specimens of each mixture was measured in accordance with the specifications of ASTM C157. Specimens were demolded at an age of four hours and measured using a standard length comparator (Figure 3.9). Specimens were then stored at 23±2 ˚C and 50±5 %RH. The length change was monitored for a period of 7 days. Drying shrinkage strain was calculated according to ASTM C157 Equation 1.

Figure 3.7 Compressometer for determination of modulus of elasticity (ASTM C469)

Figure 3.8 Splitting tensile (Brazilian) test (ASTM C496)

Figure 3.9 Length comparator (ASTM C157)

Setting Time

Setting times were determined by Acme penetration resistance in accordance with the specifications of ASTM C403. The Acme penetration resistance test estimates the setting times of mortar sieved from fresh concrete mixtures. Initial setting time corresponds to penetration resistance of 500 psi; final setting time corresponds to penetration resistance of 4000 psi. The penetration resistance was measured using a 0.1 in^2 needle every few minutes until each mixture reached final set.

Restrained Shrinkage Cracking

The resistance to cracking due to restrained shrinkage was evaluated by the restrained ring shrinkage test, performed in accordance with the specifications of ASTM C1581. This test determines the average time to cracking under restrained shrinkage conditions. The restrained shrinkage ring is shown in Figure 3.10. Testing typically begins at age 24 hours. Since repair media are expected to perform well at early age, the test method was modified to begin at age 4 hours. Due to limited number of shrinkage ring apparatus, this test included a single replicate per mixture.

Creep

Creep shrinkage was evaluated in accordance with the specifications of ASTM C512. Four cylindrical specimens from each mixture were loaded into the creep frames shown in Figure 3.12 and loaded to 40% of their ultimate compressive strength, starting at 48 hours. Length change was monitored at the measuring locations depicted in Figure 3.11 using the strain gauge shown in Figure 3.13. Measurements were taken until the length change measurement stabilized or until 120 days.

Freeze Thaw Durability

The resistance of repair media to freezing and thawing was evaluated in accordance with the specifications of ASTM C666 Procedure A. Two 3×3×16-in specimens from each mixture were cured for 14 days, after which they were subjected to rapid freeze/thaw cycling. The change in mass was recorded after each cycle of freezing and thawing. Each specimen was subjected to 300 cycles.

Figure 3.10 Restrained ring shrinkage test (ASTM C1581)

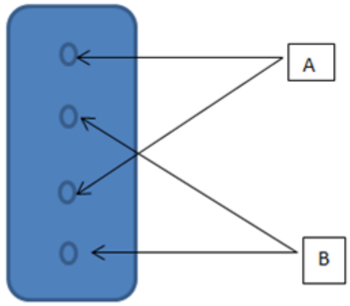

Figure 3.11 Reference measurement locations for creep shrinkage strain

Figure 3.12 Creep testing frame (ASTM C512)

Figure 3.13 Creep strain gauge

Chapter 4: Summary of Results

This section presents the results of experimental testing of proprietary repair media as well as Phase I and Phase II non-proprietary Type II/V, Type III, and CSA cement repair media.

Proprietary Mixture Results and Comparisons

Compressive Strength

Only two to three specimens (due to a limited number of cylinders) were tested from each mixture at 4 hours and 24 hours and the average compressive strength was plotted in the bar graph as shown in Figure 4.1. Since the concrete compressive strength is dependent on the type of curing used, all specimens were cured in the same conditions. P2 obtained the highest compressive strength at 4 hours and 24 hours with approximately 5,900 psi and 7,300 psi, respectively.

Modulus of Elasticity

The average Modulus of Elasticity of each mixture can be seen in Figure 4.2. P2 obtained the highest Modulus among all proprietary mixtures at 4,100 ksi at 4 hours.

Split Tension

The average splitting tensile strength of each proprietary mixture is plotted as shown in Figure 4.3. P1 attained the highest split tension at approximately 280 psi at 4 hours.

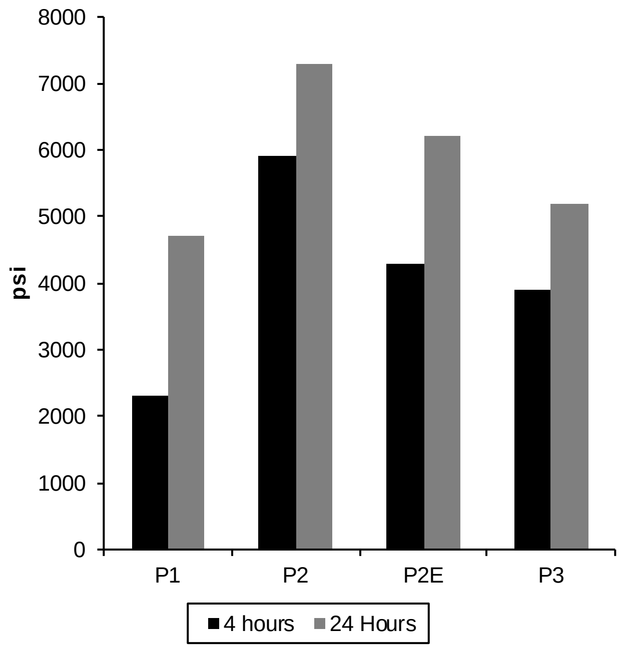

Figure 4.1 Compressive strength of proprietary materials (age = 4 and 24 hours)

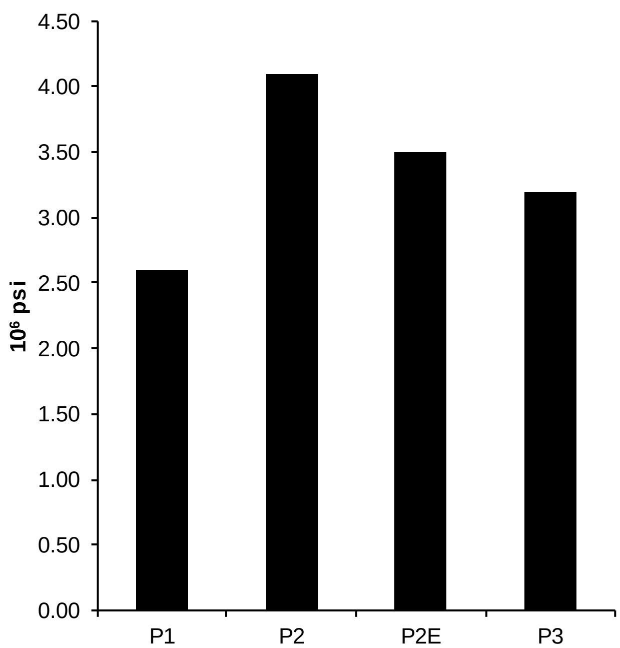

Figure 4.2 Modulus of elasticity of proprietary materials (age = 4 hours)

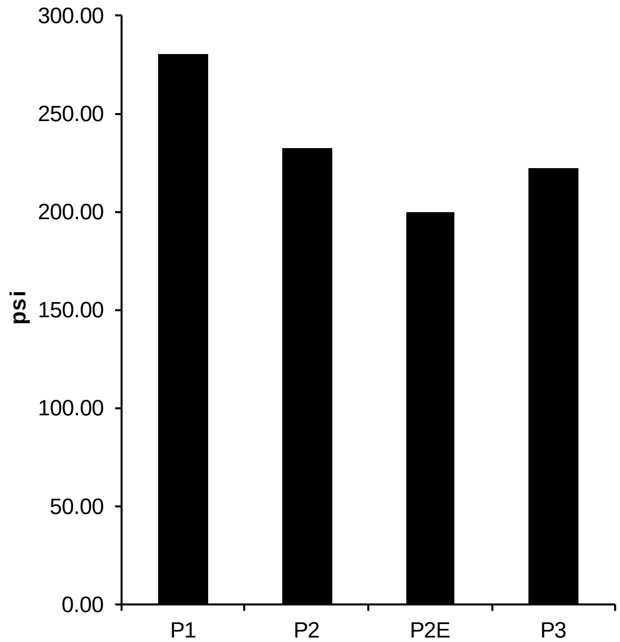

Figure 4.3 Splitting tensile strength of proprietary materials (age = 4 hours)

Drying Shrinkage

Figure 4.4 shows drying shrinkage strain on each proprietary mixture. It is important to note that these measurements do not indicate that the proprietary materials have stopped shrinking. P1 obtained the highest drying shrinkage at the end of the measurements.

Setting times

Initial and final setting times for proprietary repair media are shown in Figure 4.5. The fastest setting repair medium was P3, with initial and final setting times of 9 and 22 minutes, respectively. The slowest setting medium was P2, with initial and final setting times of 50 and 65 minutes.

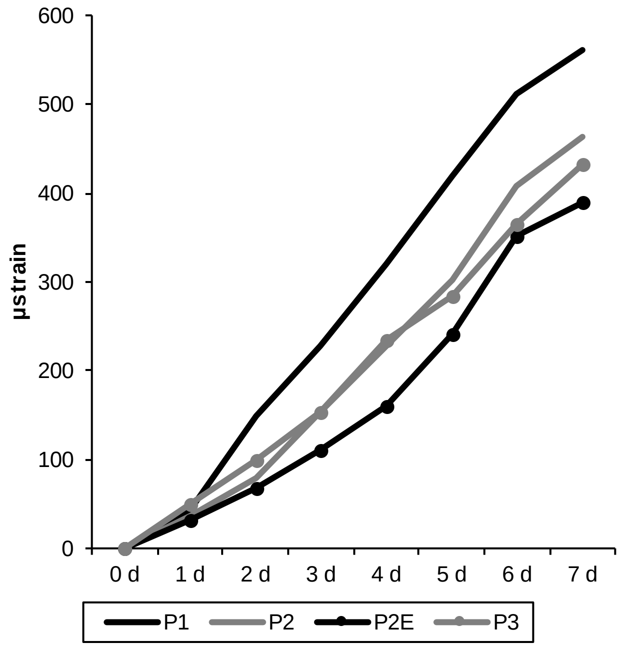

Figure 4.4 Drying Shrinkage Strain for proprietary materials

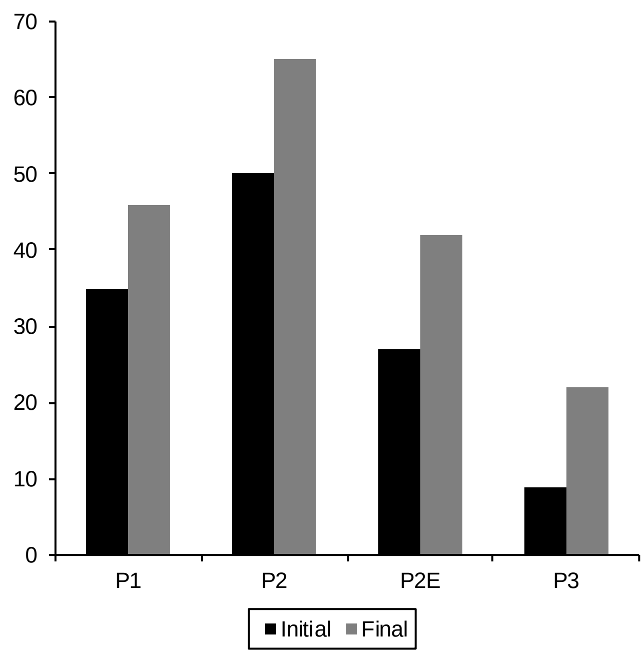

Figure 4.5 Initial and Final setting times (min) of proprietary materials

Comparison of Results from Proprietary Mixtures

P1 had a good amount of workability time (35 min) but had the lowest compressive strength of all the proprietary mixtures (approximately 2,300 psi in 4 hours). P2 exhibited the highest compressive strength of all proprietary materials tested. It ranked first in both compressive strength and early strength gain (5,900 psi at 4 hours). This mixture had the longest workability time (50 min for initial setting). These results are questionable because the mixture contained fine aggregates rather than coarse aggregates and obtained greater compressive strengths than P2E which had coarse aggregate. It is likely that this mixture was designed to work as a mortar instead of being used with coarse aggregate as it could possess little adhesive capacity for larger aggregates. P2 could be tested to see how it performs with PSLWA in future research.

The P2E mixture provided the second highest compressive strength of all the mixtures at about 4,300 psi in 4 hours. This could mean that P2E is stronger when it is not extended, or the aggregates for its extension are ones specified by the manufacturer, or else P2E will compromise mechanical properties.

P3 had the lowest workability time of all the mixtures tested (9 minutes for initial setting), which may have been caused by temperature, although the mixture was made in the temperature range specified by the manufacturer. Table 4.1 presents a summary of the tests performed on the proprietary mixtures.

Table 4.1 lists the results of tests performed on the proprietary products side-by-side for comparison. A final decision on “best” should be made situational to take advantage of different properties, if desired

Table 4.1 Summary of Test Results for Phase I Proprietary Products

Property	P1	P2	P2E	P3
Unit Weight, lb/ft^3	132	139	146	151
Compressive Strengths (ASTM C-39), psi				
4 Hours	2300	5900	4300	3900
24 Hours	4700	7300	6200	5200
Initial Set, min	35	50	27	9
Final Set, min	46	65	42	22
Splitting T. Strength (ASTM C496), psi				
4 Hours	280	232	200	222
Elastic Modulus, 10^6 psi	2.1	3.5	1.9	3.06

Phase I Non-Proprietary Mixtures

Each Trial Mixture was prepared and mixed in Utah State University laboratories. After mixing, the concrete was cast into molds and was promptly put into a temperature controlled room to be air cured before each test. The specimens were demolded 4 hours after the water contacted the cement and were then air cured at 70 +/- 3 °F and 50 +/- 5% Relative Humidity. The following results are reported:

Compressive Strength

Figure 4.6 contains compressive strengths of mixtures with type II/V cement. Typically, type II/V cements do not gain strength rapidly. Mixture 3 had the highest 4 hour compressive strength observed at about 2,100 psi. Mixtures 4 and 5 with more accelerator failed to gain more strength than Mixtures 2 and 3 (at age 4) and this is different from what has been observed throughout the study (more accelerator equals higher early compressive strength). The unknown water content of the accelerator may be affecting Mixtures 4 and 5 by compromising their strength gain.

The CSA mixture results are presented in Figure 4.7. These mixtures had strengths in excess of 7,000 psi at 4 hours, and the cement content used in these mixtures was greater than recommended by the manufacturer. This was done to do a one-to-one comparison to the other mixtures.

Type III OPC mixtures compressive strengths are presented in Figure 4.8. Due to discrepancies noted with the Type II/V cement mixtures, Mixtures 4 and 5 are modifications of Mixtures 2 and 3 with 150 oz/cwt of accelerator (50 oz/cwt more). Type III OPC mixtures seem to possess slightly higher (10%-25%) compressive strengths than Type II/V OPC mixtures. Mixtures 3, 4 and 5 obtained the highest compressive strengths with about 2,200 psi, 2000 psi and 2,100 psi at 4 hours, respectively.

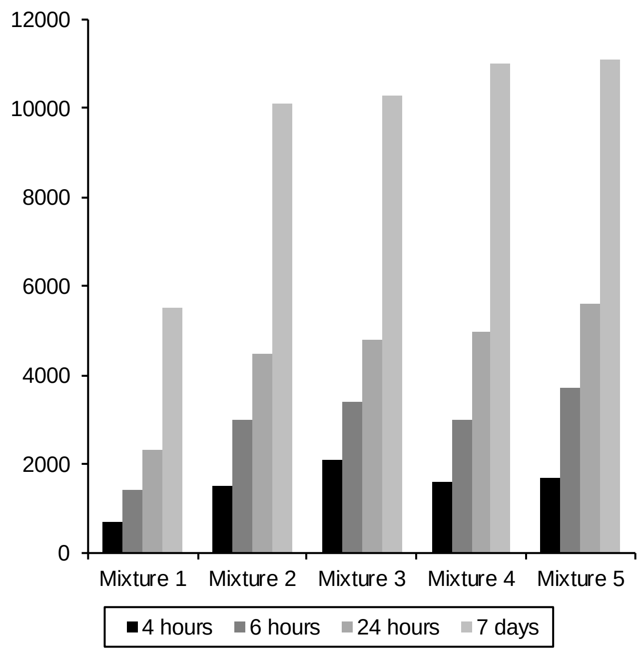

Figure 4.6 Type II/V Compressive Strengths

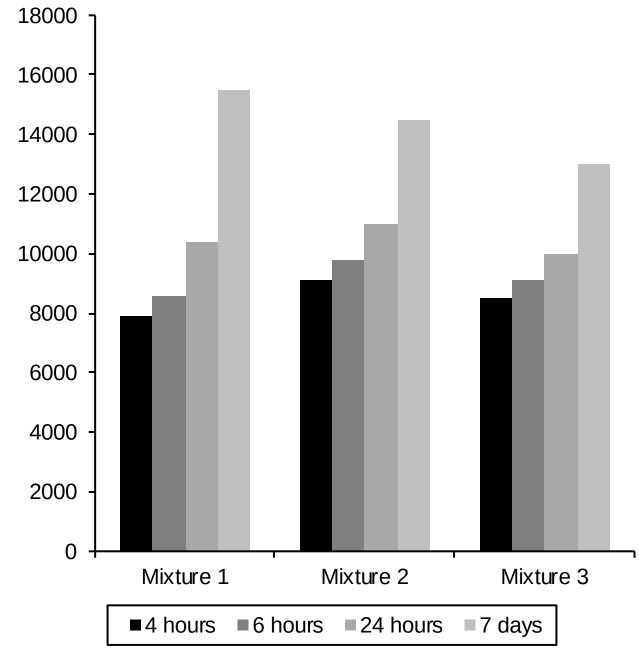

Figure 4.7 CSA Compressive Strengths

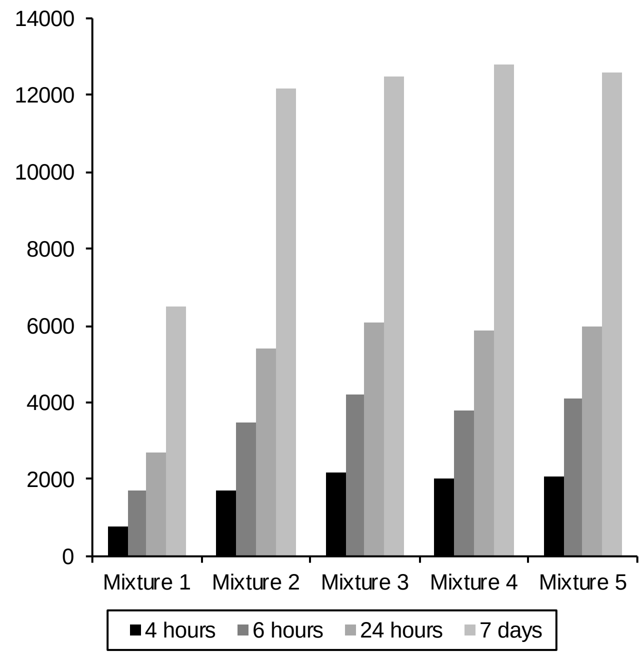

Figure 4.8 Type III Compressive Strengths

Based on the above results, Type II/V was discarded due to Type III mixtures obtaining between 10% and 25% more compressive strength when compared at same ages. Mixtures 3, 4 and Mixture 5 were selected for continued study, including PSLWA full and partial replacement

(IC), Silica Fume replacement, and investigation into durability and dimensional stability, similar to the tests performed on the proprietary materials.

Phase II Non-Proprietary Repair Media

Workability

The workability of Phase II non-proprietary repair media was evaluated by the slump test as discussed previously. Slump values are given in Table 4.2 Poor workability and early slump loss due to rapid hydration precluded slump measurements in CSA cement-based repair media. This is denoted by 'N/A' in Table 4.2. Increased dosage of high range water reducer or inclusion of retarding admixtures would mitigate this issue.

Table 4.2 Workability of Phase II non-proprietary repair media

	Units	CSA1	OPCSF20	OPC1	OPCIC	OPCSF30IC	CSAIC	CSAICF	OPCSF30ICF
Slump	in	N/A	4	3.5	4	4.5	N/A	N/A	3.8

Air Content

Table 4.3 presents air content measurements of Phase II Mixtures, according to ASTM C173. These values are between 4 and 6 percent. As with the slump test, N/A results indicate that the mixture set so fast that the test could not be performed accurately with the selected method. In general, every mixture was within the acceptable levels of air content percentage, which varied from 4% to 7%.

Table 4.3 Air Content results for Phase II Mixtures

Test	Units	CSA1	OPCSF20	OPC1	OPCIC	OPCSF30IC	CSAIC	CSAICF	OPCSF30 ICF
Air Content	%	N/A	4.6	5.2	5.6	5.4	N/A	N/A	4.6

Unit Weight

Unit weight for each Phase II Mixture is presented in Table . Mixtures OPCIC, OPCSF30IC, and CSAIC had lower unit weights due to their aggregates being lightweight.

Table 4.18 Unit Weight results for Phase II Mixtures

Test	Units	CSA1	OPCSF20	OPC1	OPCIC	OPCSF30IC	CSAIC	CSAICF	OPCSF30 ICF
Unit Weight	lb/ft^3	139	145	141	116	112	120	131	142

Compressive Strength

The compressive strength of Phase II non-proprietary repair media was determined in accordance with the specifications of ASTM C39 at ages of 4, 6, and 24 hours, and at 7 days. The compressive strength results are shown in Figure 4.9. Beshr and Almusallam (2003) tested the compressive strength of different concretes using type III OPC while varying their coarse aggregate composition. They reported compressive strengths between 3.9 and 7.3 ksi at 24 hours and between 4.2 and 7.7 ksi at 7 days, which are consistent with the results reported here. Péra and Ambroise tested three CSA concrete mixtures and reported compressive strengths of 5.1, 5.8, and 7.0 ksi at 6 hours, which is consistent with the results reported here for CSA mixtures (CSA1, CSAIC, and CSAICF) (Péra & Ambroise, 2004). Ioannou et al. (2014) tested the properties of a ternary calcium sulfoaluminate-calcium sulfate-fly ash cement and reported compressive strengths of 5.3 ksi at 24 hours and 8.3 ksi at 7 days.

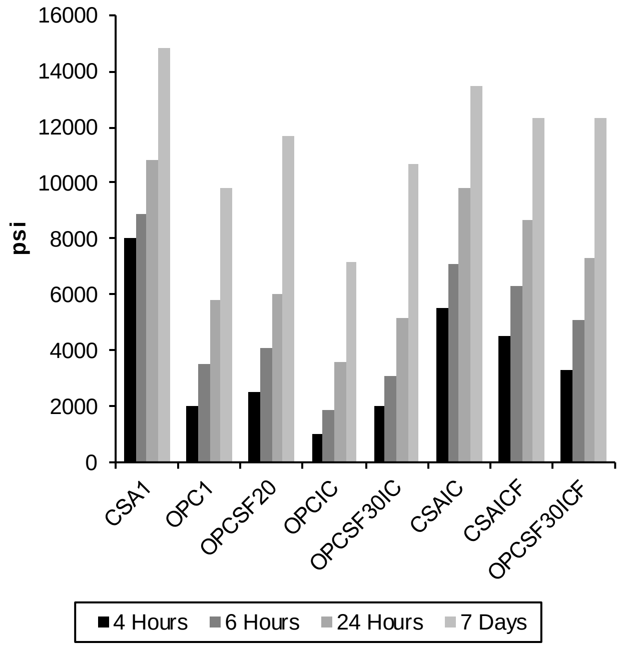

Figure 4.9 Compressive strength of Phase II non-proprietary repair media

The CSA Mixtures (CSA1, CSAIC, and CSAICF) successfully met the 4X4 acceptance criterion (compressive strength of at least 4,000 psi within 4 hours). These mixtures had the highest compressive strength of the Phase II Mixtures. Mixture OPCSF30ICF was near this criterion, with compressive strength of about 3,300 psi at 4 hours.

Elastic Modulus

Static moduli of elasticity of Phase II non-proprietary repair media are shown in Figure 4.10. Elastic moduli in the range 1.7–4.6 × 10^6 psi were observed at 4 hours. This is lower than previously observed values by Donza et al. (Donza, Cabrera, & Irassar, 2002) for CSA mixtures, which were in the range 4.64–5.65 × 10^6 psi, and those observed by Beshr and Almusallam (2003) for type III OPC mixtures, which were in the range 3.13–4.29 × 10^6 psi. However, these values were observed at 28 days, and are thus expected to be higher. Also shown in Figure 4.10, are the predicted elastic moduli for Phase II non-proprietary repair media. Predicted moduli of elasticity are determined by the following equation from ACI 318:

$$E = 57000 * \sqrt{f_c'} \text{ (in psi)}$$

E = Elastic modulus

f_c' = Concrete compressive strength

In general, the predicted and observed moduli of elasticity were within 10% of one another. There is little data within the literature to support agreement of experimental data and actual performance for CSA cement concrete.

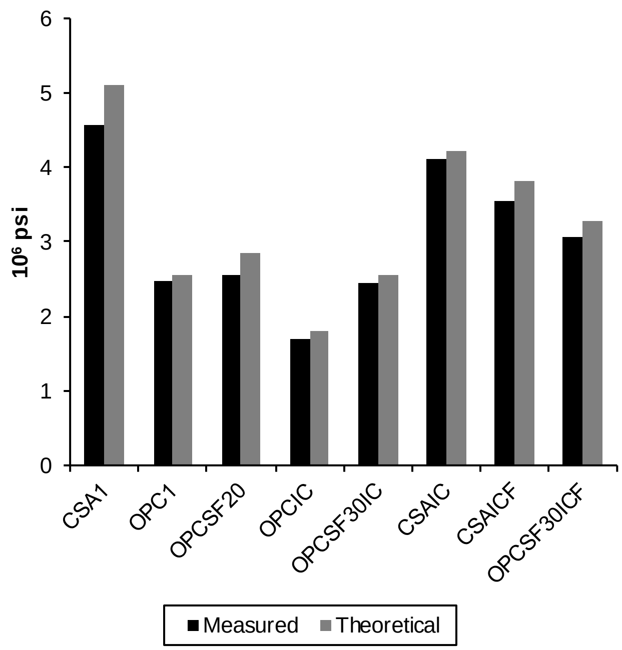

Figure 4.10 Predicted and measured moduli of elasticity of Phase II non-proprietary repair media

Splitting Tensile Strength

Split tensile strength (ASTM C496) results for each Phase II mixture are shown in Figure 4.11. These results reflect the 4 hour old split tensile strength for the mixtures. Beshr and Almusallam (2003) tested the split tensile strength of different concretes using type III OPC, varying the coarse aggregate composition, and obtained values from 320 psi to 544 psi at 14 days.

Donza et al. reported splitting tensile strengths between 487 and 565 psi at 28 days (Donza, Cabrera, & Irassar, 2002). Nevertheless, these results were presented at 14 days and 28 days and are expected to be higher.

Compressive strength is not the most important value for pavement design and therefore is unlikely to be the most important for rapid pavement repair concrete. Flexural strength is more important for the design of pavement (ACI Committee 330, 2008; Southararajah, et al., 2016). The values obtained for the split tensile strength test are 1.75 times higher than the uniaxial tensile strength of the mixtures according to ACI 318. Statistical analysis software was used to produce an equation (see Figure 4.12) to determine the flexural strength from the split tensile strength using results from Bhanja and Sengupta (2005) and from Nazari et al. (2010). ACI 330R developed an empirical equation using data from four different studies to establish an approximate relationship between compressive strength and flexural strength. (ACI Committee 330, 2008). All methods are shown in Table 4.4.

$$f_{flexural} = 2.3 * f'c^{2/3}$$

$f_{flexural}$ = Flexural strength of concrete (psi)

$f'c$ = Compressive strength of concrete (psi)

Table 4.4 Split Tensile Strength (ksi) at 4 hours of Phase II Mixtures

Test	Units	CSA1	OPC 1	OPCSF20	OPCIC	OPCSF30IC	CSAIC	CSAIC F	OPCSF30ICF
Tension Strength	psi	352	189	210	115	165	325	305	189
Statistics	psi	745	558	583	474	531	714	691	558
ACI 330-R	psi	920	365	424	230	365	717	627	510

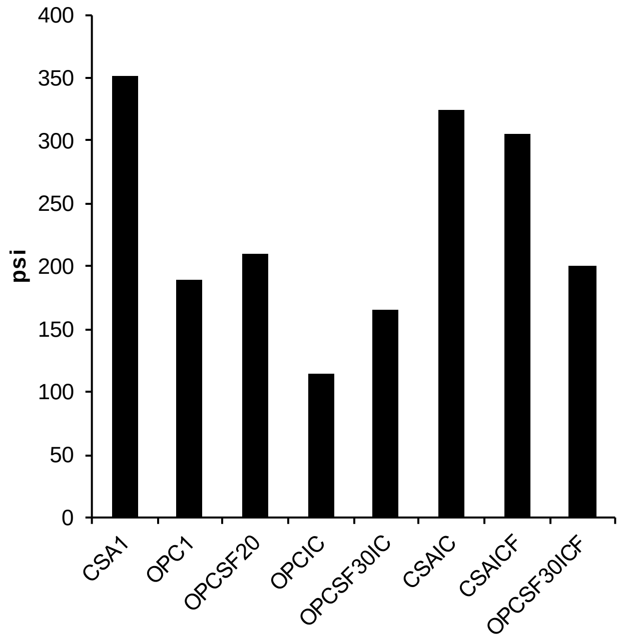

Figure 4.11 Splitting tensile strength of Phase II non-proprietary repair media

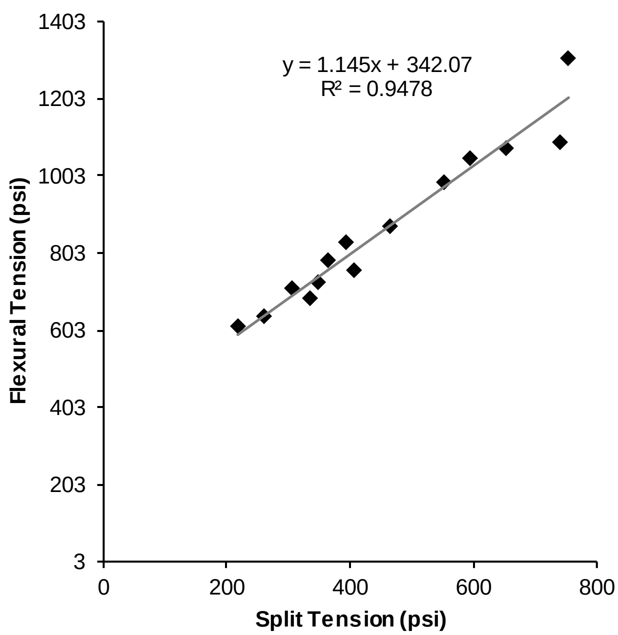

Figure 4.12 Fitted data to a linear regression equation with an R square value of 0.94 from Split Tensile and Flexural Strength data

The linear regression and the ACI 330-R equation present an average absolute percentage difference of approximately 23% between themselves. When used to predict flexural strength of

IC mixtures, these methods' predictions are closer (lower than 9% difference), but when predicting other mixtures the difference increases (up to 34%, excluding one outlier: OPCIC).

Setting time

The initial and final setting times for Phase II mixtures are presented in Figure 4.13. These results were obtained by following ASTM C403. Clearly, many of the mixtures have their initial set under 16 minutes, namely the CSA cement mixtures (CSA1, CSAIC, and CSAICF, with 9, 16, 13 minutes, respectively). The setting speed of these mixtures indicates that construction crews will have difficulty placing and finishing the mixture, and ready-mix companies may not be willing to provide concrete from a batch plant and so this concrete may need to be mixed on site. The lowest initial setting time for CSA concretes has been determined to be under 5 minutes and as high as 45 minutes by using additives (Ioannou, Reig, Paine, & Quillin, 2014; Glasser & Zhang, 2001).

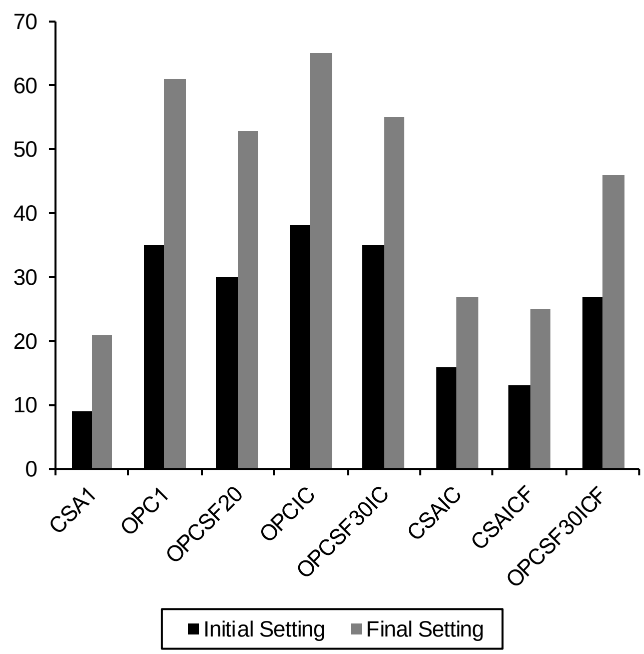

Figure 4.13 Initial and final setting times of Phase II non-proprietary repair media

Drying Shrinkage

A detailed bar graph of the drying shrinkage of the Phase II mixtures can be seen in Figure 4.14, in micro-strains. Bescher observed between 550 and 900 με expansion (negative shrinkage) during drying shrinkage tests of several rapid hardening hydraulic cement concretes at 7 days (Bescher, 2015). This is also consistent with the results obtained for the CSA Mixtures (CSA1, CSAIC, and CSAICF).

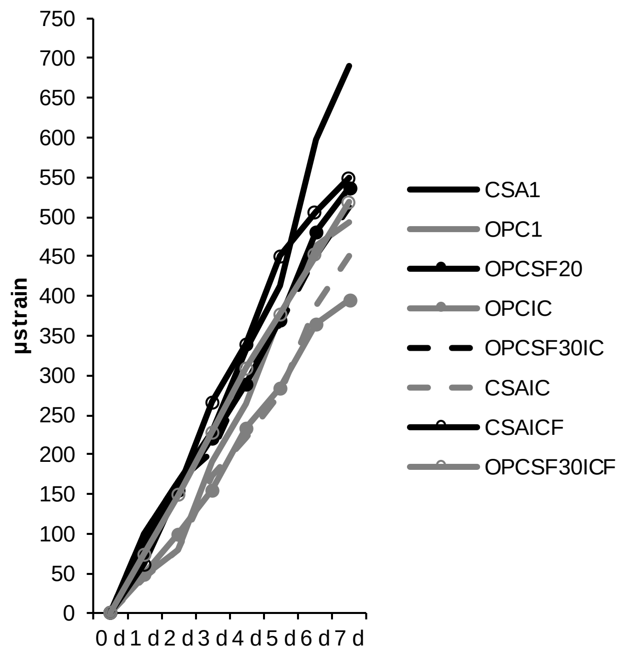

Figure 4.14 Drying shrinkage in Phase II mixtures

Shrinkage Ring

The cracking day reported refers to the day the first crack appeared in the ring, as can be seen in Figure 4.15. The results account for micro-cracks that could have developed because of small changes in temperature. The data regarding rapid set mixtures obtained from this test can be compared to the data obtained by Bescher (2015). Bescher obtained failure at 7 days with an Accelerated Portland Type II Cement BASF 4 × 4 mixture. Yatagan (2015) also reported between

5 and 12 days to first crack in shrinkage rings for different types of Accelerated Type I cement concrete mixtures.

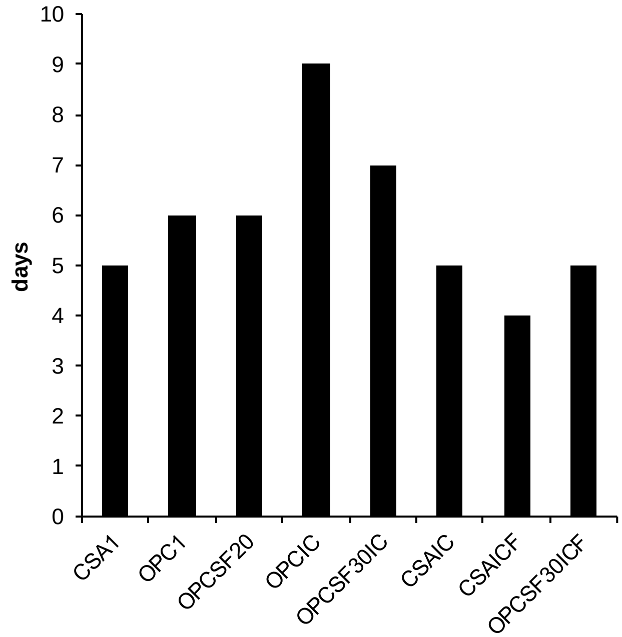

Figure 4.15 Time to first crack in restrained ring shrinkage tests of Phase II mixtures

There was not a noticeable difference between Phase II Mixtures in the Shrinkage Ring tests (see Figure 4.15). This was probably due to an electrical malfunction that destroyed the data logger attached to the rings, compromising all of the data obtained by the strain gauges, and only manual visual inspection data was available for the tests. Manual visual inspection detected the first crack in every ring, regardless of size, which can be misleading as some small cracks may appear and may not be caused by autogenous shrinkage.

Freeze Thaw

Mass retained values for the Phase II mixtures are presented in Table 4.5. Similar mass retained values have been presented by Ozyildirim (2009) for concretes with similar constituents.

Table 4.5 Mass retained after 300 cycles of freezing and thawing

Test	Units	CSA1	OPCSF 20	OPC1	OPCIC	OPCSF 30IC	CSAIC	CSAICF	OPCSF 30ICF
Mass Retained	%	96	94	95	94	94	98	97	95

Compression Creep

The compression creep results for Phase II Mixtures can be seen in Figure 4.16 to Figure 4.23. Vincent (2003) obtained similar results with his research regarding the lightweight aggregate mixtures. The results indicate that CSA1, CSAIC, and CSAICF had noticeable less creep strain at 120 days than the rest of the mixtures.

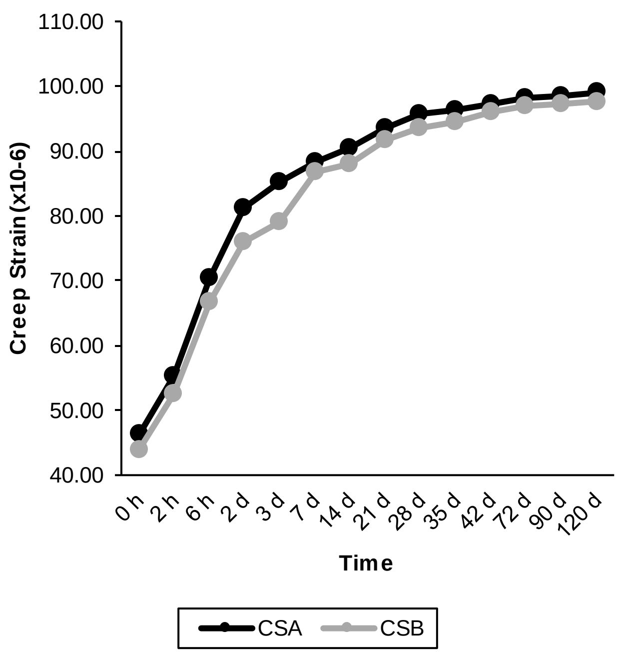

Figure 4.16 Creep shrinkage for CSA1

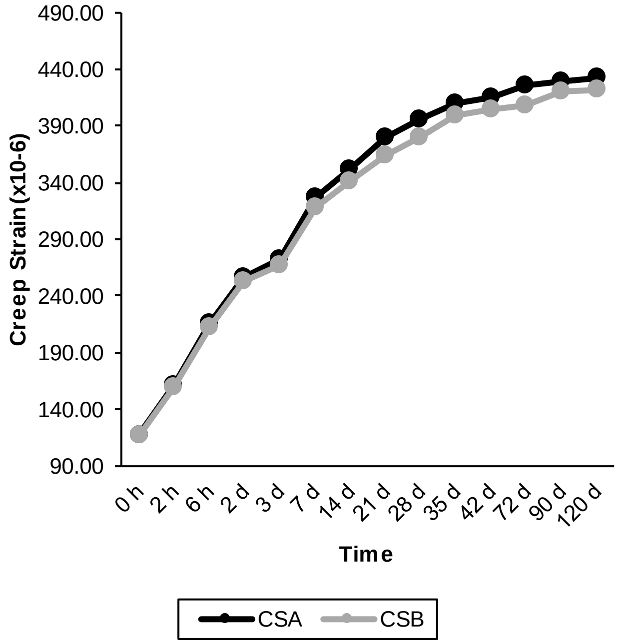

Figure 4.17 Creep shrinkage for OPC1

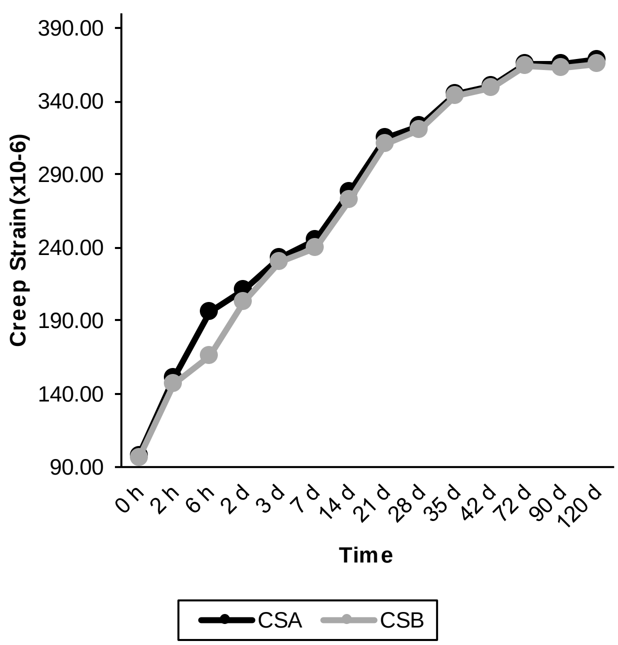

Figure 4.18 Creep shrinkage for OPCSF20

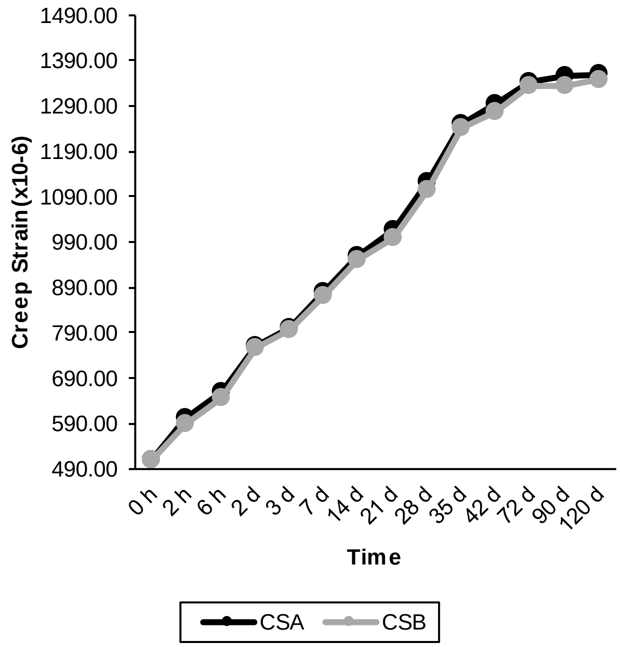

Figure 4.19 Creep shrinkage for OPCIC

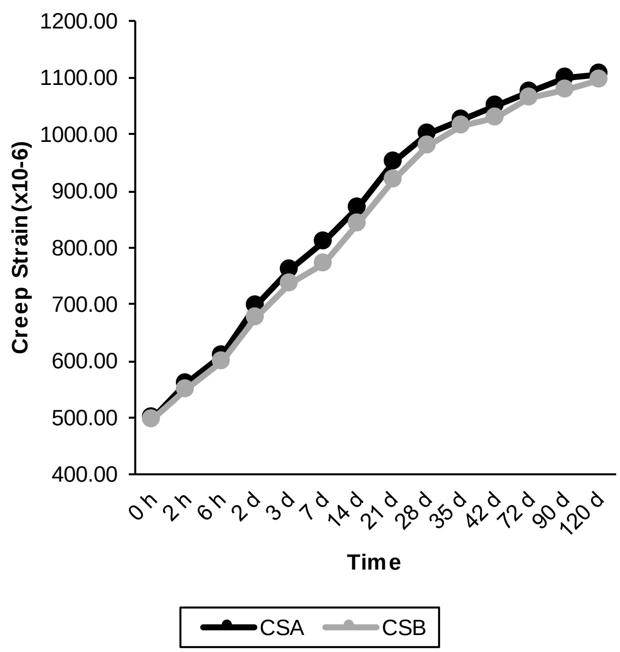

Figure 4.20 Creep shrinkage for OPCSF30IC

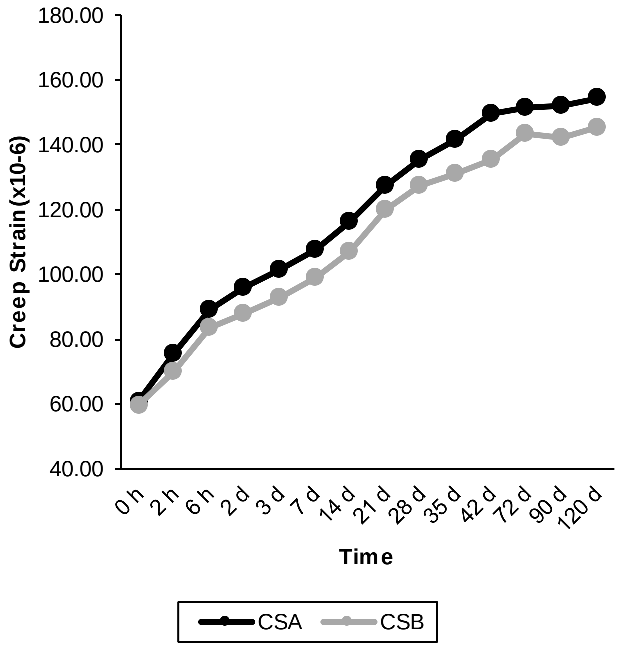

Figure 4.21 Creep shrinkage for CSAIC

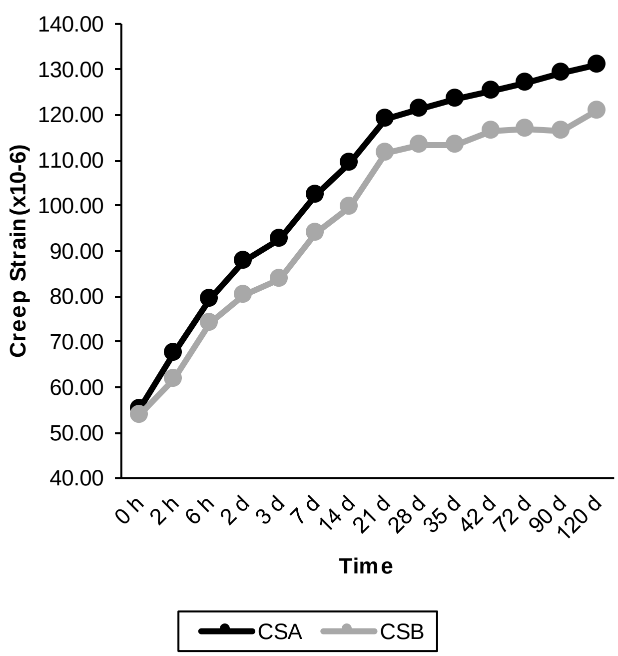

Figure 4.22 Creep shrinkage for CSAICF

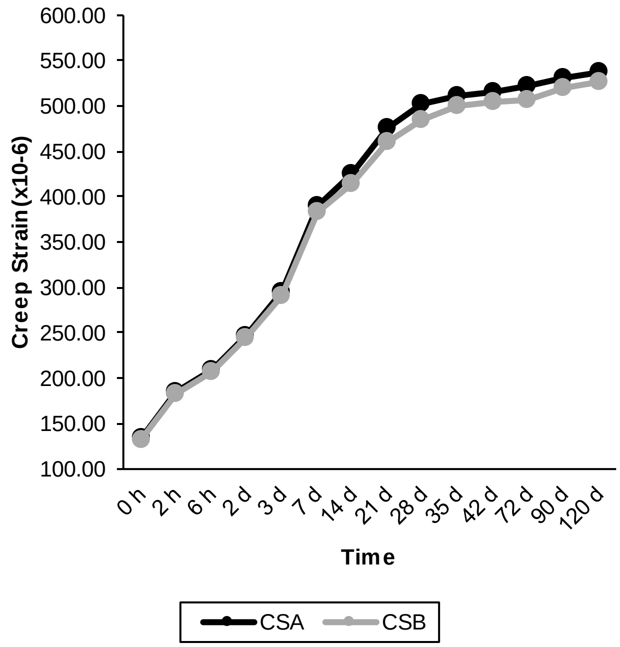

Figure 4.23 Creep shrinkage for OPCSF30ICF

Figure 4.24 shows the maximum creep measured for Phase II mixtures and the drying shrinkage micro-strain observed at 7 days. The Creep Coefficient in Figure 4.25 was calculated as the ratio of the creep at 120 days over the first measurement per mixture. In Figure 4.25, a ratio between drying shrinkage and creep coefficient is shown. High values represent low creep and high shrinkage and low values represent high creep and low shrinkage, which is desired in this project.

Statistical Analysis

A statistical analysis was performed on the mixtures components and their results (see Appendix). This analysis was meant to find any relationships between materials used and the mechanical, volume and time dependent properties of each mixture. The Correlation Procedure showed the following relationships between variables:

- Initial and Final setting time are significantly dependent on the type of cement used (p-value = 0.0005 and <0.0001, respectively for OPC, and 0.0006 and 0.0008, respectively for CSA).
- Drying Shrinkage is significantly dependent on the percentage of entrained air. (p-value = 0.02405)
- The Elastic Modulus is not dependent on the amount nor type of aggregates used per mixture (p-value = >0.5001, in all cases) ; however, it is extremely dependent on the amount and type of cement used (p-value = <0.0025, in all cases).
- Mass retained in Freeze Thaw is significantly dependent on the Compressive Strength values obtained at 24 hours and 7 days (p-value = 0.0394 and 0.0501, respectively).

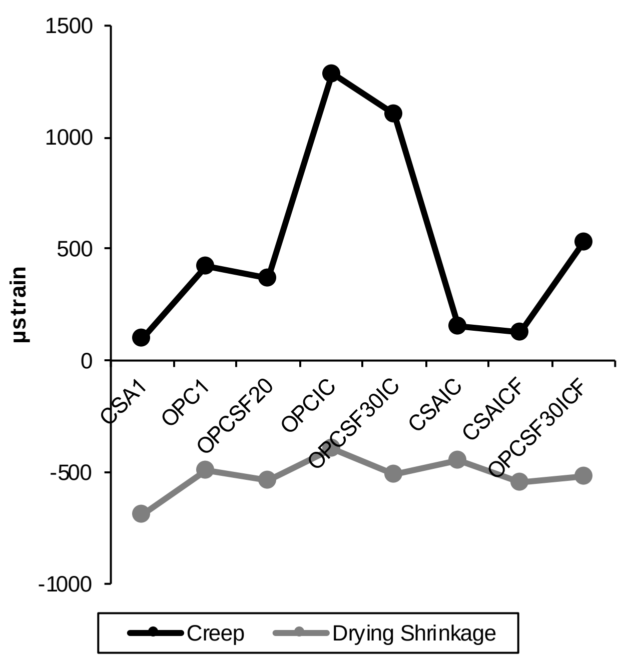

Figure 4.24 Length Change and Max Creep per Mixture in Microstrain

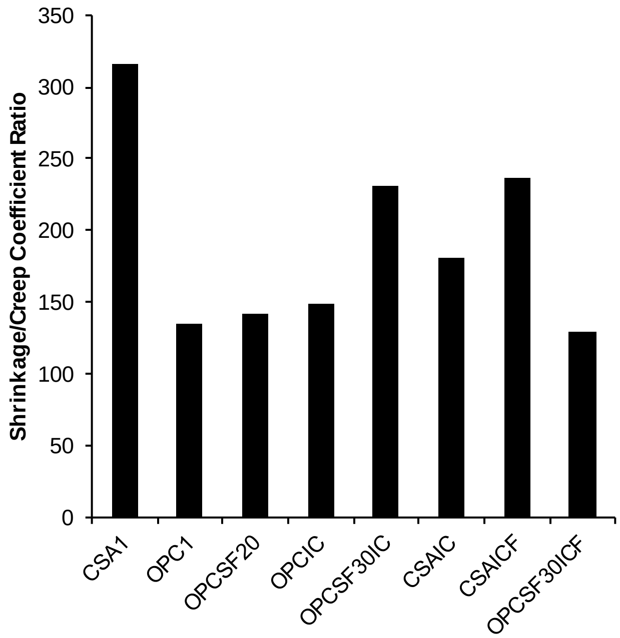

Figure 4.25 Shrinkage/Creep Coefficient Ratio

Chapter 5: Conclusions and Recommendations

This study investigated the fresh, mechanical, and durability properties of high early strength concrete materials intended for rapid pavement repair applications. This included several proprietary and non-proprietary materials. This chapter presents conclusions and recommendations based on the test results presented above.

Compressive and Tensile Strength

CSA1 obtained the highest compressive strength of all the mixtures at approximately 8,000 psi. This mixture was a CSA mixture and had the highest early strength at 4 hours. From the results, it can be concluded that it is unlikely that a Type II/V or Type III concrete mixture will reach 4,000 psi in 4 hours, even with significant silica fume replacement and large doses of accelerator. Without using CSA cement, the closest result to these criteria was OPCSF30ICF, which obtained approximately 3,300 psi in 4 hours. However, if there is flexibility with time, OPCSF30ICF would be a good candidate because of its compressive strength.

Flexural strength was not directly measured for the reasons discussed above. There is a clearly defined relationship, empirically and mechanically, between uniaxial split and flexural tension strengths for concrete. The criterion for flexural strength is 400 psi, which is met by the CSA Mixtures. Using the average of the ACI 330-R equation and linear regression predictions, every mixture will attain more than 400 psi of flexural strength at 4 hours except for OPCIC. These results indicate that it is possible to create a nonproprietary mixture that has an acceptable high early compressive and flexural strength at 4 hours. Furthermore, if mixtures were allowed 5 or 6 hours to cure, it is very likely that all or nearly all Phase II mixtures would meet the flexural strength criteria.

Time to set

From all the Phase II Mixtures, the one providing the most time for workability is OPCIC, with 38 minutes. All Phase II Mixtures set in less than 40 minutes, and workability will always be a major concern. Workability time can be increased if more HRWR is added to the mixture or if a retarder is used, but this would also delay strength gain. CSA Mixtures can attain higher times (50 and 100 minutes) of initial setting by utilizing different admixtures (Péra & Ambroise, 2004; Ioannou, Reig, Paine, & Quillin, 2014).

Shrinkage and Creep

The CSA mixtures obtained low creep values due to their high strength. Maximum creep values were obtained by the OPC mixtures (OPCIC and OPCSF30IC). OPCSF30ICF provided the highest compressive strength with the lowest Shrinkage/Creep Coefficient ratio (see Figure 4.24). According to these results, IC and/or SF help to reduce shrinkage in both OPC and CSA mixtures.

Shrinkage Ring Testing

Although no noticeable difference was observed in the results, there may be some relationship between the amount of creep and the days for the rings to crack. This might be due to relaxed restraint stresses occurring because of low creep. Autogenous shrinkage is known to be a major issue with high early strength concretes, and the authors suspect that this is the case (American Concrete Institute, 1987; Zia, Ahmad, & Leming, 1993), but it cannot be measured with the tests performed herein. The recommendations for IC provided by the ESCSI (ESCSI, 2012) might not provide enough PSLWA replacement for high early strength mixtures; therefore, mixtures with more PSLWA would attain higher creep strains and lower shrinkage values than the ones herein.

Freeze Thaw Durability

Results presented in Table 4.5 are consistent with the air content in each mixture. Similar value ranges were obtained by Ozyildirim (2009) for both air content and remaining mass percentage of normal and light weight concretes. There is not a significant observable difference between the remaining mass percentages of Phase II Mixtures. This is probably due to the mixtures having similar air contents.

Final Recommendations

After reviewing and comparing the results obtained, CSAICF will meet the strength requirements in the required time (approximately 4,500 psi at 4 hours), have a high resistance to Freeze Thaw and high creep values. Some problems with this mixture are its low workability time(initial setting time is around 13 minutes which can be extended using High Range Water Reducers or other admixtures), and high drying shrinkage.

Another candidate is the OPCSF30ICF, which almost meets the strength criteria (3,300 psi in 4 hours), has a high resistance to Freeze Thaw, has low shrinkage and high creep values, and has decent workability (initial setting time is 27 minutes).

IC Mixtures showed losses in compressive strength between 30% and 40% in the CSA Mixtures, and approximately 50% in the OPC Mixtures, when compared to CSA1 and OPC1 at 4 hours, respectively. SF proved to be efficient at controlling these losses in strength. OPCSF30IC had no loss of strength at 4 hours compared to OPC1. Furthermore, OPCSF30ICF showed an increase in compressive strength (by approximately 60%) at 4 hours, when compared to OPC1. A reduction in drying shrinkage can be observed when the mixtures have IC PSLWA, nevertheless also an increase in creep is exhibited by these mixtures.

It's safe to assume that IC may compromise strength to some degree, provides better curing conditions for the rapid repair media, helps mitigate drying shrinkage of concrete, and bestows more workability time (almost 70% more time).

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Appendix

Statistical Analysis Software (SAS) Results

26 Variables:	cmty3 ctscm sfquant water nwcoarse nwfine lwcoarse lwfine w2cmratio acc hrwr slump air unitw compr4 compr6 compr24 compr7d emod split iset fset drysh ring creepc freeze

Simple Statistics						
Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
cmty3	8	446.25000	382.16255	3570	0	850.00000
ctscm	8	256.25000	355.00252	2050	0	750.00000
sfquant	8	85.00000	120.20815	680.00000	0	255.00000
water	8	234.75000	28.49436	1878	195.00000	255.00000
nwcoarse	8	875.00000	724.56884	7000	0	1400
nwfine	8	450.00000	621.05900	3600	0	1200
lwcoarse	8	356.25000	491.67171	2850	0	950.00000
lwfine	8	499.40000	429.19570	3995	0	910.00000
w2cmratio	8	0.29800	0.00566	2.38400	0.28400	0.30000
acc	8	93.75000	77.63238	750.00000	0	150.00000
hrwr	8	14.37500	6.23212	115.00000	10.00000	25.00000
slump	5	3.96000	0.36469	19.80000	3.50000	4.50000
air	5	5.08000	0.46043	25.40000	4.60000	5.60000
unitw	8	130.75000	13.02470	1046	112.00000	145.00000
compr4	8	3.56963	2.31856	28.55700	0.95000	7.99400
compr6	8	4.72938	2.41817	37.83500	1.85000	8.85000
compr24	8	6.83900	2.75839	54.71200	4.12000	10.74600
compr7d	8	8.89063	2.22991	71.12500	6.79900	12.56000
emod	8	3060000	963253	24480000	1700000	4580000
split	8	232.62500	84.43922	1861	115.00000	352.00000
iset	8	15.43750	5.68631	123.50000	8.40000	22.00000
fset	8	27.27500	6.77490	218.20000	18.70000	36.00000
drysh	8	-0.07125	0.02100	-0.57000	-0.10000	-0.04000
ring	8	5.87500	1.55265	47.00000	4.00000	9.00000
creepc	8	2.90685	0.76535	23.25477	2.18257	4.00130
freeze	4	94.75000	0.95743	379.00000	94.00000	96.00000

Pearson Correlation Coefficients
Prob > \|r\| under H0: Rho=0
Number of Observations

	cmty3	ctscm	sfquant	water	nwcoarse	nwfine	lwcoarse	lwfine	w2cmratio
cmty3	1.00000 8	-0.96328 0.0001 8	0.35948 0.3818 8	0.94839 0.0003 8	-0.07674 0.8567 8	0.13813 0.7443 8	0.07674 0.8567 8	-0.07970 0.8512 8	0.47182 0.2379 8
ctscm	-0.96328 0.0001 8	1.00000 8	-0.58332 0.1290 8	-0.96015 0.0002 8	0.09233 0.8279 8	-0.01458 0.9727 8	-0.09233 0.8279 8	-0.01976 0.9630 8	-0.56198 0.1471 8
sfquant	0.35948 0.3818 8	-0.58332 0.1290 8	1.00000 8	0.57431 0.1365 8	0.00000 1.0000 8	-0.19518 0.6432 8	0.00000 1.0000 8	0.14889 0.7249 8	0.28571 0.4927 8
water	0.94839 0.0003 8	-0.96015 0.0002 8	0.57431 0.1365 8	1.00000 8	-0.00727 0.9864 8	0.18163 0.6669 8	0.00727 0.9864 8	-0.13612 0.7479 8	0.30842 0.4573 8
nwcoarse	-0.07674 0.8567 8	0.09233 0.8279 8	0.00000 1.0000 8	-0.00727 0.9864 8	1.00000 8	0.60000 0.1158 8	-1.00000 <.0001 8	-0.79220 0.0191 8	-0.29277 0.4816 8
nwfine	0.13813 0.7443 8	-0.01458 0.9727 8	-0.19518 0.6432 8	0.18163 0.6669 8	0.60000 0.1158 8	1.00000 8	-0.60000 0.1158 8	-0.96353 0.0001 8	-0.48795 0.2199 8
lwcoarse	0.07674 0.8567 8	-0.09233 0.8279 8	0.00000 1.0000 8	0.00727 0.9864 8	-1.00000 <.0001 8	-0.60000 0.1158 8	1.00000 8	0.79220 0.0191 8	0.29277 0.4816 8
lwfine	-0.07970 0.8512 8	-0.01976 0.9630 8	0.14889 0.7249 8	-0.13612 0.7479 8	-0.79220 0.0191 8	-0.96353 0.0001 8	0.79220 0.0191 8	1.00000 8	0.47015 0.2398 8
w2cmratio	0.47182 0.2379 8	-0.56198 0.1471 8	0.28571 0.4927 8	0.30842 0.4573 8	-0.29277 0.4816 8	-0.48795 0.2199 8	0.29277 0.4816 8	0.47015 0.2398 8	1.00000 8
acc	0.96694 <.0001 8	-0.99621 <.0001 8	0.58554 0.1272 8	0.98081 <.0001 8	-0.06667 0.8754 8	0.06667 0.8754 8	0.06667 0.8754 8	-0.02855 0.9465 8	0.48795 0.2199 8
hrwr	-0.93684 0.0006 8	0.95443 0.0002 8	-0.56731 0.1425 8	-0.97441 <.0001 8	-0.08305 0.8450 8	-0.13841 0.7438 8	0.08305 0.8450 8	0.13336 0.7529 8	-0.36470 0.3744 8
slump	-0.55146 0.3353 5	. . 5	0.55146 0.3353 5	. . 5	-0.72591 0.1650 5	-0.52566 0.3630 5	0.72591 0.1650 5	0.63312 0.2516 5	. . 5
air	0.51555 0.3739 5	. . 5	-0.51555 0.3739 5	. . 5	-0.83270 0.0800 5	-0.35687 0.5555 5	0.83270 0.0800 5	0.54164 0.3458 5	. . 5
unitw	0.04025 0.9246 8	-0.01970 0.9631 8	0.04653 0.9129 8	0.10913 0.7970 8	0.93777 0.0006 8	0.69405 0.0562 8	-0.93777 0.0006 8	-0.84313 0.0086 8	-0.25594 0.5407 8
compr4	-0.88855 0.0032 8	0.89866 0.0024 8	-0.34916 0.3966 8	-0.77297 0.0245 8	0.27487 0.5100 8	0.20014 0.6346 8	-0.27487 0.5100 8	-0.24462 0.5593 8	-0.77105 0.0251 8
compr6	-0.92481 0.0010 8	0.94060 0.0005 8	-0.42759 0.2906 8	-0.84909 0.0076 8	0.24748 0.5546 8	0.13787 0.7447 8	-0.24748 0.5546 8	-0.18796 0.6558 8	-0.68853 0.0590 8
compr24	-0.93028 0.0008 8	0.96297 0.0001 8	-0.54126 0.1659 8	-0.91407 0.0015 8	0.06274 0.8827 8	0.03402 0.9363 8	-0.06274 0.8827 8	-0.04694 0.9121 8	-0.57231 0.1382 8
compr7d	-0.89487 0.0027 8	0.96158 0.0001 8	-0.61287 0.1062 8	-0.88120 0.0038 8	0.12525 0.7676 8	0.10053 0.8128 8	-0.12525 0.7676 8	-0.11858 0.7797 8	-0.66489 0.0720 8

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations									
	cmty3	ctscm	sfquant	water	nwcoarse	nwfine	lwcoarse	lwfine	w2cmratio
emod	-0.91834 0.0013 8	0.89715 0.0025 8	-0.29992 0.4705 8	- 0.81632 0.0134 8	0.26650 0.5235 8	0.12322 0.7713 8	-0.26650 0.5235 8	-0.18314 0.6642 8	-0.63760 0.0890 8
split	-0.93895 0.0005 8	0.93703 0.0006 8	-0.41392 0.3080 8	- 0.88460 0.0035 8	0.30360 0.4648 8	0.17366 0.6809 8	-0.30360 0.4648 8	-0.23403 0.5770 8	-0.57124 0.1391 8
iset	0.93945 0.0005 8	-0.93817 0.0006 8	0.44412 0.2703 8	0.90996 0.0017 8	-0.25181 0.5474 8	-0.14138 0.7384 8	0.25181 0.5474 8	0.19208 0.6486 8	0.50007 0.2070 8
fset	0.98419 <.0001 8	-0.92920 0.0008 8	0.30417 0.4639 8	0.93208 0.0007 8	-0.19455 0.6443 8	0.09269 0.8272 8	0.19455 0.6443 8	-0.00563 0.9894 8	0.40407 0.3208 8
drysh	0.65434 0.0783 8	-0.57363 0.1371 8	0.14430 0.7332 8	0.66782 0.0703 8	-0.44358 0.2710 8	-0.08214 0.8467 8	0.44358 0.2710 8	0.21104 0.6159 8	-0.02405 0.9549 8
ring	0.72137 0.0434 8	-0.63337 0.0918 8	0.06506 0.8784 8	0.65145 0.0801 8	-0.60000 0.1158 8	-0.11111 0.7934 8	0.60000 0.1158 8	0.28546 0.4931 8	0.22771 0.5876 8
creepc	0.60164 0.1146 8	-0.63359 0.0917 8	0.38706 0.3435 8	0.59945 0.1163 8	0.49848 0.2086 8	0.31708 0.4441 8	-0.49848 0.2086 8	-0.40862 0.3148 8	0.38237 0.3499 8
freeze	-0.80440 0.1956 4	0.87039 0.1296 4	-0.52223 0.4778 4	- 0.87039 0.1296 4	0.52223 0.4778 4	0.52223 0.4778 4	-0.52223 0.4778 4	-0.52223 0.4778 4	-0.87039 0.1296 4

Pearson Correlation Coefficients
Prob > $|r|$ under H0: Rho=0
Number of Observations

	acc	hrw r	slump	air	unitw	compr4	compr6	compr24	compr7d
cmty3	0.96694 <.0001 8	-0.93684 0.0006 8	-0.55146 0.3353 5	0.51555 0.3739 5	0.04025 0.9246 8	-0.88855 0.0032 8	-0.92481 0.0010 8	-0.93028 0.0008 8	-0.89487 0.0027 8
ctscm	-0.99621 <.0001 8	0.95443 0.0002 8	. . 5	. . 5	-0.01970 0.9631 8	0.89866 0.0024 8	0.94060 0.0005 8	0.96297 0.0001 8	0.96158 0.0001 8
sfquant	0.58554 0.1272 8	-0.56731 0.1425 8	0.55146 0.3353 5	-0.51555 0.3739 5	0.04653 0.9129 8	-0.34916 0.3966 8	-0.42759 0.2906 8	-0.54126 0.1659 8	-0.61287 0.1062 8
w ater	0.98081 <.0001 8	-0.97441 <.0001 8	. . 5	. . 5	0.10913 0.7970 8	-0.77297 0.0245 8	-0.84909 0.0076 8	-0.91407 0.0015 8	-0.88120 0.0038 8
nw coarse	-0.06667 0.8754 8	-0.08305 0.8450 8	-0.72591 0.1650 5	-0.83270 0.0800 5	0.93777 0.0006 8	0.27487 0.5100 8	0.24748 0.5546 8	0.06274 0.8827 8	0.12525 0.7676 8
nw fine	0.06667 0.8754 8	-0.13841 0.7438 8	-0.52566 0.3630 5	-0.35687 0.5555 5	0.69405 0.0562 8	0.20014 0.6346 8	0.13787 0.7447 8	0.03402 0.9363 8	0.10053 0.8128 8
lw coarse	0.06667 0.8754 8	0.08305 0.8450 8	0.72591 0.1650 5	0.83270 0.0800 5	-0.93777 0.0006 8	-0.27487 0.5100 8	-0.24748 0.5546 8	-0.06274 0.8827 8	-0.12525 0.7676 8
lw fine	-0.02855 0.9465 8	0.13336 0.7529 8	0.63312 0.2516 5	0.54164 0.3458 5	-0.84313 0.0086 8	-0.24462 0.5593 8	-0.18796 0.6558 8	-0.04694 0.9121 8	-0.11858 0.7797 8
w 2cmratio	0.48795 0.2199 8	-0.36470 0.3744 8	. . 5	. . 5	-0.25594 0.5407 8	-0.77105 0.0251 8	-0.68853 0.0590 8	-0.57231 0.1382 8	-0.66489 0.0720 8
acc	1.00000 8	-0.96886 <.0001 8	. . 5	. . 5	0.04768 0.9107 8	-0.86730 0.0053 8	-0.92024 0.0012 8	-0.95605 0.0002 8	-0.94486 0.0004 8
hrw r	-0.96886 <.0001 8	1.00000 8	. . 5	. . 5	-0.13420 0.7514 8	0.81568 0.0136 8	0.87752 0.0042 8	0.95231 0.0003 8	0.91621 0.0014 8
slump	. . 5	. . 5	1.00000 5	0.29181 0.6338 5	-0.72129 0.1690 5	-0.18756 0.7626 5	-0.36186 0.5495 5	-0.39593 0.5094 5	-0.80816 0.0979 5
air	. . 5	. . 5	0.29181 0.6338 5	1.00000 5	-0.84633 0.0706 5	-0.89454 0.0405 5	-0.69190 0.1955 5	-0.12443 0.8420 5	0.01548 0.9803 5
unitw	0.04768 0.9107 8	-0.13420 0.7514 8	-0.72129 0.1690 5	-0.84633 0.0706 5	1.00000 8	0.23167 0.5809 8	0.17822 0.6729 8	0.00048 0.9991 8	0.06012 0.8875 8
compr4	-0.86730 0.0053 8	0.81568 0.0136 8	-0.18756 0.7626 5	-0.89454 0.0405 5	0.23167 0.5809 8	1.00000 8	0.98347 <.0001 8	0.92185 0.0011 8	0.93618 0.0006 8
compr6	-0.92024 0.0012 8	0.87752 0.0042 8	-0.36186 0.5495 5	-0.69190 0.1955 5	0.17822 0.6729 8	0.98347 <.0001 8	1.00000 8	0.96900 <.0001 8	0.97016 <.0001 8
compr24	-0.95605 0.0002 8	0.95231 0.0003 8	-0.39593 0.5094 5	-0.12443 0.8420 5	0.00048 0.9991 8	0.92185 0.0011 8	0.96900 <.0001 8	1.00000 8	0.98392 <.0001 8
compr7d	-0.94486 0.0004 8	0.91621 0.0014 8	-0.80816 0.0979 5	0.01548 0.9803 5	0.06012 0.8875 8	0.93618 0.0006 8	0.97016 <.0001 8	0.98392 <.0001 8	1.00000 8
emod	-0.87973 0.0040 8	0.85551 0.0067 8	-0.19413 0.7544 5	-0.82170 0.0879 5	0.22648 0.5896 8	0.97876 <.0001 8	0.98559 <.0001 8	0.94103 0.0005 8	0.92497 0.0010 8
split	-0.92879 0.0009 8	0.89670 0.0025 8	-0.30467 0.6182 5	-0.88157 0.0480 5	0.24371 0.5608 8	0.94672 0.0004 8	0.97079 <.0001 8	0.94534 0.0004 8	0.92612 0.0010 8
iset	0.93747 0.0006 8	-0.89820 0.0024 8	-0.01059 0.9865 5	0.77194 0.1262 5	-0.17731 0.6744 8	-0.87988 0.0040 8	-0.90074 0.0023 8	-0.88868 0.0032 8	-0.86759 0.0052 8

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations	acc	hrw r	slump	air	unitw	compr4	compr6	compr24	compr7d
fset	0.93810 0.0006 8	-0.90889 0.0018 8	-0.19944 0.7478 5	0.83774 0.0765 5	-0.08880 0.8344 8	-0.86966 0.0050 8	-0.90591 0.0019 8	-0.89434 0.0027 8	-0.85106 0.0074 8
drysh	0.60787 0.1099 8	-0.60713 0.1104 8	0.23521 0.7033 5	0.92586 0.0240 5	-0.41388 0.3080 8	-0.50234 0.2046 8	-0.54016 0.1670 8	-0.51362 0.1929 8	-0.44894 0.2645 8
ring	0.64444 0.0845 8	-0.59977 0.1160 8	0.37065 0.5391 5	0.84493 0.0716 5	-0.51039 0.1962 8	-0.69015 0.0582 8	-0.73585 0.0374 8	-0.65768 0.0763 8	-0.60759 0.1101 8
creepc	0.62842 0.0952 8	-0.58577 0.1271 8	-0.75946 0.1364 5	-0.84288 0.0730 5	0.68160 0.0627 8	-0.42417 0.2949 8	-0.46476 0.2459 8	-0.56088 0.1481 8	-0.54552 0.1620 8
freeze	-0.87039 0.1296 4	0.87039 0.1296 4	-1.00000 <.0001 3	0.11471 0.9268 3	0.35286 0.6471 4	0.87190 0.1281 4	0.92978 0.0702 4	0.96067 0.0393 4	0.94863 0.0514 4

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations								
	emod	split	iset	fset	drysh	ring	creepc	freeze
cmty3	-0.91834 0.0013 8	-0.93895 0.0005 8	0.93945 0.0005 8	0.98419 <.0001 8	0.65434 0.0783 8	0.72137 0.0434 8	0.60164 0.1146 8	-0.80440 0.1956 4
ctscm	0.89715 0.0025 8	0.93703 0.0006 8	-0.93817 0.0006 8	-0.92920 0.0008 8	-0.57363 0.1371 8	-0.63337 0.0918 8	-0.63359 0.0917 8	0.87039 0.1296 4
sfquant	-0.29992 0.4705 8	-0.41392 0.3080 8	0.44412 0.2703 8	0.30417 0.4639 8	0.14430 0.7332 8	0.06506 0.8784 8	0.38706 0.3435 8	-0.52223 0.4778 4
w ater	-0.81632 0.0134 8	-0.88460 0.0035 8	0.90996 0.0017 8	0.93208 0.0007 8	0.66782 0.0703 8	0.65145 0.0801 8	0.59945 0.1163 8	-0.87039 0.1296 4
nw coarse	0.26650 0.5235 8	0.30360 0.4648 8	-0.25181 0.5474 8	-0.19455 0.6443 8	-0.44358 0.2710 8	-0.60000 0.1158 8	0.49848 0.2086 8	0.52223 0.4778 4
nw fine	0.12322 0.7713 8	0.17366 0.6809 8	-0.14138 0.7384 8	0.09269 0.8272 8	-0.08214 0.8467 8	-0.11111 0.7934 8	0.31708 0.4441 8	0.52223 0.4778 4
lw coarse	-0.26650 0.5235 8	-0.30360 0.4648 8	0.25181 0.5474 8	0.19455 0.6443 8	0.44358 0.2710 8	0.60000 0.1158 8	-0.49848 0.2086 8	-0.52223 0.4778 4
lw fine	-0.18314 0.6642 8	-0.23403 0.5770 8	0.19208 0.6486 8	-0.00563 0.9894 8	0.21104 0.6159 8	0.28546 0.4931 8	-0.40862 0.3148 8	-0.52223 0.4778 4
w 2cmratio	-0.63760 0.0890 8	-0.57124 0.1391 8	0.50007 0.2070 8	0.40407 0.3208 8	-0.02405 0.9549 8	0.22771 0.5876 8	0.38237 0.3499 8	-0.87039 0.1296 4
acc	-0.87973 0.0040 8	-0.92879 0.0009 8	0.93747 0.0006 8	0.93810 0.0006 8	0.60787 0.1099 8	0.64444 0.0845 8	0.62842 0.0952 8	-0.87039 0.1296 4
hrw r	0.85551 0.0067 8	0.89670 0.0025 8	-0.89820 0.0024 8	-0.90889 0.0018 8	-0.60713 0.1104 8	-0.59977 0.1160 8	-0.58577 0.1271 8	0.87039 0.1296 4
slump	-0.19413 0.7544 5	-0.30467 0.6182 5	-0.01059 0.9865 5	-0.19944 0.7478 5	0.23521 0.7033 5	0.37065 0.5391 5	-0.75946 0.1364 5	-1.00000 <.0001 3
air	-0.82170 0.0879 5	-0.88157 0.0480 5	0.77194 0.1262 5	0.83774 0.0765 5	0.92586 0.0240 5	0.84493 0.0716 5	-0.84288 0.0730 5	0.11471 0.9268 3
unitw	0.22648 0.5896 8	0.24371 0.5608 8	-0.17731 0.6744 8	-0.08880 0.8344 8	-0.41388 0.3080 8	-0.51039 0.1962 8	0.68160 0.0627 8	0.35286 0.6471 4
compr4	0.97876 <.0001 8	0.94672 0.0004 8	-0.87988 0.0040 8	-0.86966 0.0050 8	-0.50234 0.2046 8	-0.69015 0.0582 8	-0.42417 0.2949 8	0.87190 0.1281 4
compr6	0.98559 <.0001 8	0.97079 <.0001 8	-0.90074 0.0023 8	-0.90591 0.0019 8	-0.54016 0.1670 8	-0.73585 0.0374 8	-0.46476 0.2459 8	0.92978 0.0702 4
compr24	0.94103 0.0005 8	0.94534 0.0004 8	-0.88868 0.0032 8	-0.89434 0.0027 8	-0.51362 0.1929 8	-0.65768 0.0763 8	-0.56088 0.1481 8	0.96067 0.0393 4
compr7d	0.92497 0.0010 8	0.92612 0.0010 8	-0.86759 0.0052 8	-0.85106 0.0074 8	-0.44894 0.2645 8	-0.60759 0.1101 8	-0.54552 0.1620 8	0.94863 0.0514 4
emod	1.00000 8	0.97229 <.0001 8	-0.89530 0.0026 8	-0.91831 0.0013 8	-0.60095 0.1151 8	-0.78994 0.0197 8	-0.37360 0.3619 8	0.89060 0.1094 4
split	0.97229 <.0001 8	1.00000 8	-0.96678 <.0001 8	-0.95200 0.0003 8	-0.71565 0.0459 8	-0.81110 0.0146 8	-0.39461 0.3333 8	0.85548 0.1445 4
iset	-0.89530 0.0026 8	-0.96678 <.0001 8	1.00000 8	0.95564 0.0002 8	0.77920 0.0227 8	0.74169 0.0352 8	0.45696 0.2550 8	-0.70346 0.2965 4

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations								
	emod	split	iset	fset	drysh	ring	creepc	freeze
fset	-0.91831 0.0013 8	-0.95200 0.0003 8	0.95564 0.0002 8	1.00000 8	0.77084 0.0252 8	0.81451 0.0138 8	0.46915 0.2409 8	-0.76177 0.2382 4
drysh	-0.60095 0.1151 8	-0.71565 0.0459 8	0.77920 0.0227 8	0.77084 0.0252 8	1.00000 8	0.82692 0.0113 8	-0.04837 0.9095 8	-0.08362 0.9164 4
ring	-0.78994 0.0197 8	-0.81110 0.0146 8	0.74169 0.0352 8	0.81451 0.0138 8	0.82692 0.0113 8	1.00000 8	-0.02829 0.9470 8	-0.70353 0.2965 4
creepc	-0.37360 0.3619 8	-0.39461 0.3333 8	0.45696 0.2550 8	0.46915 0.2409 8	-0.04837 0.9095 8	-0.02829 0.9470 8	1.00000 8	-0.53089 0.4691 4
freeze	0.89060 0.1094 4	0.85548 0.1445 4	-0.70346 0.2965 4	-0.76177 0.2382 4	-0.08362 0.9164 4	-0.70353 0.2965 4	-0.53089 0.4691 4	1.00000 4