Report No. UT-19.08

RAPID CONCRETE REPAIR

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Submitted By:

Utah State University
Department of Civil & Environmental Engineering

Authored By:

Ivan Quezada
Robert J. Thomas, Ph.D.
Marc Maguire, Ph.D.

Final Report
May 2019

RESEARCH
UDOT Keeping Utah Moving
Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

DISCLAIMER

ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals from UDOT on the Technical Advisory Committee for helping to guide the research:

- Tom Hales, UDOT Research
- Jason Richins, UDOT Research
- David Eixenberger, Eixenberger Group
- Scott Andrus, UDOT Materials
- Lonnie Marchant, UDOT Region 2 – Materials
- Jason Simmons, UDOT Region 2 – Materials
- PJ Roubinet, UDOT Region 1
- Tim Ularich, UDOT Maintenance
- Mark Sweat, Alta View Concrete
- Bryan Lee, UDOT Materials
- David Stevens, UDOT Research

TECHNICAL REPORT ABSTRACT

1. Report No. UT- 19.08	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A

4. Title and Subtitle RAPID CONCRETE REPAIR	5. Report Date May 2019 6. Performing Organization Code
7. Author(s) Ivan Quezada, Robert J. Thomas, Marc Maguire	8. Performing Organization Report No.
9. Performing Organization Name and Address Utah State University Department of Civil & Environmental Engineering 4110 Old Main Hill Logan, UT 84322-4110	10. Work Unit No. 5H08005H 11. Contract or Grant No. 15-8507
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410	13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

Investigations to develop a full depth durable concrete mixture (15 year life) to be used for pavement with 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 a better curing by 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.

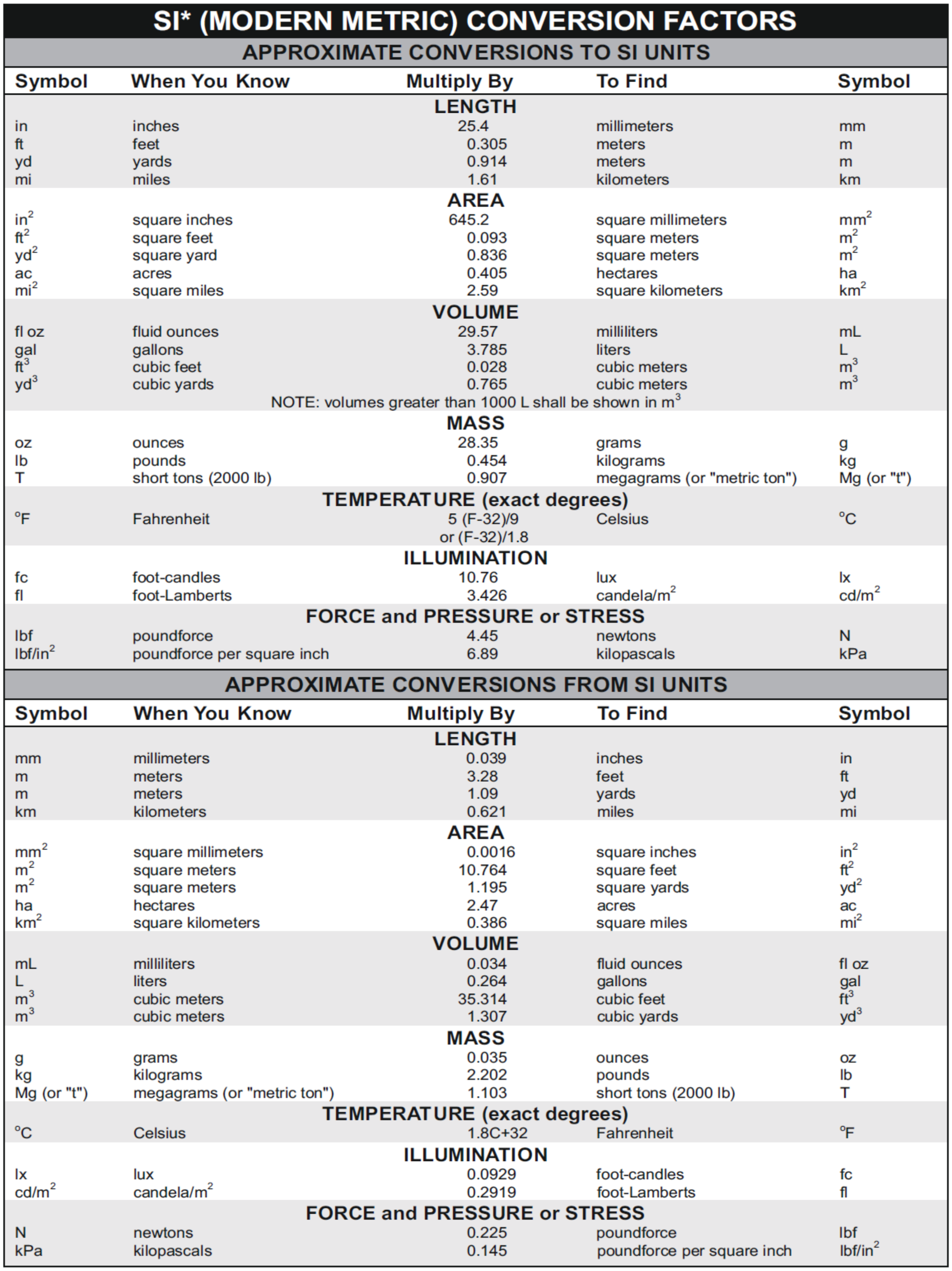
17. Key Words Concrete, pavement, repair, rapid, calcium sulfoaluminate, internal curing, shrinkage, drying, autogenous, creep		18. Distribution Statement Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal N/A
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 83	22. Price N/A	

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

UNIT CONVERSION FACTORS



SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

FHWA	Federal Highway Administration
UDOT	Utah Department of Transportation
CSA	Calcium sulfoaluminate

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).

1.0 INTRODUCTION

1.1 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).

Much of this material is also presented in a report to the Center for Advanced Infrastructure Technology, which provided matching funds for this UDOT sponsored study (Quezada, Thomas, & Maguire, 2018).

1.2 **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.

2.0 LITERATURE REVIEW

2.1 **General Overview**

Mixture design for repair media typically relies on practitioner experience. Practitioners 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.

2.1.1 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). **Error! Reference source not found.** shows an adaptation from Emmons et al. of the factors that affect the durability of concrete repairs:

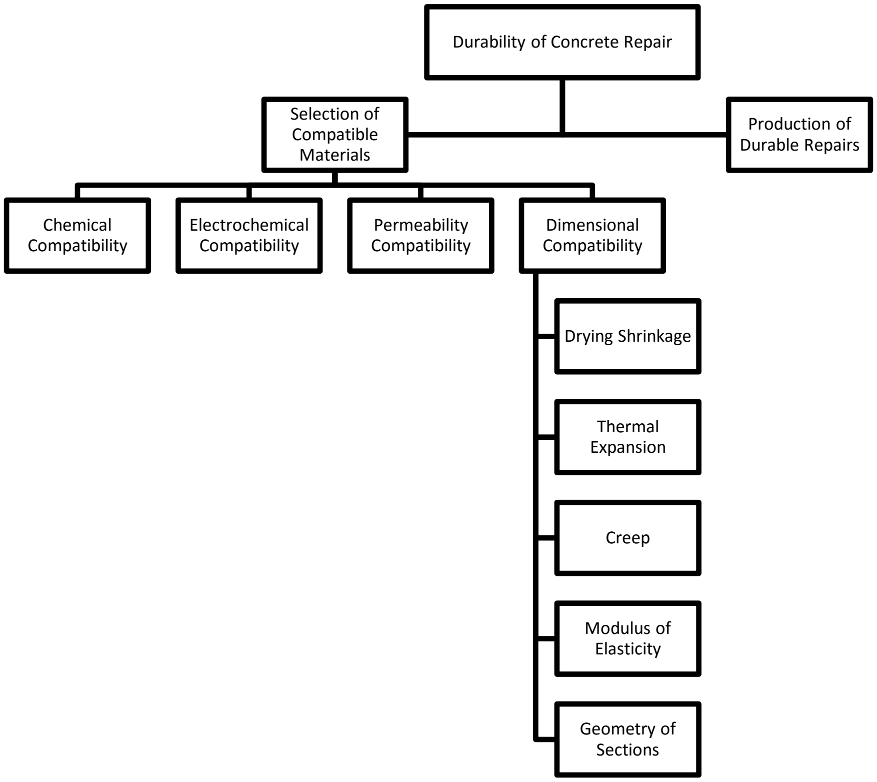


Figure 2.1 Factors affecting the durability of concrete repairs (Emmons, Vaysburd, & McDonald, 1993)

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 **Error! Reference source not found.**. 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.

2.1.2 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.

2.2 **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 2.1. 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 repair media for structural compatibility (Emberson & Mays, 1990)

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.

2.3 **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/cm* of 0.40, which is relatively low in comparison to conventional concrete. With a low *w/cm*, 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/cm* 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).

2.4 **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. Respondents from 15 states participated in the survey and provided feedback (**Error! Reference source not found.**). In addition, 5 states participated and responded that they did not usually use concrete pavement (**Error! Reference source not found.**). 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.

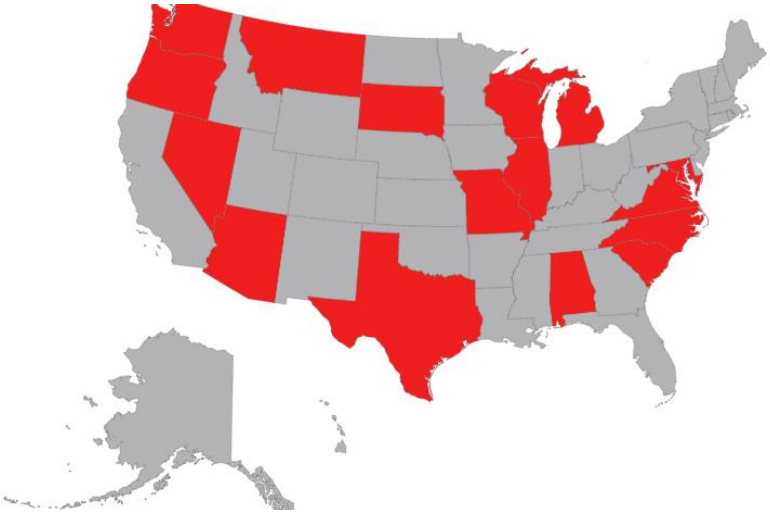


Figure 2.2 Survey respondents using concrete pavement

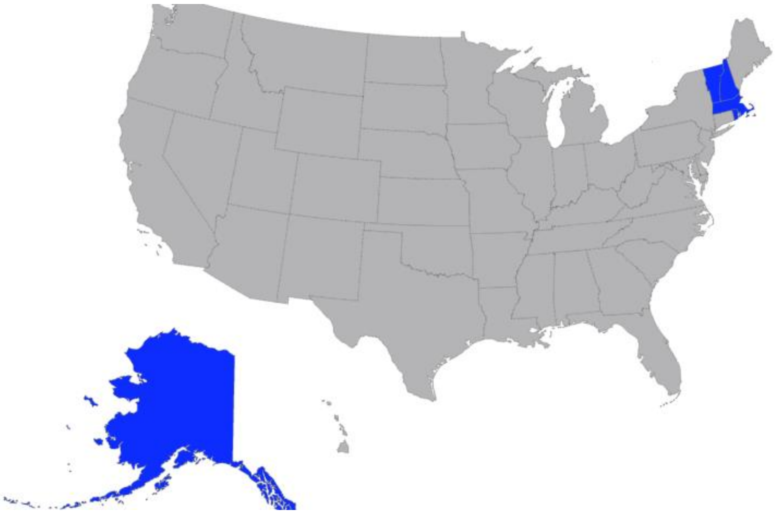


Figure 2.3 Survey respondents not using concrete pavement

2.5 **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 (**Error! Reference source not found.**). A summary of the survey results is included below.

Question 1 asked agencies to report the environmental zone in which they operate (dry no-freeze, dry freeze, wet no-freeze, or wet freeze). **Error! Reference source not found.** shows the responses, which included 6 in wet freeze zones, 4 in wet no-freeze zones, 4 in dry freeze zones, and only 2 in dry no-freeze zones.

Question 2 asked agencies to rank the quality of their full depth repair program from 1 (worst) to 5 (best). **Error! Reference source not found.** shows the responses, which were all between 3 (average) and 5 (best). In general, responding organizations think highly of their own repair programs.

Question 3 asked agencies to report the expected life cycle of full depth repairs. **Error! Reference source not found.** presents responses, which varied greatly from less than ten years to more than 25. The range of responses was unexpected; concrete pavement repairs are not likely to last 25 years even in the best of conditions.

Question 4 asked agencies to report the typical actual life cycle of full depth repairs. **Error! Reference source not found.** presents the results. The responses are more tightly grouped near the low end, suggesting that most of the responding organizations overestimate the useful life of full depth repairs. Only three organizations reported design lives under ten years, while double that number reported actual repair life cycles of less than ten years. Similarly, four organizations reported design life cycles over twenty years, but only two reported actual life cycles in that range.

Question 5 asked if agency employees, contractors, or both groups performed full depth repairs. **Error! Reference source not found.** presents responses, which indicate that most organizations use either contractors or a combination of contractors and agency employees to perform full depth repairs.

Question 6 asked agencies to provide a range of typical opening times. **Error! Reference source not found.** presents the low end of the reported range, and **Error! Reference source not found.** reports the high end. These figures show that most organizations open full depth repairs to traffic between 4 and 72 hours after placement. ‘N/I’ signifies that agencies did not respond or marked this as a parameter that was not of interest to the agency and records were not available.

Question 7 asked agencies to report criteria for opening full-depth repairs to traffic. Most agencies responded with either a minimum required compressive strength or a minimum open time. **Error! Reference source not found.** reports minimum strength criteria, where ‘Contractor’ signifies that the decision to open repairs is left to the contractor. Similarly, **Error! Reference source not found.** reports minimum open times. Responses varied greatly. Some organizations require less than 2,000 psi compressive strength to open repairs, while others require 4,000 psi or more. Several organizations allow opening after as little as 4 h, while others require a minimum open time of 72 h.

Question 8 asked agencies to report the material or practice that gave the best performance for full depth repairs. Table 2.2 lists the responses, which include ordinary Portland cement concrete, type III Portland cement concrete, Portland cement concrete with specialty admixtures, rapid set cement concretes, and more. These responses were classified as Portland cement concrete, Portland cement concrete with special aggregates or admixtures, jointed plain concrete pavement (JPCP), or high early strength concrete in **Error! Reference source not found.**.

Question 9 asked agencies to report the material or practice that gave the worst performance for full depth repairs. Table 2.3 lists the responses, which include Portland cement concrete with limestone aggregates, chloride accelerators, asphalt, rapid setting products, and high cement content concretes. These responses were classified as Portland cement concrete, Portland cement concrete with special aggregates or admixtures, continuously reinforced concrete pavement (CRCP), rapid setting products, or asphalt in **Error! Reference source not found.**.

Question 10 asked agencies to report the three most important criteria in selecting a repair material or practice. **Error! Reference source not found.** presents responses, which suggest that closure time is the most important consideration for most agencies. Other important considerations include strength, quality, and durability.

Finally, Question 11 asked agencies to report the estimated cost of completing a full depth 12 ft × 10 ft × 10 in repair using current practices. **Error! Reference source not found.** presents the responses. Responses were highly varied, with several estimates under $1,000 and equally many over $2,000.

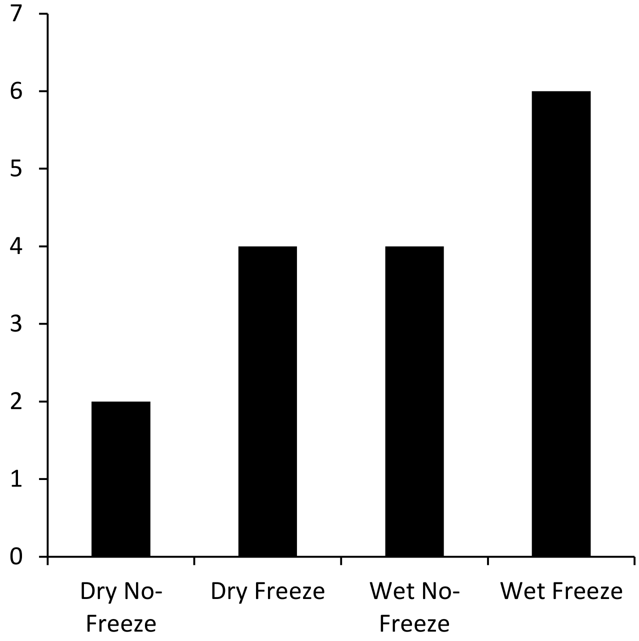


Figure 2.4 Survey Q1 responses: Environmental zone

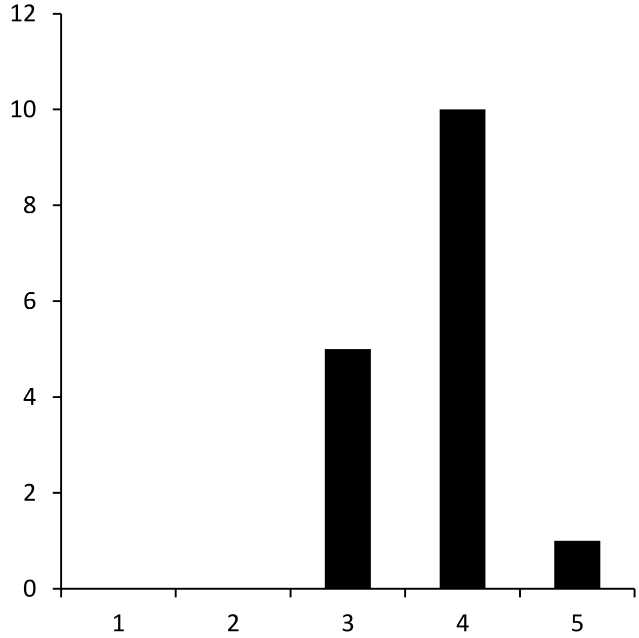


Figure 2.5 Survey Q2 responses: Repair rating

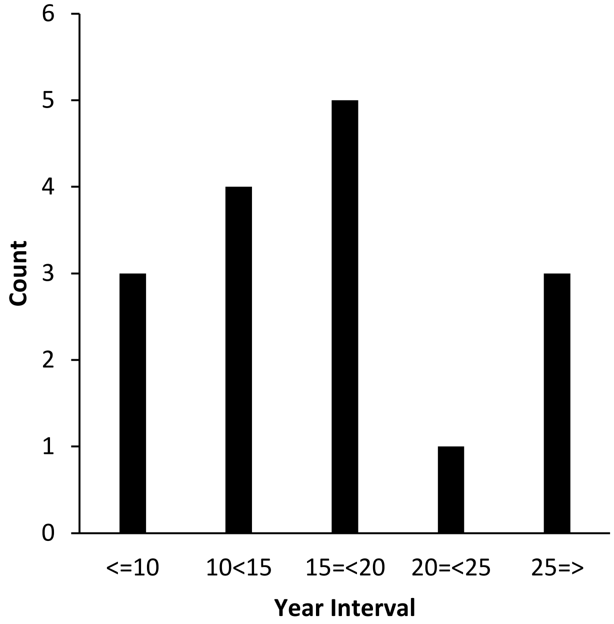


Figure 2.6 Survey Q3 responses: Design life of repairs

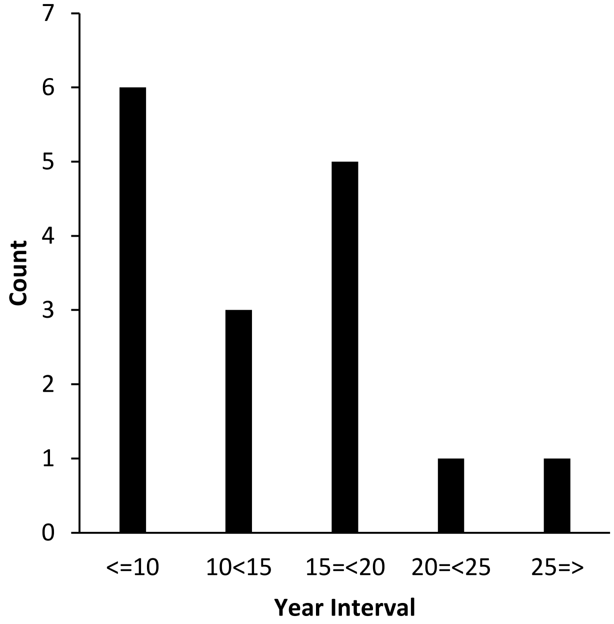


Figure 2.7 Survey Q4 responses: Actual life of repairs

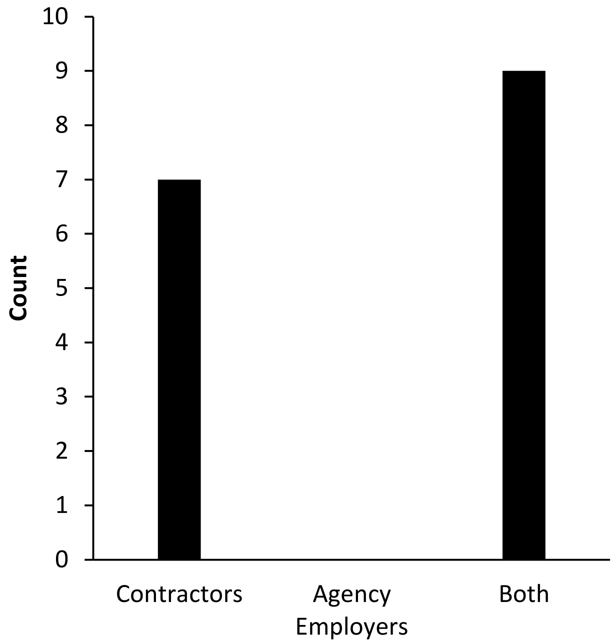


Figure 2.8 Survey Q5 responses: Who performs repairs?

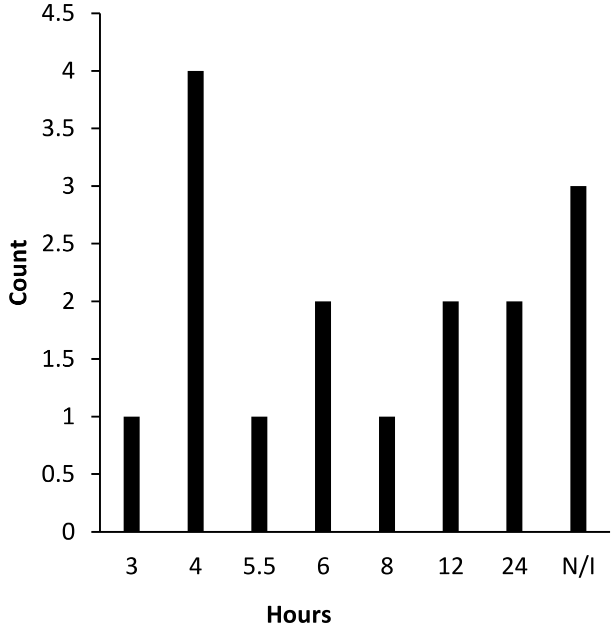


Figure 2.9 Survey Q6 responses: Typical open time (low end)

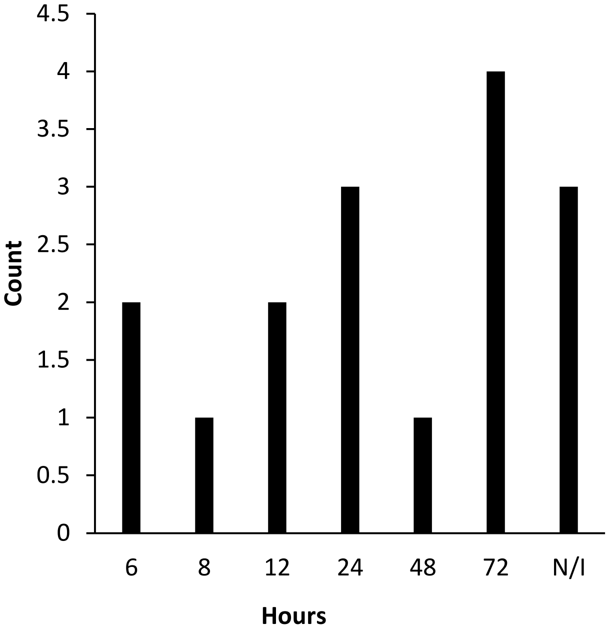


Figure 2.10 Survey Q6 responses: Typical open time (high end)

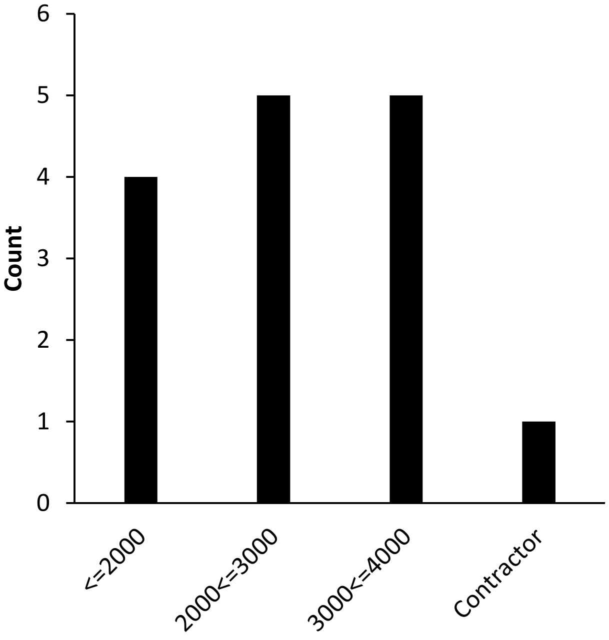


Figure 2.11 Survey Q7 responses: Minimum strength before opening (‘Contractor’ means decision to open is made by contractor)

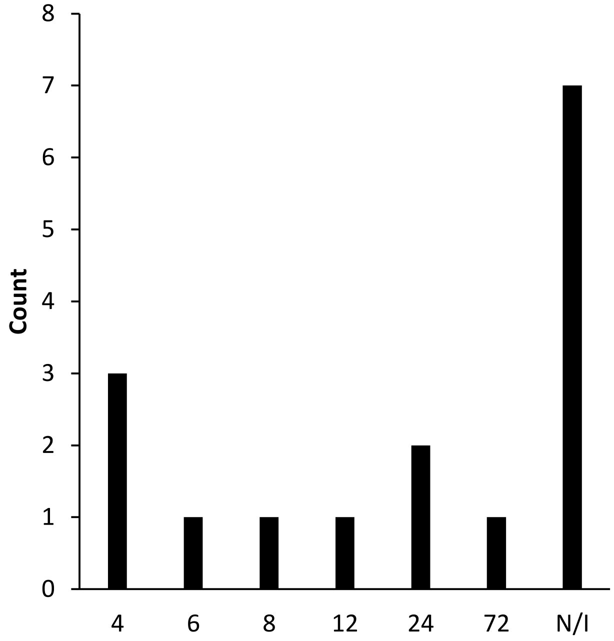


Figure 2.12 Survey Q7 responses: Minimum allowable time before opening (N/I means this is not a parameter of interest to the respondent)

Table 2.2 Survey Q8 responses: Best performing full depth repair material

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

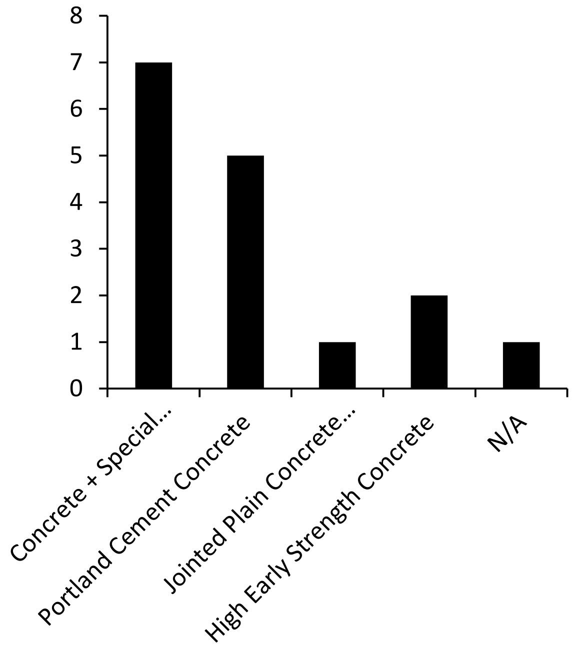


Figure 2.13 Survey Q8 responses: Best performing full depth repair material

Table 2.3 Survey Q9 responses: Worst performing full depth repair material

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

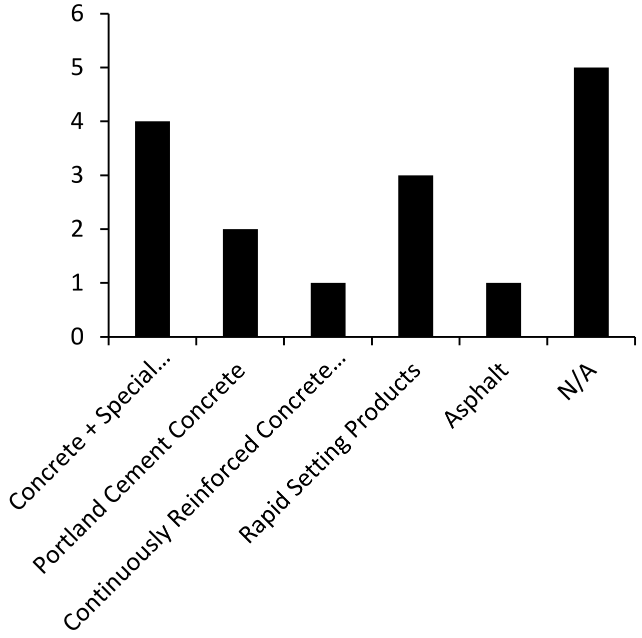


Figure 2.14 Survey Q9 responses: Worst performing full depth repair material

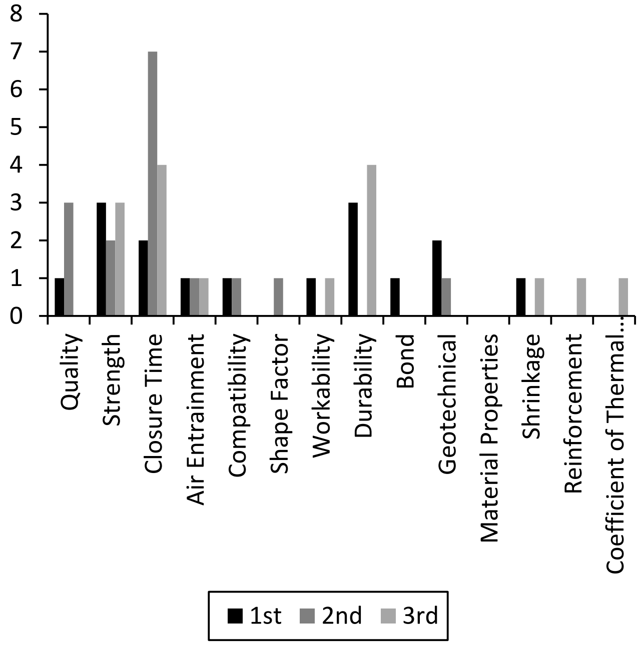


Figure 2.15 Survey Q10 responses: Top three priorities for full depth repairs

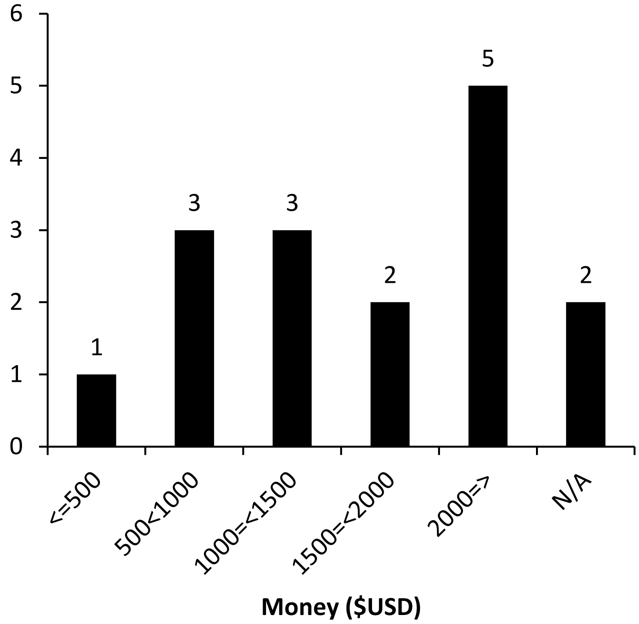


Figure 2.16 Survey Q11 responses: Estimated cost of 12 ft × 10 ft × 10 in repair

2.5.1 Results Analysis

The survey responses were analyzed using a commercial statistical analysis software package in order to evaluate correlation of responses between questions. Table 2.4 presents a Pearson correlation matrix for the following numerical survey response 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)

The Pearson correlation matrix reports Pearson's correlation coefficient and the p-value for each combination of variables. Pearson's correlation coefficient ρ ranges from $\rho = -1$ for a perfect negative linear correlation to $\rho = 1$ for a perfect positive linear correlation. A value of $\rho = 0$ indicates no linear correlation between variables. The p-value determines the significance of the relationship, where $p \leq 0.05$ indicate a significant relationship. Shaded cells in Table 2.4 denote significant correlations between variables.

Interestingly, there was little correlation between any of the survey response values. The only significant correlation was between estimated cost of repair and minimum required open time. This correlation was positive, suggesting that agencies that estimated higher repair costs also specify longer open times. At minimum, the researchers expected to find correlations between design repair life and actual repair life, repair program rating and actual repair life, and repair cost and actual repair life. However, none of these exhibited any reasonable correlation. This suggests that, while agencies report that their repair programs rate mostly 4-5 out of 5, there is much room for improvement in repair programs across the United States.

Table 2.4 Pearson correlation matrix for survey responses

(top number is Pearson's coefficient, bottom number is p-value)

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

3.0 EXPERIMENTAL METHODS

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

3.1 **Aggregate Properties**

3.1.1 Normal weight Aggregate

Normal weight 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 **Error! Reference source not found.** and **Error! Reference source not found.**, respectively. Select physical properties of the aggregates, also determined by CMT Engineering Laboratories, are given in Table 3.1 and Table 3.2.

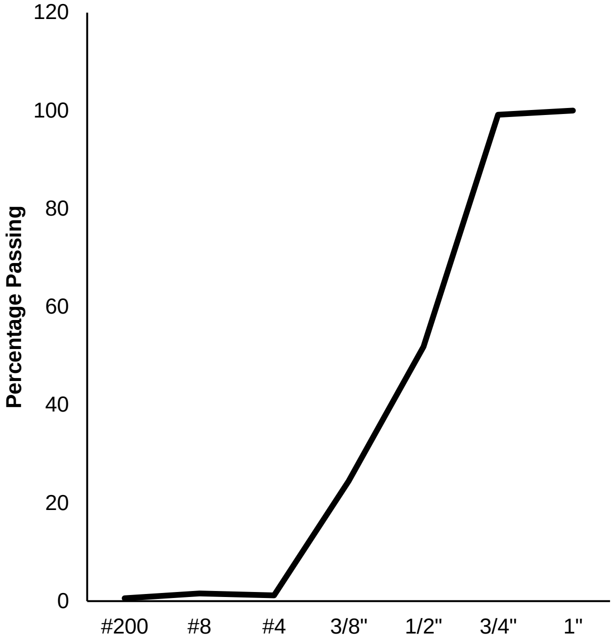


Figure 3.1 Gradation of normal weight coarse aggregate

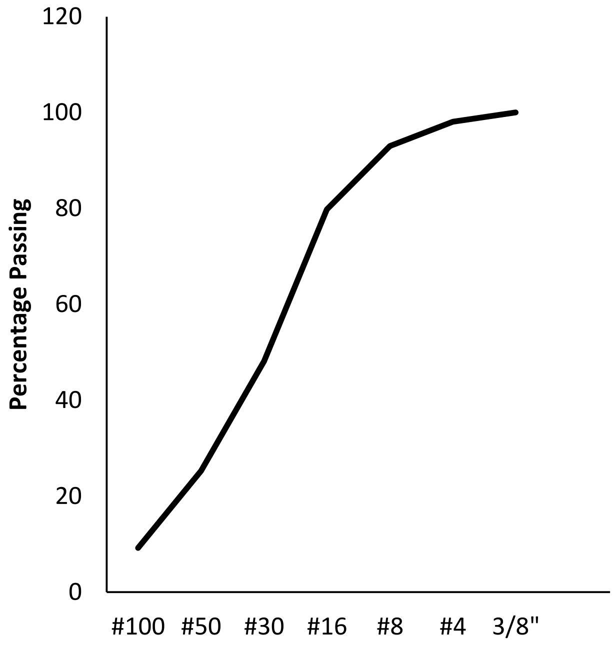


Figure 3.2 Gradation of normal weight fine aggregate

Table 3.1 Physical properties of normal weight 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 Physical properties of normal weight fine aggregate

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

3.1.2 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. **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**show the gradation curve for each LWA.

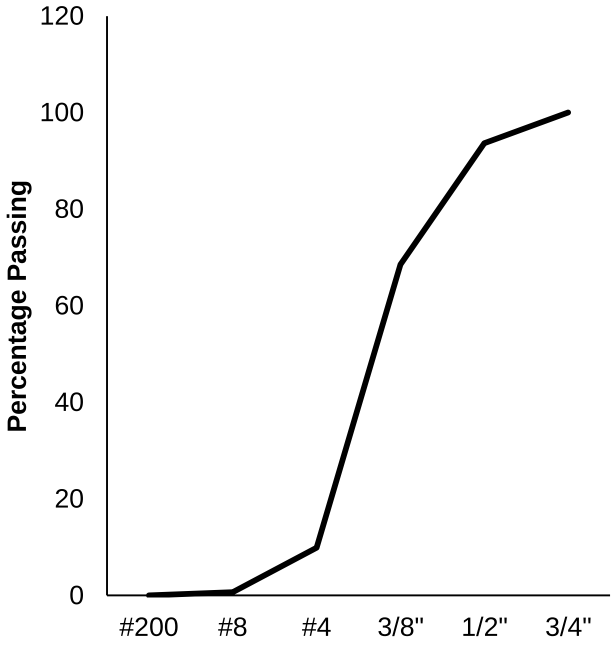


Figure 3.3 Gradation of lightweight coarse aggregate

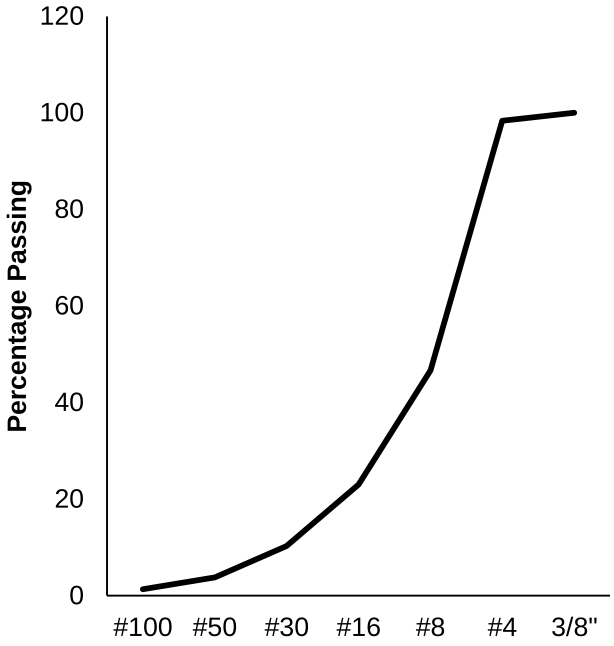


Figure 3.4 Gradation of lightweight fine aggregate

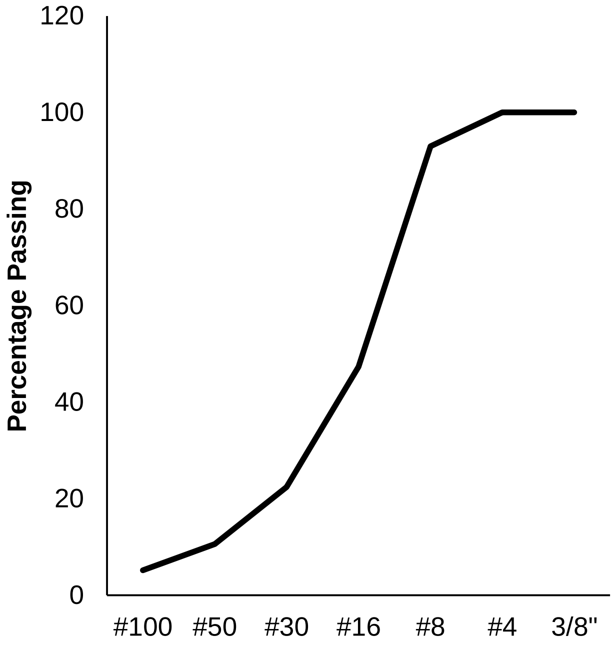


Figure 3.5 Gradation of lightweight crushed fines

3.2 **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.

3.3 **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 (Thomas, Maguire, Sorensen, & Quezada, 2018). 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 Description of proprietary repair media

Product	P1	P2	P3
Base	Cement	Cement	Cementitious
One component	Yes	Yes (Mortar)	Yes
Additional materials	N/A	N/A	Fiber
Sack weight (lb)	65	50	53.5
Yield (ft^3/unit	0.5	0.43	0.4
Yield when 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
Temperature range for mixing (°F)	40–95	50–85	40–120
Compressive strength (psi)			
2 h	2500	N/A	>2500
3 h	3000	3000	N/A
1 d	5000	4000	>5000
7 d	6000	N/A	>7000
28 d	7500	7400-8000	>9000
Initial Set (min)	40-50	50	20-25
Final Set (min)	50-60	80	30-40
Splitting tensile strength (psi)			
1 d	400	400	N/A
7 d	600	N/A	N/A
28 d	N/A	450	>500
Drying shrinkage (%)	<0.06	<0.05	<0.045
Freeze thaw durability factor (%)	>90	100	100

3.3.1 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.

3.3.2 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.

3.3.3 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 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/cm	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

3.4 **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. Mixture 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.

3.5 **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 time of water addition (Step 5).

3.6 **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 Mixture proportions for Phase II non-proprietary mixtures

Material	Units	CSA	CSAIC	CSAICF	OPC1	OPCIC	OPCSF20	OPCSF30IC	OPCSF30ICF
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

3.6.1 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 **Error! Reference source not found.**.

3.6.2 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 (**Error! Reference source not found.**) 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 Compression testing setup

3.6.3 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 **Error! Reference source not found.**. Splitting tensile strength is known to underestimate the tensile strength of concrete compared to direct tension or flexural testing (Metha & Monteiro, 2006) (Olufunke, 2014).

3.6.4 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 (**Error! Reference source not found.**). 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 Extensometer cage for determination of modulus of elasticity

Figure 3.8 Splitting tensile test setup

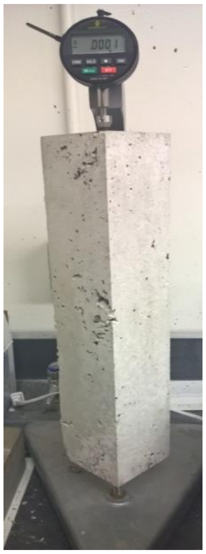


Figure 3.9 Length comparator for drying shrinkage measurement

3.6.5 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.

3.6.6 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 **Error! Reference source not found.**. 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.

3.6.7 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 **Error! Reference source not found.** and loaded to 40% of their ultimate compressive strength, starting at 48 hours. Length change was monitored at the measuring locations depicted in **Error! Reference source not found.** using the strain gauge shown in **Error! Reference source not found.**. Measurements were taken until the length change measurement stabilized or until 120 days.

3.6.8 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 3×4×16-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

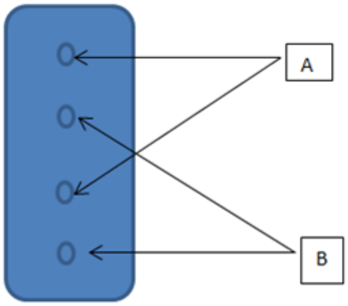


Figure 3.11 Reference measurement locations for creep tests

Figure 3.12 Creep testing frame

Figure 3.13 Creep strain measurement device

4.0 SUMMARY OF RESULTS

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

4.1 **Proprietary Mixture Results and Comparisons**

4.1.1 Compressive Strength

Error! Reference source not found. shows the compressive strength of proprietary repair media at 4 and 24 h. P2 exhibited the highest compressive strength, reaching about 6,000 psi in 4 h and 7,000 psi in 24 h. The extended version (P2E) suffered a 1,600 psi reduction in compressive strength at 4 h and a 1,100 psi reduction at 24 h. P1 and P3 did not meet the 4X4 criterion (4,000 psi in 4 h) criterion; P3 reached 3,900 psi in 4 h but P1 only reached 2,300 psi in 4 h. Both P1 and P3 reached acceptable compressive strength within 24 h. These results show that only P2 and P2E should be accepted based on the strength criterion, but since P3 was only 100 psi short of the required 4,000 psi at 4 h, it should also be accepted.

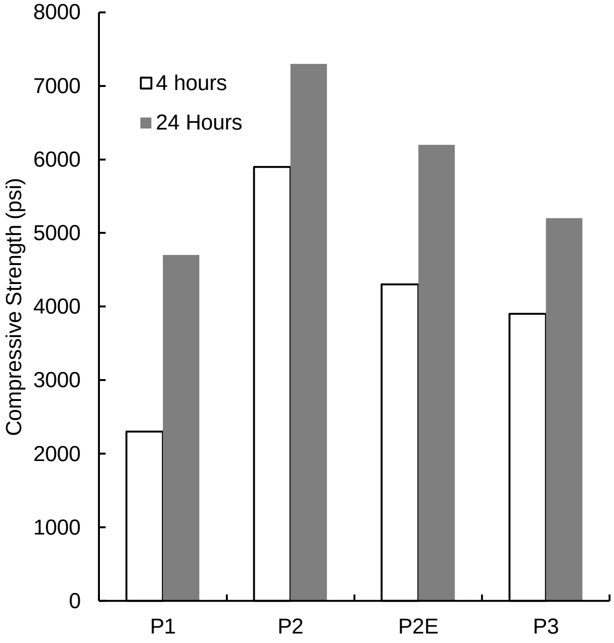


Figure 4.1 Compressive strength of proprietary repair media at 4 and 24 h

4.1.2 Modulus of Elasticity

Error! Reference source not found. shows the modulus of elasticity of proprietary repair media at 4 h. P2 exhibited the highest modulus of elasticity, exceeding 4 million psi. As with compressive strength, the extended P2E suffered about a 10% reduction in modulus of elasticity. Modulus of elasticity followed the same trend as strength; P1 exhibited both the lowest strength and the lowest modulus of elasticity. Since the best repair performance is realized when the substrate and repair medium are close to the same stiffness, there is no set criterion for modulus of elasticity. Instead, the user should select the material based on the property of the substrate, if known.

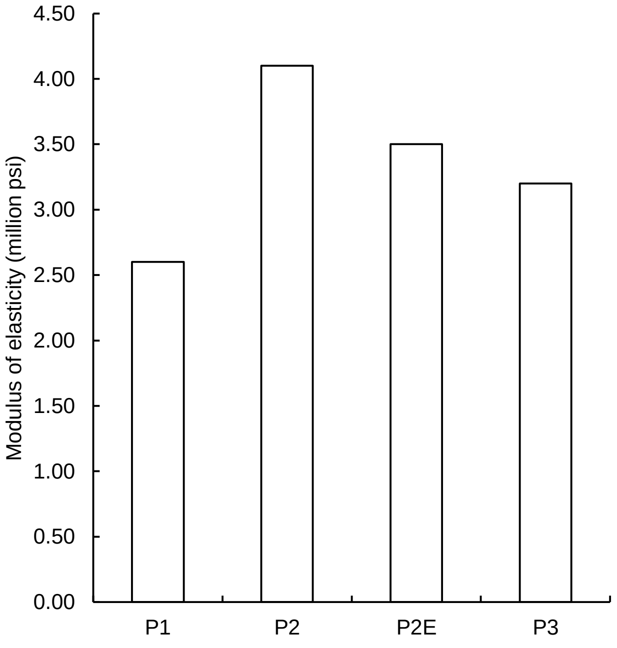


Figure 4.2 Modulus of elasticity of proprietary repair media at 4 h

4.1.3 Split Tension

Error! Reference source not found. shows splitting tensile strengths of proprietary repair media at 4 h. Like modulus of elasticity, tensile strength typically trends with compressive strength. However, despite having the lowest compressive strength and modulus of elasticity, P1 exhibited the highest splitting tensile strength of 280 psi in 4 h. P2 and P3 exhibited about 50 psi lower tensile strengths. P2E exhibited the lowest splitting tensile strength of 200 psi. Despite the absence of any strict criterion for tensile strength, it should be noted that the values observed here are significantly lower than would be expected for concretes with compressive strengths in the range of 4,000 psi. This is fairly important to the study because pavement performance depends more on flexural and tensile strength than on compressive strength.

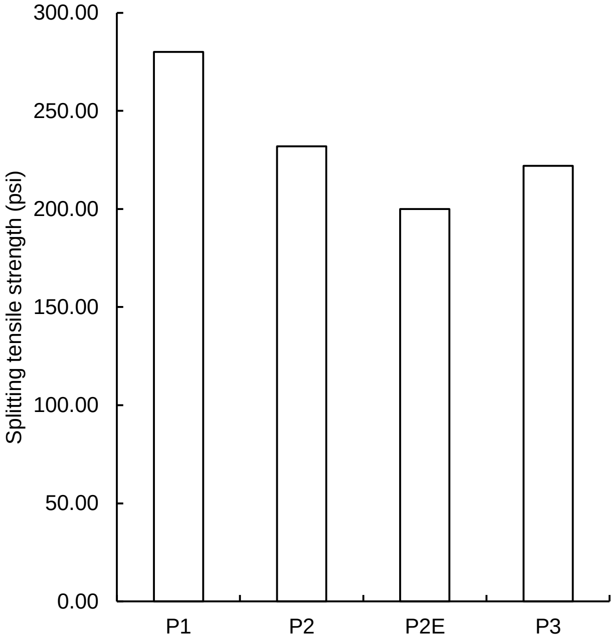


Figure 4.3 Splitting tensile strength of proprietary repair media at 4 h

4.1.4 Drying Shrinkage

Error! Reference source not found. shows drying shrinkage strain in proprietary repair media for the first 7 d. P1 was the least stable, exhibiting nearly 600 με of shrinkage in 7 d. P2 and P3 both exhibited less than 500 με of shrinkage in the same time. P2E exhibited the lowest shrinkage, which is expected due to reduced paste volume. In general, extending repair media with aggregates will improve volume stability. Users should specify extended repair media in order to limit shrinkage and associated damage.

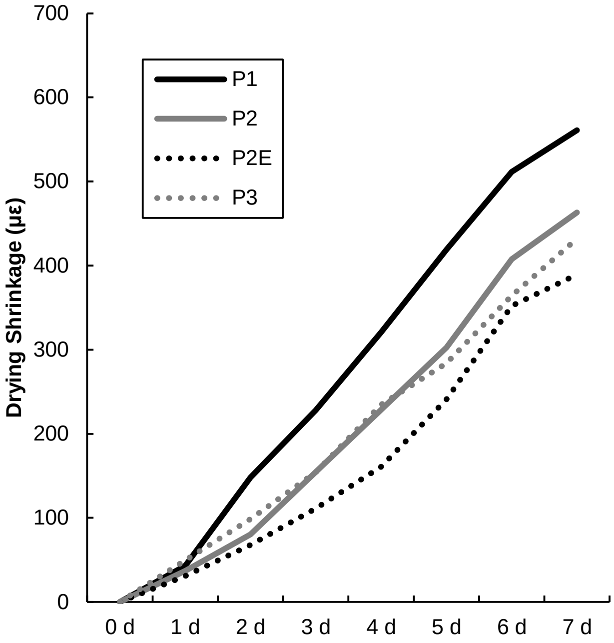


Figure 4.4 Drying shrinkage in proprietary repair media (demolded at 4 h)

4.1.5 Setting times

Error! Reference source not found. shows initial and final setting times for proprietary repair media. In practical terms, initial set corresponds to the time within which the repair medium must be placed and finished, while final set refers to the time at which the material can support some amount of load. Since the load-bearing criterion was defined in terms of compressive strength, the initial setting time is of most concern for this study. The fastest setting repair medium was P3, which reached initial set in only 9 min. P2 was the slowest setting repair medium, reaching initial set in 50 min. P2E reached initial set in about half the time of P2. Extending a material with aggregate can have mixed effects on setting time due to dilution, absorption, and other phenomena. At a minimum, the effect of extending on setting time is expected to depend on the type, amount, and water content of the added aggregate. It should also be noted that the setting time of all cementitious media is expected to depend on ambient temperature. Hot and dry summer days can significantly reduce setting times, and users should take this into consideration when selecting a repair medium.

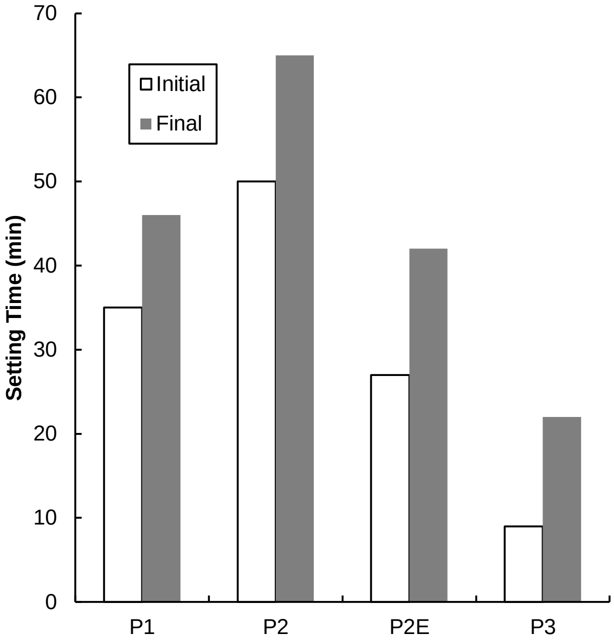


Figure 4.5 Setting times of proprietary repair media

4.2 Comparison of Results from Proprietary Mixtures

Table 4.1 summarizes the results for proprietary repair media. P2 and P2E both met the 4X4 compressive strength criterion, and P3 nearly met it. The same mixtures also exhibited the best shrinkage performance. They also provide a range of setting times from as short as 9 min to as long as 50 min. P1 did not meet the 4X4 strength criterion and should not be considered for applications that require strict adherence to that criterion.

Table 4.1 Summary of test results for proprietary repair media

	P1	P2	P2E	P3
Unit weight (lb/ft^3)	132	139	146	151
Compressive strength (psi)				
4 h	2300	5900	4300	3900
24 h	4700	7300	6200	5200
Initial set (min)	35	50	27	9
Final set (min)	46	65	42	22
Splitting tensile strength (psi)				
4 h	280	232	200	222
Elastic modulus (10^6 psi)	2.1	3.5	1.9	3.06

4.3 **Phase I Non-Proprietary Mixtures**

4.3.1 Compressive Strength

Error! Reference source not found. shows the compressive strength of Type II/V Portland cement concrete repair media. 7 d compressive strengths ranged from 5,500 psi to over 10,000 psi. However, early age strengths were not sufficient for repair applications. None of the mixtures reach 4,000 psi in 4 h. The fastest strength gain was observed for Mixture 3, which reached a mere 2,100 psi in 4 h. These mixtures could be considered for repair applications in which closure time is not critical, but are not considered further in this study.

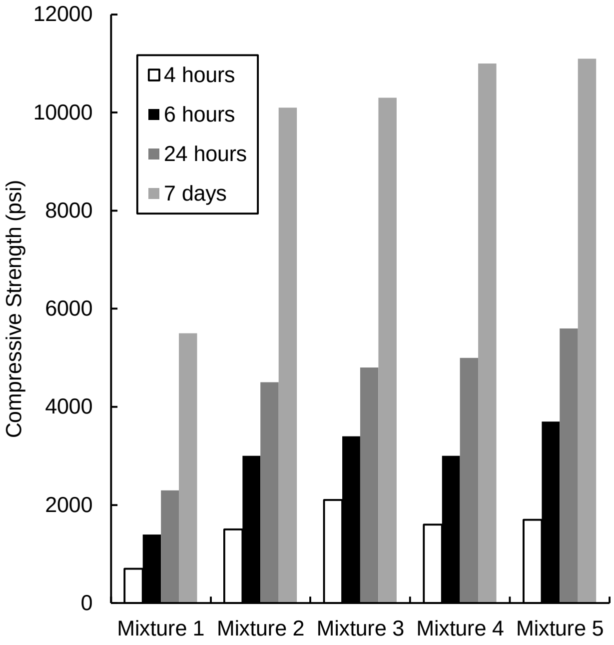


Figure 4.6 Compressive strength of Phase I Type II/V repair media

Error! Reference source not found. shows the compressive strength of CSA repair media. The compressive strength development was far more rapid than in Type II/V Portland cement mixtures. 7 d compressive strength were between 13,000 and 15,500 psi. All three mixtures reached compressive strengths around 8,000 psi in 4 h, greatly exceeding the 4X4 criterion. Since all of the mixtures greatly exceeded the required strength, suggesting that the cement content of 850 b/yd^3 was excessive, a modified mixture with reduced cement content was selected for continued study in Phase II in order to improve the efficiency of the mixture.

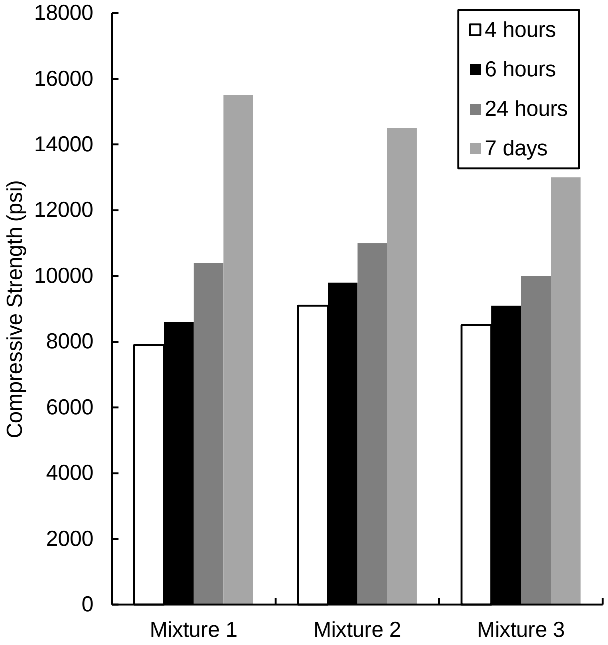


Figure 4.7 Compressive strength of Phase I CSA repair media

Error! Reference source not found. shows compressive strength development in Type III Portland cement concrete repair media. 7 d compressive strengths ranged from about 6,000 psi to more than 12,000 psi. However, early age compressive strengths were insufficient. The highest 4 h strength was observed for Mixture 3, which reached only 2,200 psi. Conversations with cement suppliers and users in Utah suggest that, although the cement supply meets ASTM specifications for Type III cement, the supply of Type III cement in Utah is not of a high quality and tends not to hydrate as quickly as desired. This was not corroborated by any extensive chemical or physical analysis, but does provide some context for the results presented here.

These results demonstrate the feasibility of producing non-proprietary repair media, but also demonstrate the associated difficulties. Even with very high dosages of accelerators, Type II/V Portland cement is not useful for rapid concrete repair. Type III Portland cement should be a viable option, but the supply of Type III cement in Utah is not of sufficient quality to reach the required early age strengths. In general, there is a need to adopt non-Portland cements for rapid repair if proprietary repair media are not desired. CSA cement is one very viable option.

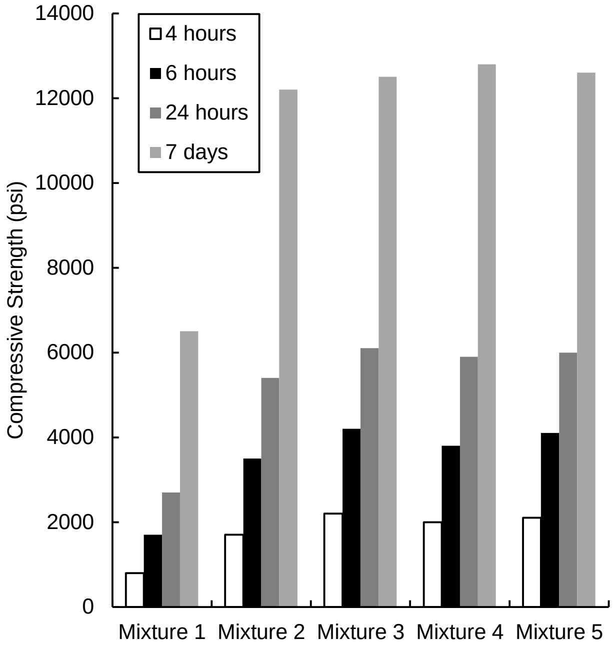


Figure 4.8 Compressive strength of Phase I Type III repair media

4.4 **Phase II Non-Proprietary Repair Media**

4.4.1 Fresh Properties

Table 4.2 presents the workability (slump), air content, and unit weight of Phase II non-proprietary repair media. Rapid hydration in CSA mixtures made it difficult to perform slump and air content measurements before setting. All Portland cement based repair media had slumps between 3.5 and 4.5 in. This was considered adequate and was fairly consistent with the workability of the proprietary repair media. Air content in Portland cement based repair media was between 4.6% and 5.6%, which is generally sufficient for good freeze/thaw durability. This assumption will be verified with actual freeze/thaw testing. The unit weight of most non-proprietary mixtures—those based on both CSA and Portland cement—was near the typical 140 lb/ft^3, with the exception of those made with lightweight aggregate.

Table 4.2 Fresh properties of Phase II non-proprietary repair media

Mixture	Slump (in)	Air content (%)	Unit weight (lb/ft^3)
OPC1	3.5	5.2	141
OPCSF20	4	4.6	145
OPCIC	4	5.6	116
OPCSF30IC	4.5	5.4	112
OPCSF30ICF	3.8	4.6	142
CSA1	--	--	139
CSAIC	--	--	120
CSAICF	--	--	131

4.4.2 Compressive Strength

Error! Reference source not found. shows compressive strength development for the first 7 d for Phase II mixtures. All mixtures based on CSA cement met the 4X4 acceptance criterion. The best strength performance was observed for the base CSA mixture ('CSA'), which reached 8,000 psi in 4 h and 15,000 psi in 7 d. Internal curing with presaturated lightweight aggregate (PSLWA) reduced the compressive strength, as expected. This effect was magnified when internal curing was achieved with only fine PSLWA rather than with both fine and coarse PSLWA. None of the repair media based on Portland cement met the 4X4 criterion. The best performing Portland cement media were those than included silica fume as a supplementary cementitious material. The internally-cured Portland cement and silica fume mixture reached 3,300 psi in 4 h. This echoes the conclusions of the Phase I compressive strength study; if the 4X4 criterion is critical, non-Portland cement (i.e., CSA) cement options should be considered. If internal curing is employed to mitigate volume stability issues, the strength reduction associated with inclusion of lightweight aggregate is significant, but the strength and its rate of development are still more than sufficient for repair applications.

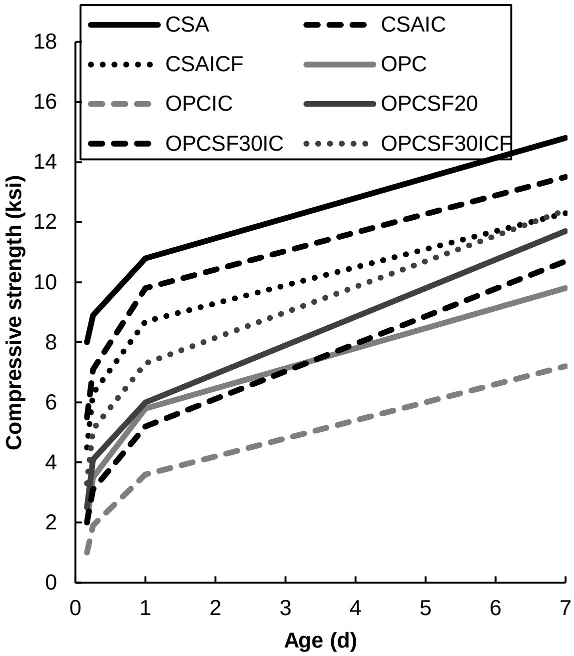


Figure 4.9 Compressive strength of Phase II non-proprietary repair media

4.4.3 Elastic Modulus

Error! Reference source not found. shows the modulus of elasticity for Phase II mixtures after 4 h. CSA mixtures exhibited moduli of elasticity between 3.5 and 4.6 million psi. As with compressive strength, internal curing with PSLWA reduced the modulus of elasticity. Since the modulus of elasticity of the based mixture—4.5 million psi—is quite high, and since the durability of repairs depends on strain compatibility between the substrate and the repair, the reduction in stiffness associated with internal curing with PSLWA may be a benefit. This is especially true since internal curing does not reduce the compressive strength below the 4X4 acceptance criterion.

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.

It should also be noted that the ACI 318 equation to predict modulus of elasticity E from compressive strength f_c', viz. $E = 57000 * \sqrt{f_c'}$ (in psi) predicts the values shown in **Error! Reference source not found.** fairly well. Predicted moduli of elasticity were within about 10%

of the measured values. This means that users can estimate modulus of elasticity for repair media. This will aid in the selection of appropriate repair media based on the properties of the substrate without requiring additional testing beyond compressive strength.

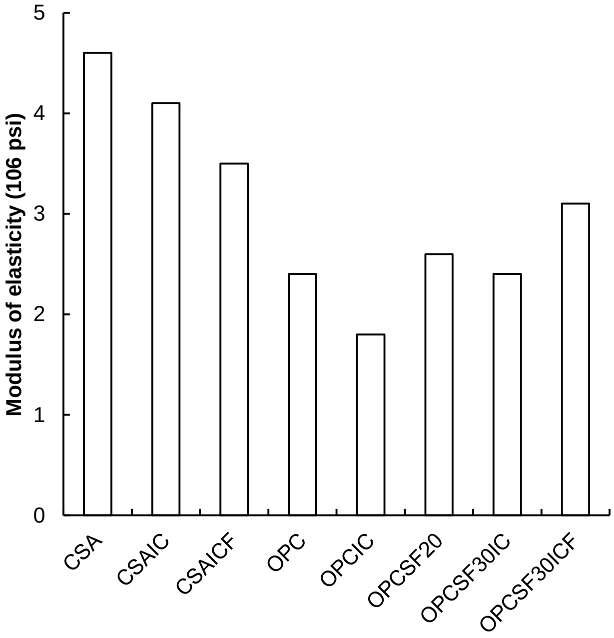


Figure 4.10 Modulus of elasticity of Phase II non-proprietary repair media at 4 h

4.4.4 Splitting Tensile Strength

Error! Reference source not found. shows splitting tensile strengths for Phase II mixtures at 4 h. The best tensile strength performance (350 psi) was observed for the base CSA mixture (‘CSA’). The Portland cement mixture with 20% silica fume also performed well with splitting tensile strength around 325 psi. The internally cured Portland cement and silica fume mixture reached a tensile strength just over 300 psi. The remaining mixtures showed relatively poor tensile strength performance. Internally cured CSA mixtures showed tensile strengths of only about 200 psi. The Portland cement mixture without silica fume (‘OPC’) exhibited the worst performance, but internal curing (‘OPCIC’) improved the tensile strength by about 25%.

The results presented here show that internal curing generally reduces the tensile strength, especially in CSA repair media. Internal curing also reduced the compressive strength, but not to such a detrimental effect. The reduced compressive strength of internally cured CSA media was still above the 4X4 criterion. However, the tensile strength of internally cured CSA repair media is only half that without internal curing. If CSA repair media are to be applied, the user should study the tradeoff between volume stability and strength in internally cured mixtures. If Portland cement and silica fume repair media are to be used, there may be less concern over reduced tensile strength in internally cured mixtures.

ACI 330R (ACI Committee 330, 2008) predicts the flexural tensile strength f_{ft}, which is a more direct measurement of the property of interest for pavements, as a function of f_c', viz. $f_{ft} = 2.3 * f_c'^{2/3}$. This equation overestimates the splitting tensile strengths shown in **Error! Reference source not found.** by more than 100%. However, experience suggests that the flexural strength of concrete is typically much higher than the splitting tensile strength. Since flexural strength was not measured as a part of this study, more work should be performed to determine if the ACI 330 equation can be used with repair media.

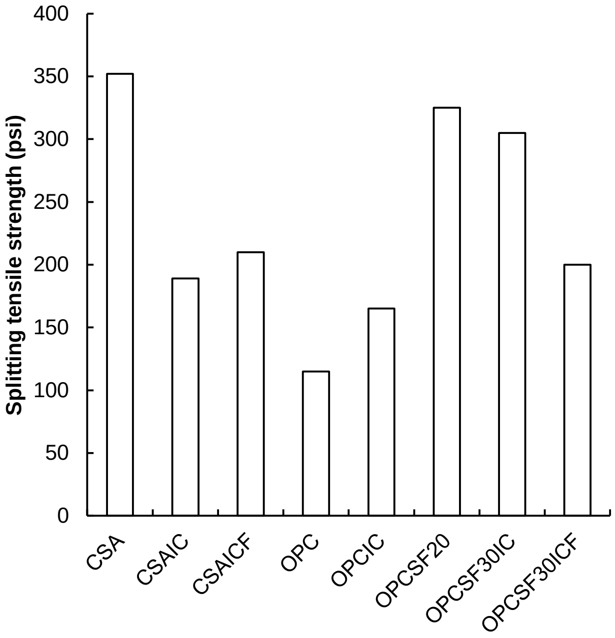


Figure 4.11 Splitting tensile strength of Phase II non-proprietary repair media at 4 h

4.4.5 Setting time

Error! Reference source not found. shows setting times for Phase II mixtures. As before, since the criterion for closure time is based on compressive strength and not on final setting time, the initial setting time, which determined the amount of time allowed for mixing, placement, and finishing, is more important for this study. The base CSA mixture has an initial setting time of 9 min. Internal curing extended that setting time to between 13 and 16 min. Application of admixtures like citric acid, boric acid, or some commercial retarders can extend this setting time. Portland cement- based mixtures set more slowly, with setting times between 25 and 40 min. Again, retarders or accelerators could be used to tune setting times to desired values based on project needs. Considering this, all of these mixtures are considered acceptable from a setting time standpoint.

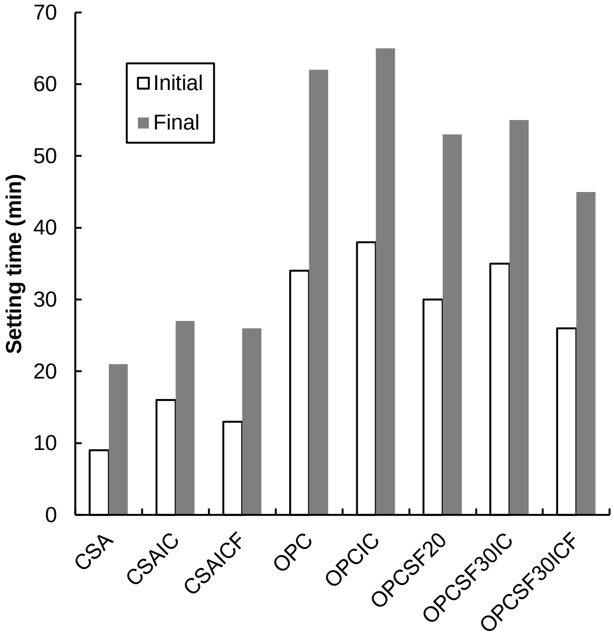


Figure 4.12 Setting times of Phase II non-proprietary repair media

4.4.6 Drying Shrinkage

Error! Reference source not found. shows drying shrinkage in Phase II repair media. The reader should recall that these data represent the modified drying shrinkage test, wherein measurements commenced after 4 h rather than after 24 h of hydration. This modified test is more representative of the field condition (i.e., traffic ready in 4 h). Mixtures without internal curing exhibited the highest drying shrinkage, as expected. However, all mixtures exhibited ultimate drying shrinkage of less than 0.07%, which is certainly acceptable for most applications. It should be noted that repairs made in hot and arid climates (i.e., Utah) will shrink more significantly and faster than what is represented by this test (50% RH and 23 ˚C). Internal curing reduced the shrinkage, as expected.

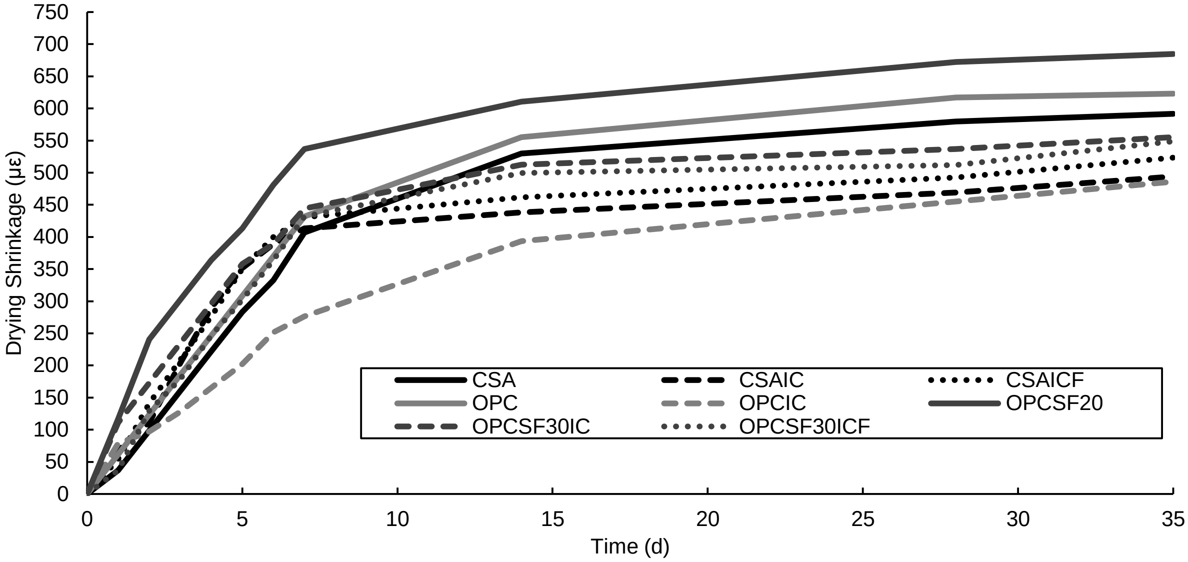


Figure 4.13 Drying shrinkage in Phase II non-proprietary repair media

4.4.7 Autogenous Shrinkage

Error! Reference source not found. shows autogenous shrinkage in Phase II repair media. As with drying shrinkage, media without internal curing exhibited the highest autogenous shrinkage. In both cases, CSA repair media showed the highest shrinkage. The control Portland cement (‘OPC’) mixture exhibited the second highest, and the mixture with 20% silica fume (‘OPCSF20’) exhibited the third highest. Internal curing with PSLWA was effective at tempering both autogenous and drying shrinkage. Under autogenous conditions, internal curing created expansion within the first 2 to 4 hours. The lowest shrinking mixtures were internally cured Portland cement or Portland cement and silica fume. However, the ultimate shrinkage values were relatively low for all mixtures, as with drying shrinkage. Even the highest shrinking mixture exhibited autogenous shrinkage of less than 0.035%.

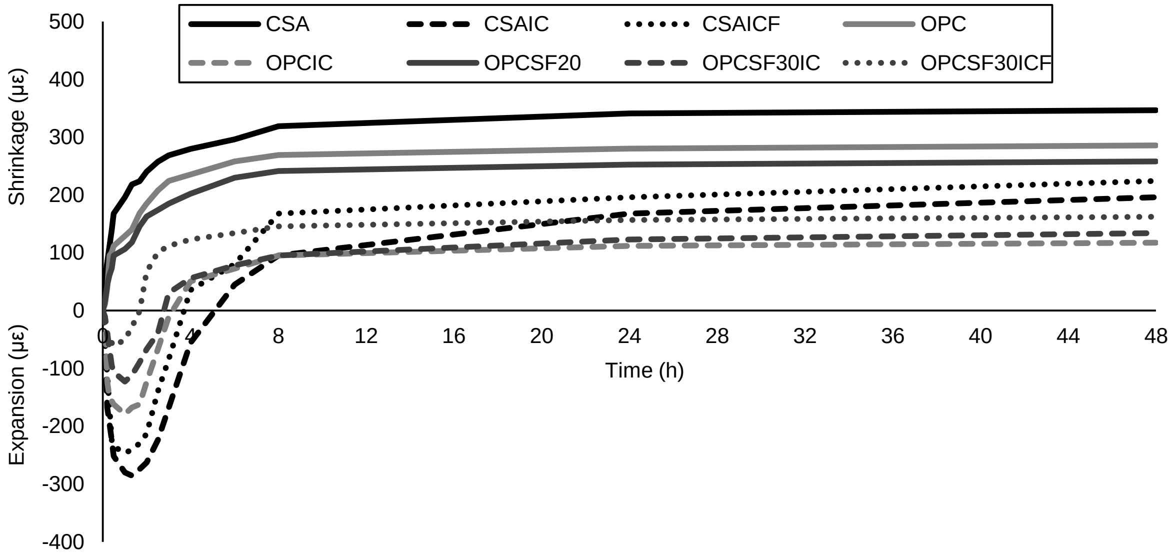


Figure 4.14 Autogenous shrinkage in Phase II non-proprietary repair media

4.4.8 Restrained Ring Shrinkage Tests

Error! Reference source not found. shows the average time to cracking of three Phase II repair media specimens under the restrained ring shrinkage test. Portland cement repair media performed well under the restrained shrinkage test. OPC cracked in about 35 days, while internally cured OPC ('OPCIC') cracked in about 45 days. Inclusion of silica fume reduced the time to cracking to about 27, and internal curing again improved the performance. CSA repair media cracked in 12 days; internal curing again improved the performance, extending cracking to 17-21 d. These results are consistent with those reported elsewhere for repair media. Bescher (2015) 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. These results suggest that internal curing should be used to prevent cracking in rapid-repair media, especially those based on CSA cement. The amount of PSLWA used should be determined by optimizing mechanical strength, volume stability, and cracking. Additional and more detailed discussion on this topic is presented elsewhere (Quezada, Thomas, & Maguire, 2018).

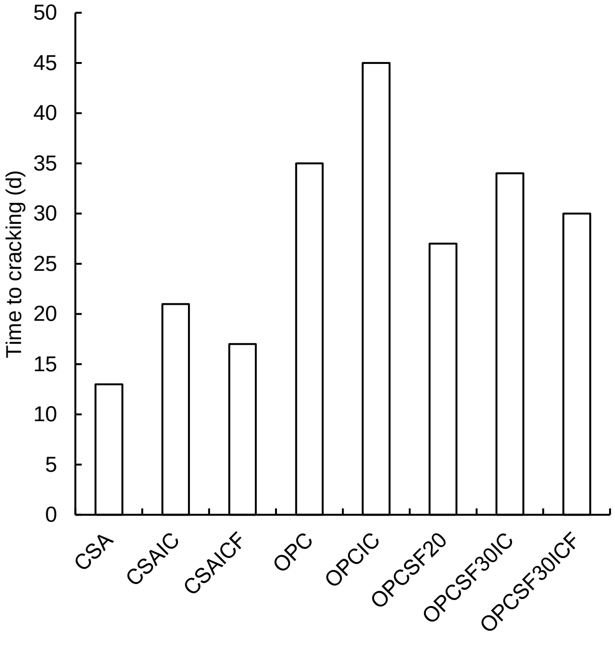


Figure 4.15 Time to cracking of Phase II non-proprietary repair media under restrained ring shrinkage test

4.4.9 Freeze/Thaw Durability

Freeze/thaw durability results are presented in Table 4.3. Each of the mixtures tested exhibited excellent freeze/thaw durability, with at least 94% of mass retained after 300 cycles of freezing and thawing. Based on these results, any of the non-proprietary repair media are acceptable.

Table 4.3 Mass retained in Phase II non-proprietary repair media after 300 freeze/thaw cycles

Test	Units	CSA1	OPCSF20	OPC1	OPCIC	OPCSF30IC	CSAIC	CSAICF	OPCSF30ICF
Mass Retained	%	96	94	95	94	94	98	97	95

4.4.10 Creep

Error! Reference source not found. shows creep deformation in Phase II non-proprietary mixtures. CSA repair media exhibited very low creep, but internal curing resulted in increased creep, as expected with the inclusion of lightweight aggregates, but the increase was minor. Portland cement and Portland/silica fume repair media exhibited fairly significant creep. Again, internal curing with PSLWA increased the creep, but the increase was much more extensive than in CSA repair media.

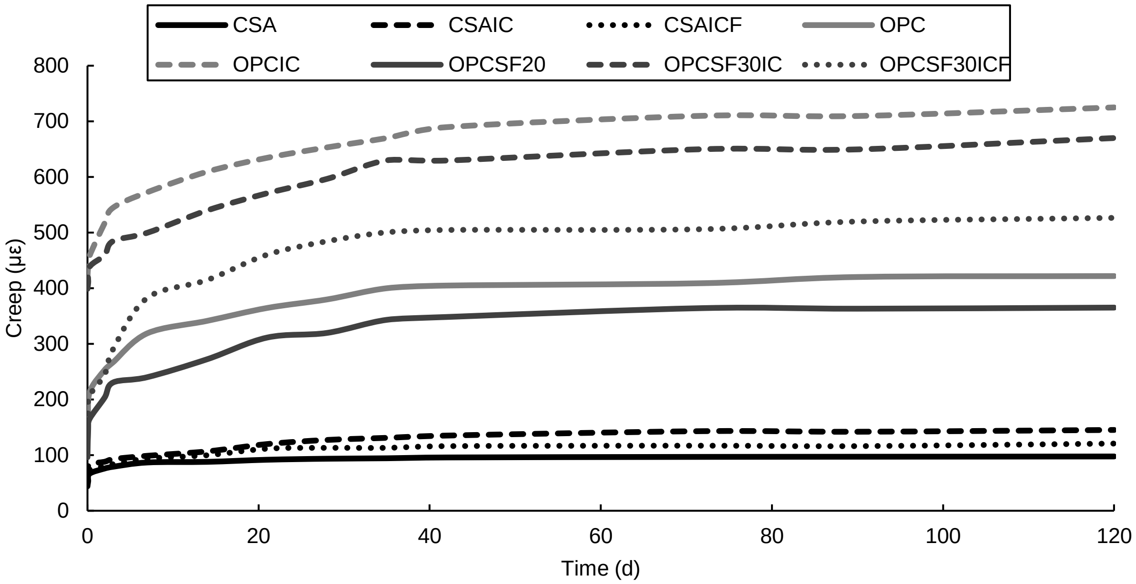


Figure 4.16 Creep in Phase II non-proprietary repair media

4.5 **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).

5.0 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.

5.1 Proprietary Repair Media

Three proprietary repair media were investigated; one was investigated in its non-extended (without coarse aggregate) and extended (with coarse aggregate) forms. Only one repair medium (P2 and its extended version P2E) met the 4X4 compressive strength acceptance criterion. A third (P3) almost met the criterion (3,900 psi in 4 h). P2, P2E, and P3 provided a wide range of setting times, good volume stability, and good mechanical performance (compressive strength, tensile strength, and modulus of elasticity). The user should select from these materials based on project needs, including mechanical compatibility between the substrate and repair (modulus of elasticity) and setting time.

5.2 Non-Proprietary Repair Media

Non-proprietary repair media based on Type II/V Portland cement, Type III high early strength Portland cement, and CSA cement were evaluated. Portland cement-based mixtures did not gain strength sufficiently quickly to meet the 4X4 compressive strength acceptance criterion. Addition of silica fume helped with this, but the required addition was very high (20–30%). Additionally, addition of silica fume worsened the volume stability, which is a problem of considerable concern for repair media. Repair media based on CSA cement performed very well in terms of strength development and mechanical performance. Set times were very low, but can be extended with inexpensive citric or boric acid admixtures. The volume stability and time to cracking of CSA repair media are not exemplary, but can be improved significantly by internal curing with PSLWA. If UDOT wishes to consider non-proprietary repair media, the authors recommend they be based on internally cured CSA cement. Other binder systems may also be appropriate (e.g., geopolymers (Thomas, 2016)).

REFERENCES

ACI 546, A. C. (2014). ACI 546.3R-14 Guide to Materials Selection for Concrete Repair. *American Concrete Institute*, 1-72.

ACI Committee 330. (2008). *Guide for the Design and Construction of Concrete Parking Lots.* American Concrete Institute.

Austin, S., Robins, P., & Pan, Y. (1999). Shear bond testing of concrete repairs. *Cement and Concrete Research, 29*, 1067-1076.

Bescher, E. (2015). *Calcium Sulfoaluminate-Belite Concrete: Structure, Properties, Practice.* Los Angeles: University of California.

Beshr, H., & Almusallam, A. (2003). Effect of coarse aggregate quality on the mechanical properties of high strength concrete. *Construction and Building Materials*, 97-103.

Bhanja, S., & Sengupta, B. (2005). Influence of silica fume on the tensile strength of concrete. *Cement and Concrete Research*, 743-747.

Cabrera, J., & Al-Hassan, A. (1997). Performance properties of concrete repair materials. *Construction and Building Materials*, *11*, 283-290.

Courard, L., Piotrowski, T., & Garbacz, A. (2014). Neat-to-surface properties affecting bond strength in concrete repair. *Cement & Concrete Composites, 46*, 73-80.

Donza, H., Cabrera, O., & Irassar, E. (2002). High-strength concrete with different fine aggregate. *Cement and Concrete Research*, 1755-1761.

Emberson, N., & Mays, G. (1990). Significance of property mismatch in the patch repair of structural concrete, part 1: Properties of REpair Systems. *Magazine of Concrete Research, 42*, 147-160.

Emmons, E., Vaysburd, A., & McDonald, J. (1993). A rational approach to durable concrete repairs. *Concrete International, 15*(9), 40-45.

Emmons, P. (1993). *Concrete Repair and maintenance illustrated.* R.S. Means Company Inc.

Glasser, F., & Zhang, L. (2001). High-performance cement matrices based on calcium sulfoaluminate-belite compositions. *Cement and Concrete Research*, 1881-1886.

Heiman, J., & Koerstz, P. (1991). Performance of polymer modified cementitious mortars in chloride contaminated concrete. *Trans. Inst. Eng. Austral Civ. Eng., 33*(3), 169-175.

Hewlett, P., & Hurley, S. (1985). The consequence of polymer concrete mismatch. *Design Life of Buildings*, 179-196.

Ioannou, S., Reig, L., Paine, K., & Quillin, K. (2014). Properties of a ternanry calcium sulfoaluminate-calcium sulfate-fly ash cement. *Cement and Concrete Research, 56*, 75-83.

Marosszeky, M. (1991). Stress performance in concrete repairs. *ACI SP126,* 467-473.

Mays, G., & Wilkinson, W. (1987). Polymer repairs to concrete: their influence on structural performance. *ACI SP-100*, 351-375.

Metha, P., & Monteiro, P. (2006). *Concrete Microstructure, Properties, and Materials* (3rd ed. ed.). McGraw-Hill.

Momayez, A., Ehsani, M., Ramezanianpour, A., & Rajaie, H. (2005). Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Cement and Concrete Research, 35*, 748-757.

Momayez, A., Ramezanianpour, A., Rajaie, H., & Ehsani, M. (2004). Bi-Surface Shear Test for Evaluating Bond between Existing and New Concrete. *ACI Materials Journal, 101*(2), 99-106.

Morgan, D. (1996). Compatibility of concrete repair materials and systems. *Construction and Building Materials*, 57-67.

Nazari, A., Riahi, S., Riahi, S., Shamekhi, S., & Khademno, A. (2010). The effects of incorporation Fe2O3 nanoparticles on tensile and flexural strength of concrete. *Journal of American Science, 6*(4), 90-93.

Olufunke, A. (2014). A Comparative Analysis of Modulus of Rupture and Splitting Tensile Strength of Recycled Aggregate Concrete. *Americal Journal of Engineering Research (AJER), 3*(2), 141-147.

Ozyildirim, C. (2009). Durability of structural lightweight concrete. *LWC Bridges Workshop*.

Péra, J., & Ambroise, J. (2004). New applications of calcium sulfoaluminate cement. *Cement and Concrete Research*, 671-676.

Plum, D. (1991). Materials - what to specify. *Construction Maintenance Repair Digest*, 3-7.

Saucier, F., & Pigeon, M. (1991). Durability of new to old concrete bonding. *ACI International Conference on Evaluation and Rehabilitation of Concrete Structures and Innovation in Design*, (pp. 741-772). Hong Kong.

Sounthararajah, A., Wong, L., Nguyen, N., Hong Bui, H., Kodikara, J., & Jitsangiam, P. (2016). Flexural Properties of Cemented Granular Materials for Pavement Design. *8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements* (pp. 403-409). Springer Netherlands.

Tayeh, B., Abu Bakar, B., Johari, M., & Voo, Y. L. (2013). Evaluation of bond strength between normal concrete substrate and ultra high performance fiber concrete as a repair material. *The 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering. 54*, pp. 554-563. Procedia Engineering.

University of Maryland. (2005). *Rehabilitation and maintenance of road pavements using high early strength concrete.* State Highway Administration.

Vincent, E. (2003). *Compressive Creep of A Lightweight High Strength Concrete Mixture.* Blacksburg, VA: Virginia Polytechnic Institute and State University.

Wall, J., & Shrive, N. (1988). Factors affecting bond between new and old concrete. *ACI Materials Journal, 85*(2).

Woodson, R. (2011). Concrete Repair Preparation. In R. Woodson, *Concrete Portable Handbook* (pp. 95-102). Butterworth Heinemann.

Yatagan, M. S. (2015). The Investigation of the Relationship between drying and restrained shrinkage in view of the development of micro cracks. *Journal of Engineering Technology, 3*(3). doi:10.5176/2251-3701_3.3.136

Yuan, Y., & Marosszeky, M. (1991). Major factors influencing the performance of structural repair. *ACI SP-128, 2,* 819-837.

Zia, P., Ahmad, S., & Leming, M. (1993). *Mechanical behavior of high performance concrete: High Early Strength Concrete.* Washington, DC: Strategic Highway Research Program.

APPENDIX A: SURVEY

This appendix provides the original survey and raw results from statistical analysis software used to determine correlations between various properties in the main text of the report.

Full Depth Pavement Repair Questionnaire

Purpose: Identify what DOTs are doing for full depth pavement repairs and their success.

State Agency: ______ _________

1. **The results of this questionnaire will be included in a UDOT report and potentially peer reviewed publication. Does your agency wish to remain anonymous?**

Yes No

If remaining anonymous please indicate the agencies Environmental Zones (circle one)

Dry Freeze Dry No-Freeze Wet Freeze Wet No-Freeze

2. **Rate the performance of your current routine full-depth pavement repairs (circle one):**

Poor – 1 2 3 4 5 – Excellent.

3. **How long does your agency expect a full-depth repair to provide satisfactory performance (in years)?**

4. **How long does a typical full depth repair last (in years)?**

5. **For full depth repairs, does your agency use (circle one):**

Agency Employees Contractors Combination of both (briefly explain):

6. **For a standard replacement, how soon does the agency open to traffic?**

7. What is the criteria for full-depth pavement repair opening to traffic (X strength, X time, etc.)

8. **For cast-in-place, full-depth, full-panel replacements (non-precast) what material has provided the agency the best performance?** ***Be as specific as you want***

9. For cast-in-place, full-depth, full-panel replacements (non-precast) what material has provided the agency the worst performance? ***Be as specific as you want***

10. List the top three properties, in order of importance, the agency believes are important for a full depth repair material? (Example: closure time, specific dimensional properties, specific strength properties, specific durability properties etc.)

1.

2.

3.

11. What is your agencies estimated total cost for a 10’ x 12’ x 10” cast-in-place full-depth concrete pavement panel repair? Unit cost in $/ft2 for a large job is acceptable.

Statistical Analysis

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	hrwr	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
water	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
nwcoarse	-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
nwfine	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
lwcoarse	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
lwfine	-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
w2cmratio	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
hrwr	-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

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations									
	acc	hrwr	slump	air	unitw	compr4	compr6	compr24	compr7d
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
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
water	-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
nwcoarse	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

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations								
	emod	split	iset	fset	drysh	ring	creepc	freeze
nwfine	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
lwcoarse	-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
lwfine	-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
w2cmratio	-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
hrwr	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
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