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Investigating Rapid Concrete Repair Materials and Admixtures

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INVESTIGATING RAPID CONCRETE REPAIR MATERIALS AND ADMIXTURES

by

Ivan Quezada

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2018

ABSTRACT

Investigating Rapid Concrete Repair Materials
and Admixtures

by

Ivan Quezada, Doctor of Philosophy

Utah State University, 2018

Major Professor: Dr. Marc Maguire
Department: Civil and Environmental Engineering

Investigations to develop a full depth durable concrete mixture (15-year life) to be used for pavement with four-hour cure time and 4 ksi strength that will minimize cracking were carried out. The Internal Curing (IC) concept has been around for more than 60 years. This mechanism is a process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water which lies within Pre-Saturated Lightweight Aggregates (PSLWA). This dissertation presents a literature review of the state-of-practice for the use of IC in concrete mixtures and how structural engineers and construction engineers can adapt IC to their present and future work. 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. Rapid hydration and high early strength Portland cement and calcium sulfoaluminate (CSA) concretes are commonly used as pavement repair media. The author hypothesized that internal curing with saturated lightweight aggregate prevented or delayed restrained shrinkage cracking in rapid repair media. The fresh properties (slump, setting time), mechanical properties (elastic modulus, compressive and tensile strength), and volume stability (autogenous shrinkage, drying shrinkage, restrained ring shrinkage, and creep) of rapid repair media were evaluated with and without internal curing with saturated lightweight aggregate. Significant improvements in volume stability were also noted. Drying and autogenous shrinkage were reduced by factors up to 20% and 50%. However, detrimentally, creep shrinkage was increased by factors up to 45%, respectively. Time to cracking in restrained ring shrinkage tests was increased by factors up to 60%. These results indicate that internal curing can successfully improve volume stability and mitigate restrained shrinkage cracking in rapid repair media without compromising fresh properties or ultimate mechanical strength. Maturity was observed for CSA mixtures and exhibited a correlation with compressive strength development which could be beneficial for rapid repair media on the field.

(222 pages)

PUBLIC ABSTRACT

Investigating Rapid Concrete Repair Materials and Admixtures

Ivan Quezada, Doctor of Philosophy

This dissertation presents a literature review of the state-of-practice for the use of IC in concrete mixtures and how structural engineers and construction engineers can adapt IC to their present and future work. 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. Rapid hydration and high early strength Portland cement and calcium sulfoaluminate (CSA) concretes are commonly used as pavement repair media. The fresh properties (slump, setting time), mechanical properties (elastic modulus, compressive and tensile strength), and volume stability (autogenous shrinkage, drying shrinkage, restrained ring shrinkage, and creep) of rapid repair media were evaluated with and without internal curing with saturated lightweight aggregate. Significant improvements in volume stability were also noted. Results indicate that internal curing can successfully improve volume stability and mitigate restrained shrinkage cracking in rapid repair media without compromising fresh properties or ultimate mechanical strength. Maturity was observed for CSA mixtures and exhibited a correlation with compressive strength development which could be beneficial for rapid repair media on the field.

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CHAPTER 1

INTRODUCTION

1.1 General

In recent years, early opening of concrete pavements, roads, and pavement repairs to traffic has been given much emphasis, because of many reasons: efficiency, population comfort, political value, 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. Full-depth repairs can be designed to provide good long-term performance; however, the performance of full-depth repairs on many in service pavements has been inconsistent (Weiss, et al., 2016).

For the past 19 years, according to the America's ASCE Infrastructure Report Card, roads in the United States have been given between a D- and a D+, over 40% of America's urban highways suffer from congestion, $101 billion have been lost in time and fuel per year and an estimated $170 billon is needed yearly for major improvements (ASCE, 1998) (ASCE, 2001) (ASCE, 2005) (ASCE, 2009) (ASCE, 2013). Furthermore, according to the Federal Highway Administration, American drivers spent more than 84 billion hours driving during 2017 and 6.9 billion hours were spent on delays during the aforementioned congestions, which meant that an average driver spent 42 hours in traffic delays. These delays were not categorized and could have occurred due to accidents or ongoing repairs. Moreover, 21% of the nation’s highways had poor conditions during the same year. In 2014, traffic delays cost the United States $160 billion in wasted time and fuel. Driving on roads in need to repair cost US drivers $120.5 billion in vehicle repairs and operating costs in 2015 (ASCE, 2017). These high figures demonstrate the need for better, more efficient and durable concrete pavement repairs in the country.

Potentially, there could be a relationship between the state of the United States highway system and the traffic delays occurring. Traffic delays may occur due to different causes, however, one of them is pavement deterioration. Modelling uncertainties related to these causes (deterioration, quality of repairs, maintenance schedule, and more) has been investigated in the past in order to reduce costs and traffic delays (Thoft-Christensen, 2012). Climate change has produced higher temperatures which affect pavements increasing fatigue cracking and reducing their durability (McPherson & Muchnick, 2005). This is a call to prioritize maintenance and good repairs to maximize the lifespan of roads and try to minimize these costs and time delays.

Pavements are commonly exposed to several unavoidable weather factors and dynamic loads, which makes the study of concrete pavement repair the more important. When concrete pavement fails, the subsequent repairs need to be efficient, durable and of short duration, in order to minimize traffic jams and delays. Consequently, media utilized for repairs has been researched. Different materials, such as magnesium phosphate cement (Li, Zhang, & Cao, 2014), ferrocement (Xion, Wu, Li, & Yan, 2011), fiber reinforced concrete (Martinola, Meda, Plizzari, & Rinaldi, 2010), Calcium Sulfoaluminate Cement (CSA) (Thomas, Maguire, Sorensen,

& Quezada, 2018) and more have been researched in the past with the aim to use their properties and applications for rapid repair media. In order to increase the durability of concrete pavement, research has incurred on utilizing fiber reinforcement (Banthia, Zanotti, & Sappakittipakorn, 2014) (Nobili, Lanzoni, & Tarantino, 2013) (Martinola, Meda, Plizzari, & Rinaldi, 2010), cement-based composites for strengthening (Mechtcherine, 2013), bacteria to repair cracks (Tittleboom, De Belie, De Muynck, & Verstraete, 2010), and the internal curing method (Quezada, Thomas, & Maguire, 2018), just to name a few. Existing literature focuses on altering the properties of the repair concrete so that it becomes more durable, or to utilize new materials for a more compatible and resistant repair.

Rapid repair media tends to suffer from short setting times and poor workability, precluding contractors of effectively utilizing certain products on the field. Different techniques to modify setting times have been researched (Samson, Phelipot-Mardelé, & Lanos, 2015) (Champenois, 2015) (Atthakorn, Somchai, Chantana, & Yothin, 2014) (Thanongsak, Yoshika, Supab, & Arnon, 2015) (Gediminas, Xiangming, Castro-Gomes, Huang, & Saafi, 2015). The literature states that certain admixtures are able to delay the setting time of fast-setting concrete mixtures. These are commonly utilized for concrete pavement repair due to their high early strengths and shorten the duration of roadway closures. For example, CSA mixtures can obtained 10 ksi in less than 4 hours due to their rapid hydration properties, but possess short setting times (some mixtures set under 10 minutes) which, at times, prevent contractors of utilizing it in different applications and proper mixing, placing and vibration (Thomas, Maguire, Sorensen, & Quezada, 2018). However, contractors not always desire a fast-setting concrete because of difficulties with placement and transportation. Retarding these mixtures may be possible and thus, extending the applications of rapid repair media.

As repair media sets, it is important to know its compressive strength development, to procure a prompt opening to traffic after the repairs are complete. Commonly, contractors and engineers cast specimens and send them to laboratories to obtain compressive strengths at certain ages. Nevertheless, this process is usually expensive, with tests costing around US$75 per cylinder and around US$200 per beam. Moreover, the specimens for these tests need to obtained quickly and transported to a laboratory in order for tests to be performed at early stages. As mentioned before, early strength development is important to rapid repair media as it tends to minimize closure times. The maturity method was researched in the past (Carino N. , 1984) (Carino & Tank, 1992) (Kim, Moon, & Eo, 1998), as a way to measure the progress of concrete curing. This method requires that the thermal history of the mixture is recorded in real-time. Furthermore, it has been possible to use maturity to estimate the compressive strength development of Ordinary Portland Cement (OPC) utilizing ASTM C1074. This is important for contractors as the method provides a way for them to monitor the development of the compressive strength of repair media, thus, knowing when the concrete meets its compressive strength requirement for reopening without the need of expensive tests. Moreover, there are Bluetooth based maturity sensors in the market (around US$87 per unit) that measure maturity of the mixture and estimate compressive strength in situ utilizing ASTM C1074. These sensors are the next step for contractors, as they can monitor the compressive strength of their repair in real-time utilizing a smartphone application, providing them with the ability to open roads back to the public as soon as target strengths are met. The maturity method has been proven to efficiently predict compressive strength of OPC, and until now, it has been limited to only OPC, precluding the use of the method with other types of rapid repair media. However, if the maturity method could be extended to other types of rapid repair media, it would set a precedent for contractors to utilize more advantageous types of materials for their repairs, enabling other more efficient materials to be considered and utilized.Transportation has always been and will continue to be essential to society.

1.2 Scope of Dissertation

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, it 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).

Two main types of cements will be considered: Ordinary Portland Cement (OPC) and Calcium Sulfoaluminate (CSA) cement. OPC is the most common cement utilized for repairs, it is cheap, has relatively high setting times, offers good workability, but it demands high amounts of energy to be produced and needs admixtures to attain higher compressive strengths. CSA, despite its high cost and low setting times, offers rapid hydration, high early strength without the use of admixtures, potentially good volume stability and a lower carbon footprint compared to OPC. High early strength is often desired of rapid repair media, as the need to re-open the repaired area as early as possible is a priority. Currently, CSA is seldom utilized and it is employed mostly as rapid pavement repair material. However, CSA has the potential to be utilized in more areas of civil engineering such as precasting, if methods to combat its disadvantages are researched. OPC properties have often been object of study, thus, more emphasis will be given to CSA cement in this research for its novelty factor compared to OPC.

Experimental matrices were designed to test the mixtures presented in this dissertation. These matrices aimed to investigate fresh, mechanical and volumetric properties of the concrete or mortar mixtures. Also, one experimental matrix included a temperature history of the mixtures. This was included in order to calculate the maturity of the mixtures. Maturity of concrete has been researched in the past (Carino N. , 1984) (Carino & Tank, 1992) (Kim, Moon, & Eo, 1998), because of its capacity of estimating concrete compressive strength. Civil engineers have utilized maturity to predict compressive strength of OPC mixtures in the past (not as much CSA) (Jin, Seung, Choi, & Yeon, 2017) (Perry, Fusiek, Niewczas, Rubert, & McAlorum, 2017), and have obtained good results. Utilizing this method has permitted civil engineers to preclude high amounts of concrete cylinders for compressive strength testing, thus, reducing costs in their projects. Determining if the same could be applied to CSA, would be beneficial to civil engineering because it would provide a non-destructive method to test for compressive strength of rapid repair media, reduce costs and provide a faster re-opening in time-sensitive repair projects.

1.3 Research Objectives

This dissertation asserts specific properties of OPC and CSA concrete and mortars, which represent how these are suited for rapid repair media. Properties such as compressive strength, elastic modulus, drying, autogenous and restrained shrinkage, setting time, temperature and freeze thaw, are some of the ones presented. Focusing in rapid concrete repair, early re-opening times for repaired areas, volume compatibility, retarding workability of concrete for placing concrete and in response to the need for development of performance-based acceptance criteria for rapid concrete pavement repair media. Three big research questions were chosen:

1. How could this research improve current repair materials and practice?
2. Understanding the exceptional properties and disadvantages of CSA, could it be possible to make it workable enough for a contractor to utilize it for large scale rapid repairs, pre-casting or other applications?
3. No research up to this day had considered the maturity of CSA for compressive strength estimation. Could the maturity of CSA be a significant predictor of compressive strength, and thus, provide the same benefits that currently this method has for OPC?

After preparing these research questions, which would be the guidelines of the project, the following research objectives are selected as tools to answer them:

- 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
- Develop nonproprietary concrete rapid repair media that meet the identified acceptance criteria utilizing either OPC or CSA cement

- Optimize the fresh, mechanical and volumetric properties of selected rapid repair media

1.4 Research Plan and Progression

The first step of this dissertation was to compile the state of the art of repair concrete research to understand what had been done previously and to extract materials and practices utilized in recent times (Chapter 1). Following the literature review of repair concrete, an interesting practice was selected: Internal Curing, and thus, another literature review was conducted (Chapter 2). With enough information on the topics at hand and having fulfilled the first objective, the project moved to obtain information about current practices and future needs regarding rapid concrete pavement repair media from DOTs in the United States. Analyzing survey results, performance criteria was identified and, soon after, proprietary mixtures were prepared and tested to measure their properties. Next, non-proprietary mixtures would follow, aiming to meet the established performance criteria. The result of the survey analysis, these mixtures, which utilized either OPC or CSA, with and without internal curing, their tests results, observations and discussions are listed in Chapter 3. In Chapter 4, the research project moved into a different direction, trying to optimize the fresh, mechanical and volumetric properties of the rapid repair media, taking what was learned on Chapter 3 into consideration. Chapter 3 mixtures exhibited fast setting times, which could prove impractical on the field. Chapter 4 dived into extending the short setting time exhibited by CSA mixtures utilizing admixtures. The chapter also focused on measuring compressive strength development, obtaining the thermal history of the mixtures and computing the maturity of each one, utilizing statistical analysis to find relationships between these variables, aiming to find any relation between maturity and compressive strength of CSA mixtures.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Rapid Repair Pavement Repair Concrete

Concrete is inherently a durable material; however, this durability varies under any given set of exposure conditions, the presence and the localization of the reinforcement (e.g., flexural, shear, torsion) and the detailing, placing, finishing, curing and protection it receives. In service, it 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).

Concrete used for rapid repair applications must meet minimum strength levels before the pavement can be opened to traffic, the building to the people, the bridge to the transportation vehicles, etc. Minimum strength levels are important for repair concrete, but even more important is the initial rate of strength gain. This is typically obtained by using a high cement content, low water-cement ratio (w/c), and accelerating admixtures. Proprietary products such as sulfoaluminate, magnesium phosphate, or other special or blended cement systems may be used for even more rapid rates of strength gain. Requirements for strength at opening be achieved, but later-age strength and durability must also be adequate to ensure long term performance of the repair (10 years or more) (Whiting, Nagi, & Okamoto, 1994).

2.1.1 Repair Concrete Design

Design of repair concrete was usually based on experience of specialist contractors and making emphasis in the selection of repair materials was given to relatively short-term properties, such as strength, bond and early age plastic shrinkage/expansion. Although these properties indicate the immediate performance of the repair, they gave little information on its long-term performance with respect to cracking and efficient composite action with the substrate material to carry applied loads and deformations. It is generally accepted that deterioration processes in concrete structures, such as reinforcement corrosion, can be determined largely by the ability of the cover zone material to resist the ingress of deleterious agents from the environment. Thus, the permeability of repair materials should provide an indicator of durability against reinforcement corrosion of repaired elements (Mangat & Limbachiya, 1995).

2.1.2 Repair Media Properties

During visual inspections, structural deficiencies on concrete pavement are commonly observed. Investigating their causes can be difficult as many different factors can be considered. The right tools can help determine the cause of cracking and offer guidance to engineers to select a repair media. Researchers have seen the effect of thermal distress (Maguire, Roberts-Wollmann, & Cousins, 2018), concrete deck deterioration (Pettigrew, Barr, Maguire, & Halling, 2017), strand stresses (Maguire, Collins, Halbe, & Roberts-Wollmann, 2016), bond properties (Morcous, Hatami, Maguire, Hanna, & Tadros, 2012), and more on concrete, providing insight on what can cause structural deficiencies that may lead to repair.

Cabrera and Al-Hassan explained that engineers were faced with a wide choice of materials and little guidance on their properties, and short and long-term performance. Engineers often choose materials having properties as close as possible to those of the base concrete. Since disclosure of the composition of a repair material is not realistically possible there is need to establish a set of requirements which should be based on performance related properties (Cabrera & Al-Hassan, 1997).

When planning a concrete repair, various options must be considered and the best type of material to implement in the repair or rehabilitation of concrete structures must be evaluated thoroughly. Compressive strength, modulus of elasticity, thermal expansion bonding, drying shrinkage, creep and permeability are the most important properties to take into account (Woodson, 2011).

At the beginning of repairing concrete, engineers used conventional Portland cement-based concretes, mortars and grouts to repair concrete, however since about the 1960's, a plethora of new enhanced concrete repair materials and systems have been introduced and found increasing utilization 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).

The plain cementitious mortar will probably have mechanical properties closest to most substrate concretes. Some would argue that it is thus the most appropriate repair material to use to attain compatibility between the repair and surrounding concrete. Certain kinds of repair need specific repair material properties in order to provide the best remedial solution. For example, (Morgan, 1996):

- If the original concrete has deteriorated as a result of aggressive exposure conditions, it may be more appropriate to use a higher strength and more chemically resistant resin mortar (polymer concrete) for the repair.
- If thin hand-applied repairs are proposed for vertical or overhead surfaces, then a polymer modified cementitious mortar, with superior adhesion, cohesion and thickness of build-up characteristics may be a more suitable repair material choice.
- If repair is required to be carried out in below freezing temperatures, or rapid setting and hardening and early strength gain characteristics are required then special repair materials with high early heat of reaction, such as certain resin mortars (i.e. vinyl ester resins), magnesium phosphate cements or accelerated high alumina cements may be required.

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

Repair materials should be compatible or else they will not act together as expected, as the properties of one material could cancel the ones from the other. Compatibility is the balance of physical, chemical and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designated period of time (Emmons, Vaysburd, & McDonald, 1993). Figure 1 shows an adaptation from Emmons et al. of the factors that affect the durability of concrete repairs:

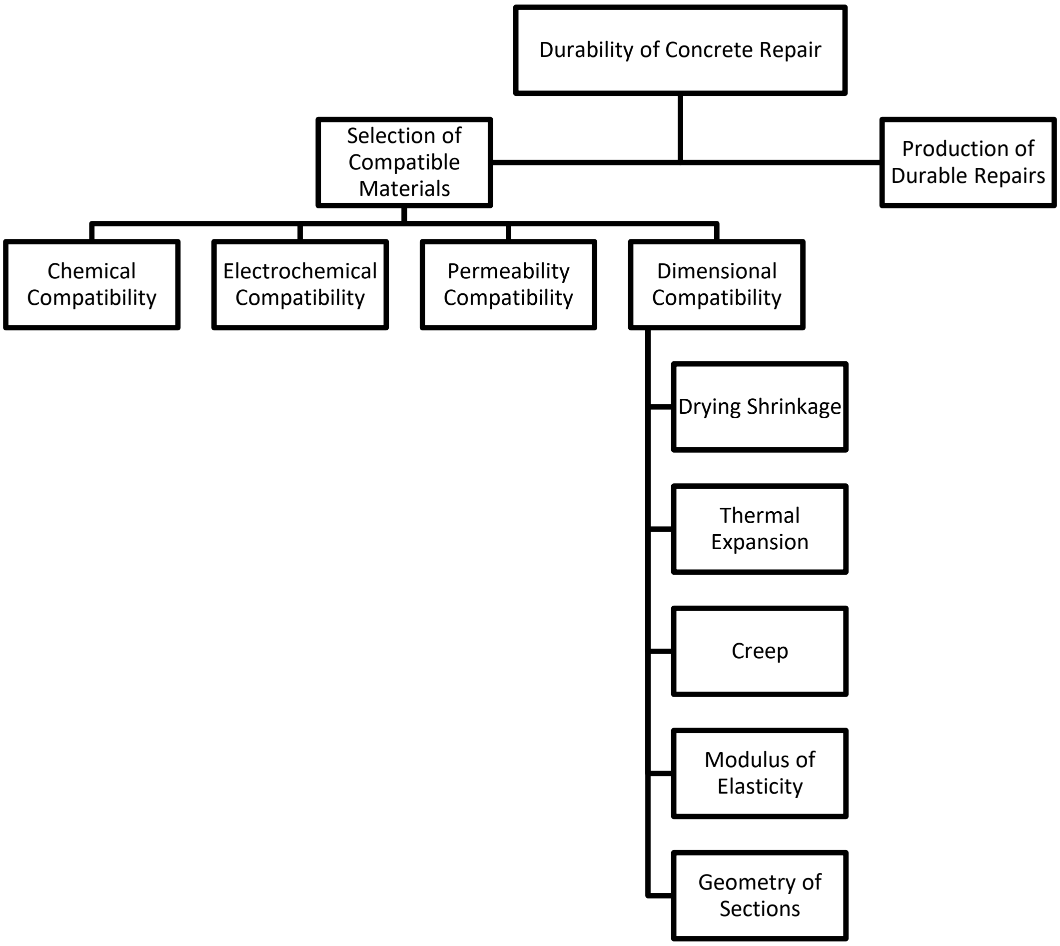

Figure 1 Factors affecting durability of concrete repairs

Of these considerations, probably the most important is the ability of the repaired area to withstand volume changes without loss of bond and delamination; this is commonly referred to as “dimensional compatibility” and includes the ability of the repaired area to carry its shared 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. A lot of parameters influence dimensional compatibility as seen in Figure 1, but also size, shape and thickness of the area being repaired, the amount of reinforcing and anchorage, and strain capacity affect in a way to the dimensional compatibility (Emmons P. , Concrete Repair and maintenance illustrated, 1993). All too often repairs have become debonded as a result of causes such as:

- 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 possess high strain capacity in order to better be able to resist imposed strains without cracking and disruption (Yuan & Marosszeky, 1991). This material therefore would be volumetrically stable, i.e. it would not undergo shrinkage nor expansion once installed and would display similar modulus of elasticity and thermal expansion characteristics to the substrate concrete. As a way to minimize cracking, it should be noted that the inclusion of fibers (steel and synthetic) can be very beneficial, and many repair materials now incorporate fibers (Morgan, 1996).

2.1.3 Bond Strength and Surface Preparation

One of the properties of repair concrete that has been studied the most is bond strength. 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 of the physical and chemical characteristics of the component, but also 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, Peter, & Y, 1999).

There are many different methods that evaluate bond strength for concrete and repair materials. Momayez et al (2004) researched the difference between Pull-Off, Slant Shear and Splitting Prism tests and developed another test: 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 in interface, friction, aggregate interlock and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age and roughness of interface surface. Friction and aggregate interlock on interface depend on aggregate size, shape and surface preparation (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005).

In the field of rehabilitation and strengthening, the bond strength between the new and old concrete generally presents a weak link in the repaired structures (Wall &

Shrive, 1988). The uniqueness of ultra-high-performance concrete (UHPC) is its extremely low porosity gives its low permeability and high durability, making it potentially suitable for rehabilitation and retrofitting reinforced concrete structures. In order to evaluate bond strength, Tayeh et al (2013) suggest that the following tests are performed: Slant shear test and Split test. The Slant Shear test is used to quantify the bond strength in shear, and the Split test to evaluate the bond strength in indirect tension (Tayeh, Abu Bakar, Johari, Voo, & Y, 2013).

Patch Repairs (one of the main processes for repairing concrete structures) are really common when repairing concrete. The efficiency and durability of it depends highly on the bond properties. By increasing surface roughness, the surface treatment of concrete substrate can promote mechanical interlocking that 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 (2013) have investigated the effect of concrete substrate surface preparation for patch repairs and proposed a bond strength estimation and a method for selecting a suitable surface treatment technique (Courard, Piotrowski, & Garbacz, 2014).

The performance of any concrete repair is highly dependent on the quality of bond of the repair material to 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 rely 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 such as (Morgan, 1996):

- 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

The first requirement of a successful repair is that the substrate concrete be properly prepared. Repair materials can be optimized for bond compatibility, strength and durability, however if the substrate concrete is not properly prepared, the repair may be doomed to failure. When preparation of concrete substrates using mechanical removal means such as chipping hammers, scabblers, scarifiers and other impacting devices and it is not followed by sandblasting or high-pressure water blasting, a bruised layer of micro-fractured aggregate and crushed mortar can be left at the exposed surface. This results in a plane of weakness just below the bond interface (Emmons, Vaysburd, & McDonald, 1993) (Mangat & Limbachiya, 1995).

While adequate short-term bond strengths may be achieved with repairs to concrete surface prepared by methods such as wire-brushing, grinding and light-duty sandblasting, the long-term durability of such repairs may be compromised (Talbolt, Pigeon, Beaupré, & Morgan, 1994).

Moisture in the substrate is crucial. For optimal bond compatibility, there is an optimal moisture and temperature condition for the substrate concrete at which maximum bond will be achieved. Based on preconstruction testing and bond pull-off tests conducted on a range of different repair projects, that best bond is achieved when using Portland cement-based materials with concrete substrates which have just dried back from a saturated surface dry condition at the time of application of the repair material. If the concrete substrate is extremely dry, moisture can be absorbed from the repair material, causing desiccation at the bond interface and reduced bond strengths. On the other hand, repair materials should not be applied to surfaces with free surface moisture because this would generate a high water/cement ratio at the bond interface which will have an even more damaging effect on bond strength (Saucier & Pigeon, 1991) (Morgan, 1996) (Pigeon & Saucier, 1991).

2.1.4 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 in Figure 1, set out the general requirements of patch repair materials for structural compatibility. 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).

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 fairly 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 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 (Marosszeky, 1991):

- 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.

Table 1 General requirements of patch repair materials for structural compatibility (Adapted from Emberson and Mays)

Property	**Relationship of Repair (R) to Concrete Substrate (C)**
Strength in Compression, Tension and Flexure	R>=C
Modulus in Compression, Tension and Flexure	R~C
Poisson 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

2.1.5 Electrochemical Compatibility

An important aspect of repair performance relates to the ability of the repair system to inhibit subsequent corrosion of reinforcement, both within the repair area and in the surrounding non-repaired reinforced concrete. Gulikers and var Mier studied the effect of removal of concrete from a corroding area and its replacement with different types of repair materials on subsequent corrosion activity in the patches and surrounding concrete. They arrived to the conclusion that strong galvanic corrosion can develop in unrepaired areas adjacent to the repair patches when repairs are conducted with Portland cement based repair mortars. By contrast they found that polymer concrete repair mortars did not affect corrosion of steel in adjacent unrepaired areas (Gulikers & van Mier, 1991).

Marosszeky and Wang found that styrene butadiene and acrylic modified Portland cement mortars provided greater protection against corrosion developing at the boundary of the original concrete and the repaired patch than ordinary Portland cement repair mortars (Marosszeky & Wang, 1991).

Both preceding studies would indicate that corrosion protection can best be achieved by using polymer concretes or polymer modified Portland cement mortars with high electrical resistivity. Emmons et al. caution that materials that are highly resistive or non-conductive have a tendency to isolate the repaired area from adjacent undamaged areas. They state that large permeability or chloride content differential between the repair and the rest of the concrete, the corrosion becomes concentrated in a restricted area and the rate of corrosion may accelerate, causing premature failure in either the repair or the adjoining concrete (Emmons, Vaysburd, & McDonald, 1994).

Researchers tend to recommend the use of repair materials of similar composition, density and permeability to the surrounding concrete in the repair area in order to maximize electrochemical compatibility (Woodson, 2011) (Morgan, 1996) (Saucier & Pigeon, 1991).

2.1.6 New Materials in Present Day Practice

One of the materials being used for repairing structures are polymer-based concretes. These have exceptional physical and chemical properties, such as low permeability to ingress of chlorides and other aggressive chemicals, ability to rapidly set and harden (even in below freezing temperatures for certain polymers) and for the structure to be quickly returned to service, excellent chemical resistance to attack from many aggressive chemicals and the ability to be applied in much thinner layers/sections than Portland cement based repair concretes (Emberson & Mays, 1990) (Morgan, 1996).

They are able to work as repair materials in certain applications because of the generally superior tensile, adhesive and shear bond strength compared to most cementitious materials, low values of total shrinkage, and the ability to redistribute stresses at the bond interface over time through creep relaxation. Polymer concrete repairs are, nonetheless, more complex to design, particularly in load-bearing situations. Their design should be generally avoided in thick sections, where stresses imposed by high heat of reaction and thermal expansion/contraction and modulus effects can lead to either bond or substrate failures (Marosszeky, 1991). Table 2 basically reviews some studies performed in recent years regarding new materials in repair concrete.

2.1.7 Performance, Durability and Strength

The future of the concrete repair industry appears to be promising and bright, judging from the projections based on current trends in repair, rehabilitation, restoration and strengthening of existing infrastructure. However, this optimism must be tempered in light of the need to change the image of the industry as one that is often self-serving (Vaysburd & Emmons, 2000).

Table 2 Summary of research of new repair materials

References	Type of Research	General Conclusions
(Ming-zhe, Li-jun, & Quan-xin, 2008)	Size effect on compressive strength of reactive powder concrete (RPC)	The size effect of compressive strength of RPC is inversely proportional: the bigger the size, the lower the strength Can be used for repair materials
(Wang, Helene, & Monteiro, 2006)	Potential use of zinc in the repair of corroded reinforced concrete	The effectiveness of zinc in the prevention of further corrosion may be influenced by various factors, such as leaking joint, zinc-steel contact area, and alkalinity of concrete pore solution.
(Martinola, Meda, Plizzari, & Rinaldi, 2010)	Strengthening and repair of RC beams with fiber reinforced concrete	The proposed technique provides a significant structural enhancement at the serviceability limit state. Due to self-leveling property, the material can be cast in a thin layer and a normal sandblasting ensures good adhesion
(Tittleboom, De Belie, De Muynck, & Verstraete, 2010)	Use of bacteria to repair cracks in concrete	Some form of enhanced crack repair might be obtained through a biological treatment in which a B.sphaericus culture is incorporated in a gel matrix and a calcium source is provided. Crack sealing by means of this biological treatment resulted in a decrease in water permeability.
(Galvão, Portella, Joukoski, & Mendes, 2011)	Use of waste polymers in concrete for repair of dam hydraulic surfaces	The addition of polymeric waste and elastomer materials reduced the workability of the fresh concrete. The use of plasticizing additive contributed in providing the concrete with the desired consistency and workability. The compressive strength was reduced with the increase of the additive.
(Xion, Wu, Li, & Yan, 2011)	Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars	The strength, ductility and energy absorption capacity of existing concrete columns can be simultaneously enhanced significantly by constructing additional ferrocement cage including steel bars. The ductility of FS confined columns is obviously higher than those of BM or FRP confined columns.
(Haddad, Al-Rousan, & Al-Sedyiri, 20113)	Repair of shear-deficient and sulfate-damaged reinforced concrete beams using FRP (fiber reinforced polymers) composites	With CFRP sheets RC repaired beams showed the best performance reaching almost that of undamaged control RC beam, followed by those repaired with GFRP sheet. FRP increased crack resistance and delayed the onset of initial flexural and shear cracking.

Table 2 continued

(Huang, Ranade, Ni, & Li, 2013)	On the use of recycled tire rubber to develop low E-modulus ECC for durable concrete repairs	Incorporating tire rubber in ECC mixtures reduces elastic modulus significantly (by over 50%) which enhances cracking resistance by lowering the tensile stress induced by restrained shrinkage. Tire rubber is an effective solution to reduce the crack tendency in terms of crack initiation time and crack number.
(Mechtcherine, 2013)	Novel cement-based composites for the strengthening and repair of concrete structures	Strengthening with textile-reinforced concrete (TRC) provides a significant increase in the ultimate load of existing structures. Its application is simple and can be adapted to complex geometric forms. Strain-hardening cement-based composites (SHCCs) layers increases the resistance of existing RC to dynamic, energetic loading as with earthquakes, impact or exposures. Both materials exhibit high deformability due to fine, well distributed cracking, the repair layers made of such materials are suited to the bridging of existing and future cracks in the substrate.
(Christodoulou, Goodier, Austin, Glass, & Webb, 2014)	A new arrangement of galvanic anodes for the repair of reinforced concrete structures	Galvanic anodes installed within an area of patch repair can provide substantial protection to the steel reinforcement in the parent concrete outside the repair. BS EN 1504 (A repair material) will not affect the performance of galvanic anodes installed in parent concrete around the edge of the repair. It localizes active corrosion spots.

Due to the increasing public concern with durability of concrete structures in general and repair/ed concrete structures in particular; a lot of structural illness are discussed and researched by engineers. Table 3 shows a summary of research done recently regarding increasing performance, durability and strength of repair concrete.

2.1.8 Conclusions

This section meant to show an updated status of the repair concrete industry. Structures, like anything man-made, deteriorate over time. Every now and then, these structures will need maintenance and repair. There are many materials available for these repairs, ranging from normal Portland cement-based to magnesium phosphate cement paste.

Table 3 Summary of research of performance, durability and strength

Reference	**Type of Research**	**General Conclusions**
(Sharif, Rahman, Al-Gahtani, & Hameeduddin, 2006)	Behaviour of patch repair of axially loaded reinforced concrete beams	For concrete columns which are repaired in an unleaded state, the patch repair is structurally effective and carries the loads once the columns are reloaded. It is highly recommended to relieve all loads from the columns and then proceed with repairs, or at least partially relieved.
(Taffese & Sistonen, 2013)	Service Life Prediction of Repaired Structures using concrete recasting method	Efficient mechanisms that can predict the service life of repaired concrete structure are highly desired. Existent models are based on numerical methods that simulate the corrosion processes of reinforcement steel. Modeling techniques should be able to deal with the nonlinear behavior of several complex interacting factors.
(Banthia, Zanotti, & Sappakittipakorn, 2014)	Sustainable fiber reinforced concrete for repair applications	Of the four major requirements for any repair material, fiber reinforced concrete meets all of them. It is able to arrest further deterioration, it is adequately impermeable to aggressive liquids and gases, able to bond properly and restore structural integrity. Also it has chemical, electrochemical, permeability and dimensional compatibility with old concrete substrate.
(Sciumè, et al., 2013)	A multi-physics model for concrete at early age applied to repair problems	A numerical model for repair concrete at early age was developed. This model uses the desorption isotherm taking into account its dependence on the hydration degree of concrete, autogenous shrinkage, mechanical damage and the 3D implementation are all input variables of the model. The model will be revised in the future for other cases of practical interest: massive structures, pre-stressed, post-stressed and reinforced concrete structures in general.
(Chen, Zhou, Yi, & Won, 2014)	Full-depth concrete pavement repair with steel reinforcement	The performance of FDR (conventional method) was quite poor, with new repairs needed just one year after. Resilient modulus values derived from DCP testing results were much lower than those in decent base and subgrade layers.

Table 3 continued

(Song, Wei, & He, 2009)	A method to repair concrete leakage through cracks by synthesizing super-absorbent resin in situ	The solution of polymer (acrylic acid-co-acrylamide) has the lower viscosity and higher osmosis, so it is adaptable to repair cracks of concrete structures, especially microcracks or even invisible cracks. The SAR synthesized in situ can firmly adhere to the pores of concrete by chemical bond. It has high absorbency for different aqueous solution which is fit to repair the dynamic deformation cracks.
(Nobili, Lanzoni, & Tarantino, 2013)	Experimental investigation and monitoring of a polypropylene-based fiber reinforced concrete road pavement	It is shown that strain levels in the pavement rest very near to the initial pre-service condition and they are fairly consistent in space and time.Overall behavior of the pavement appears almost invariable in time and the monitoring results support the validity of this design scheme for a PFRC road pavement.
(Li, Zhang, & Cao, 2014)	Laboratory evaluation of magnesium phosphate cement paste and mortar for rapid repair of cement concrete pavement	MPC paste exhibits excellent earlier strength gain. Both water resistance and toughness of could be improved substantially by blending with crumb rubber.Additionally, silica sol could greatly increase strength due to the consequent particles size optimization and reaction of silica sol with the unhydrated MgO.

Chemical, mineral, traditional, and creative mixtures have been designed in furtherance of optimizing the properties of repair concrete. Performance, early strength and durability are the primary properties that researchers have as an objective in their investigations. There is still not an all-around mixture that would satisfy all conditions for repair. Although this is yet to be discovered, different approaches have been demonstrated to be satisfactory in most cases. Future work should be focused in early strength mixtures, a need in this fast-paced world, improving durability and performance of mixtures and also developing even new procedures for repairing concrete. Concrete will always deteriorate, thus there will always be a need for repairing it.

2.2 Internal Curing

In this century, Internal Curing (IC) has appeared as an innovative technology that holds promise for producing concrete with increased resistance to early-age cracking and enhanced durability. The service life of concrete is a key component of its quality. This quality is related to providing a sustainable infrastructure capability for construction. In 2013, the American Concrete Institute (ACI) defined IC in its Terminology Guide as “process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water” (ACI, 2013).

This concept clearly identifies the two main goals of IC: increasing hydration to a maximum and decreasing self-desiccation to a minimum. IC is a procedure that reduces the stresses that accompany self-desiccation and that also may produce early-age cracking.

One of the main components of IC is Pre-saturated lightweight aggregates (PSLWA). In IC, the aggregates are not considered to be inert; rather they play an integral role in the development of the paste microstructure, fundamentally in the hydration of the concrete paste (Henkensiefken R. , 2008). The PSWLA possess high moisture content, are porous aggregates and are uniformly distributed throughout the concrete mixture and they act as an internal water reservoir (Weber & Reinhardt, 1997). The reason why PSLWA are used in IC is because they can be used as internal reservoirs that can reduce the pressure in the pore fluid by replenishing the vapor-filled voids. Water absorbed by PSLWA before setting of the concrete does not influence the porosity of the paste and therefore is not considered to be part of the w/c ratio of a given concrete mixture (Castro, Keiser, Golias, & Weiss, 2011), (Bentz & Snyder, 1999) & (Henkensiefken, Nantung, & Weiss, 2009). These lightweight aggregates have created an interesting amount of concern in the past 16 years, because their application improves the workability, strength and resistance to freezing and thawing of lightweight aggregate concrete (Kohno, Okamoto, Isikawa, Sibata, & Mori, 1999).

The PSLWA have a low particle density due to their internal cellular pore system. Strong, durable, ceramic lightweight aggregates contain a relatively uniformly distributed system of pores that have a size range of approximately 5 to 300 μm. Pores close to the surface are readily permeable and fill within the first few hours of exposure to moisture. Interior pores, on the other hand, fill extremely slowly (Holm, Ooi, & Bremner, 2004).

2.2.1 Internal Curing Evolution

Lightweight concrete has usually included IC, even if when the engineering world began using them, they did so without knowing. Since lightweight concrete is an essential part of IC, it is good to review part of its history. This type of concrete using natural lightweight aggregate is first found in Ancient Rome, with one of the most well-known examples being the Pantheon in Rome. The dome of the Pantheon was built using lightweight concrete with vesicular aggregates from natural origin, and the density of the concrete was reduced as its height within the dome increased (Bremner, 2009).

Reinforced concrete development gave birth to research for the manufacture of artificial aggregates due to the rarity of natural porous aggregates deposits (Clarke, 2002). Lightweight aggregates (LWA) were researched and developed in the United States by Stephen Hayde. He received a patent to create a firing process to produce LWA from clay, shale and slate rocks in 1918. World War I was the stage in which

Hayde decided to give the United States permission to use HIS patent at no cost in the production of LWA for concrete ships. Not only these concrete ships, but many bridge structures that were produced during that time, provided around fifty years of service and had become a testimony that lightweight concrete made with these aggregates possessed high durability (Bremner, 2009). At this time, IC wasn't recognized as responsible of this performance until many years later.

One of the first publications known to the Engineering world regarding internal curingthe potential of lightweight aggregates stated that utilizing water for curing at early ages can be precluded when utilizing lightweight aggregates, because of their absorption and desorption properties (Klieger, 1958).

Philleo, in his search for proper curing and avoidance of self-desiccation in high strength concrete, based on Klieger's research, found that internal curing was vital in order to reduce shrinkage in concrete. (Philleo, 1991). In the 90's, the investigation regarding IC had spread along other countries besides the United States. Basic research of IC was done between 1957 and the early 2000's. Some researchers who followed through Philleo's concept by actively conducting investigations regarding internal curing using PSLWA, worked in Germany (Weber & Reinhardt, 1997) and the Netherlands (van Breugel, 2000). At the end of the 2000's more research in the field was done. Materials that weren't being considered to be part of a concrete mixture became interesting for researchers, such as Super Absorbent Polymers (Dudziak & Mechtcherine, 2008) and wood-derived powders and fibers in order to mitigate self-desiccation and autogenous shrinkage (Mohr, Premenko, & Nanko, 2005). A lot of technologies have been developed since the beginning of the

IC’s history; however, research has shown that the path from theory to practice has not been easy.

PSLWA are generally produced by artificial means. They are obtained by expanding, calcining, or sintering materials such as blast-furnace slag, shale, slate, clay, diatomite, and others (Clarke, 2002). Differences in the elastic properties of lightweight aggregate can cause more change in strength and elasticity of the concrete than those of the heavier natural aggregates such as gravels and crushed stones (Klieger, 1958). In 1964, Landgren, R. conducted an investigation regarding the water-vapor absorption and desorption characteristics of selected lightweight concrete aggregates, in which he determined the water-vapor absorption-desorption isotherms for fifteen different lightweight aggregates, and there internal surface areas were calculated. Although PSLWA possessed inherent high porosity, they possessed surface areas comparable to the surface areas of equal weights of dense concrete aggregates. Landgren found out that the amount of absorbed water held by these lightweight aggregates, when dried to equilibrium at relative humidities less than 75 percent, is extremely small compared to the amounts of water absorbed by the same weight aggregates when immersed in water (Landgren, 1964). Typical water-absorption rates have been reported to be 5% and 15% (Alexander & Mindess, 2010). PSLWA provide water that is only a fraction of the theoretical saturation that “the use of the ASTM expression ‘saturated surface dry (SSD)’ is inappropriate for lightweight aggregate, theoretically inaccurate and analytically misleading” (Holm, Ooi, & Bremner, 2004).

Several researchers have investigated the desorption properties of lightweight aggregate. In 1964, Landgren studied the water absorption properties of a group of fifteen lightweight aggregates. Landgren confirmed that the large, surface exposed pores of lightweight aggregates are responsible for difficulties in obtaining reliable data on water absorption of lightweight aggregate. He discovered that the pores may be partially filled by cement paste and other fine material during mixing of concrete (Landgren, 1964). The scope of this project was useful to the United States because it was used to determine the internal surface area of the lightweight aggregate as well as the susceptibility of these to fire or freeze-thaw damage (Castro, Keiser, Golias, & Weiss, 2011).

2.2.2 Advantages

Internal curing is especially beneficial in low w/c ratio (w/c) concretes because of the chemical shrinkage that accompanies Portland cement hydration and the low permeability of the calcium-silicate hydrates (Bentz, Lura, & Roberts, 2005). Water that is chemically bound and absorbed by the cement hydration products has a specific volume less than that of bulk water, a hydrating cement paste will drain water (around 0.07g water/ g cement) from an available source (Geiker, Studies of Portland Cement Hydration: Measurement of Chemical Shrinkage and a Systematic Evaluation of Hydration Curves by Means of the Dispersion Model, 1983). While in higher w/c concretes is usually supplied by external curing, in low w/c concretes, the permeability of the concrete becomes too low to allow effective transfer of water from the surface to the concrete interior (Bentz & Snyder, 1999).

The physical properties of the PSLWA, such as mechanical strength, particle shape, and particle grading, influence the properties of both fresh and hardened concrete. To maximize the performance of IC in the concrete system, PSLWA with similar aforementioned properties are preferable. Low w/c ratio concrete mixtures are increasingly promoted for use in civil engineering infrastructure due to potential improvements in strength and durability. One of the disadvantages of low w/c mixtures is the susceptibility to early-age cracking caused by autogenous shrinkage. Using IC techniques, shrinkage can be reduced to counter these effects. With IC, the PSLWA will supply water to counteract the effect of self-desiccation after the initial pore structure of the paste has formed (Henkensiefken R. , 2008).

High Strength/High Performance Concrete (HSC/HPC) and Ultra-High-Performance Concrete (UHPC) have become objects of intense research due to their advantages: high compressive strength to density ratio, high durability, favorable workability, and others which justify the use of the term “high performance”. However, in order to achieve these kinds of concretes, the mixture needs a very low w/c ratio (below 0.4) (Dudziak & Mechtcherine, 2008). IC is an important mechanism which can mitigate curing and shrinkage, to investigate in combination with these low w/c mixtures. Furthermore, the result of using PSLWA is a concrete that is not sensitive to deficient curing. Poor curing is a major factor in structural durability, specifically for bridge decks. The result of a structure with iced hardened cement paste is more compact and fewer micro-cracks are observed (Weber & Reinhardt, 1997). Recent work has demonstrated benefits of internal curing for reducing drying shrinkage, drying shrinkage cracking, reducing the likelihood of thermal cracking, improved plastic shrinkage cracking resistance, improved freeze-thaw resistance, increase the resistance to fluid absorption, and reduce ion diffusion in concrete (Castro, Keiser, Golias, & Weiss, 2011).

2.2.3 Mechanisms

External curing cannot reach deep inside the concrete once it sets, but water absorbed by the PSLWA will be available to the cement paste providing a better and more distributed curing (see Figure 2). The volume of water in the PSLWA that must be available for the mixture is the difference between the absorption capacity of the PSLWA and the total water needed by the paste. The absorption capacity of the PSLWA is the volume of water available for the mixture. The volume of chemical shrinkage may be approximated as the volume of water that needs to be supplied by the IC agent (Henkensiefken R. e., 2009). The cement reaction and hydration process are the reason why IC is needed. Inside a concrete mixture, water reacts to form crystalline and gel hydration products, the water incorporated into these hydration products occupies less space than water in its bulk form. Water leaves the PSLWA due to pressure developed in the pore fluid due to chemical shrinkage and self-desiccation. Consequently, the movement from the water inside the PSLWA to the surrounding paste is often quantified in concrete as an increase in internal relative humidity and an increase in the critical pore size that remains saturated (Lura, 2003).

Aggregate distribution becomes a key factor because of the specific way water travels through the system. A poor distribution and the concrete will likely show poor shrinkage performance. When comparing the effectiveness of coarse and fine PSLWA, keeping water content constant, with equal PSLWA volumes, the SLWA particles distribution will be significantly different, resulting in a different volume of protected paste (Zhutovsky, Kovler, & Bentur, 2002). The protected paste concept is conventionally applied to characterizing air void systems in air-entrained concrete. In

IC, the protected paste is the volume fraction of the paste within a distance from a PSLWA particle that cannot be penetrated by water.

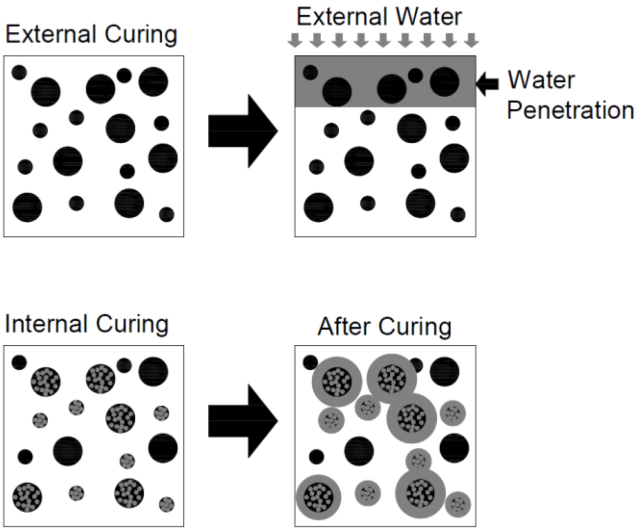

Figure 2 Difference between External and Internal Curing

After the paste sets and develops a finite resistance to being deformed, the chemical shrinkage in the absence of an additional source of water will produce a self-desiccation, as partially filled pores will be created within the microstructure of the concrete (Lura, Couch, Jensen, & Weiss, 2009).

During the hydration process shortage of water can occur, such that water from the exterior does not reach the interior of a concrete member to ensure complete hydration. This unfavorable effect can negatively affect the concrete mechanical and durability properties. External moist curing methods do not noticeably improve the properties of high strength concrete (Weber & Reinhardt, 1997). External water only penetrates a few millimeters into the concrete from curing-applied surfaces, while the interior of the concrete undergoes substantial self-desiccation (Bentz, Geiker, & Jensen, 2002). The goal of internal curing is to provide additional water to the mixture, where needed such that the hydrating cement paste microstructure remains saturated with minimized autogenous shrinkage.

2.2.4 Proportioning Mixtures

Mixture proportioning with IC provides water needed to extend saturated conditions within the hydrating cement paste. Therefore, IC contributes to an increase in the degree of reaction of the cement and any pozzolans, and also of the development of autogenous shrinkage minimization.

Not all water in the PSLWA is available during curing of the concrete. As water surrounding PSLWA migrates to a nearby hydrating cement particle, the water absorbed by the PSLWA replaces the migrating water. This process maintains saturated conditions within the hydrating cement paste and develops unsaturated conditions within the PSLWA particles. The PSLWA water content required to eliminate self-desiccation by the internal water for IC can be calculated (see Equation 1) (Zhutovsky, Kovler, & Bentur, 2002):

$$PSLWA = \frac{W_{cur}}{\Phi_{PSLWA} * S * n}$$

Equation 1 Zhutovsky et al. equation to determine PSLWA required water content

Where: Φ_{PSLWA} is the aggregate water absorption by weight (mass water per mass of dry LWA); S is degree of saturation of aggregate; n is the efficiency factor (i.e., the fraction of water absorbed in a saturated aggregate that can counteract self-desiccation).

The optimum amount of lightweight aggregate used to supply moisture is a function of the LWA properties, the w/c, the binders in the mixture, rate of desorption from the PSLWA and external moist curing (Hoff, 2003) & (ACI Committee 308;

ACI Committee 213, 2013). Equation 2 calculates the LWA mass required (Bentz & Snyder, 1999), (Bentz, Lura, & Roberts, 2005) & (Bentz & Weiss, 2010):

$$M_{LWA} = \frac{C_f * CS * \alpha_{max}}{S * \Phi_{LWA}}$$

Equation 2 LWA Mass equation

Where: mass of (dry) fine LWA needed per unit volume of concrete (kg/m^3 or lb/yd^3), M_{LWA} , cement factor (content) for concrete mixture (kg/m^3 or lb/yd^3), C_f, chemical shrinkage of cement ratio (g of water/g of cement or lb/lb), CS, maximum expected degree of hydration of cement, α_{max}, degree of saturation of aggregate (0 to 1), S, absorption of lightweight aggregate, Φ_{LWA}.

For a pure Portland cement, with w/c below 0.36, the maximum expected degree of hydration under saturated conditions can be estimated as w/c divided by 0.36 (Bentz D. , Jones, Peltz, & Stutzman, 2015). Furthermore, the densities of the dry lightweight aggregates and the conventional aggregates are substantially different suggest that the ultimate substitution in the concrete mixture should be performed on a volume basis. The determined mass of lightweight aggregates from Equation 2 should replace the same volume of conventional aggregates. Knowing the aggregate dry densities one can determine the mass of conventional aggregates to be removed, which will be more than the LWA mass determined by Equation 2.

When the binder is a binary or ternary blend, the numerator in Equation 2 can be replaced by a summation of the individual water demands for each of the binder components (i = 1,2,3 for cement, fly ash, and slag, for example) (Bentz & Weiss, 2010):

$$Water\ Demand = \sum_i C_f^i * CS^i * \alpha_{max}^i$$

Equation 3 Water demand equation for each of the binder components

Typically, chemical shrinkage for Portland Cement is on the order of 0.07 mL/g cement. However, the values for fly ash and slag can be two and three times greater, respectively (Bentz D. P., 2007). Table 4 shows previously calculated CS coefficients. To characterize the absorption of the aggregates (Φ_{LWA}) at complete saturation (S = 1), fully saturated LWA can be exposed to environments with known equilibrium RH that are maintained via saturated salt solutions. The water that escapes from the PSLWA in these exposures provides the value for Φ_{LWA} (at S = 1) that should be used in Equation 1 and/or Equation 2.

Table 4 Calculated coefficients for chemical shrinkage due to cement hydration (Bentz, Lura, & Roberts, 2005)

Cement Phase	***Coefficient, g water/ g solid cement phase***
C3S	*0.0704*
C2S	*0.0724*
C3A	*0.171* 0.115*
C3AF	*0.117* 0.086*
Silica Fume	*0.2*

The gradation of NWA used for a normal concrete mixture needs to be replaced such that the final overall gradation is conducive for quality concrete (ACI, 2013). Often this is best achieved by selecting LWA with a similar gradation to the NWA to be replaced. It is also possible to select LWA grading specifically to compensate for deficiencies in the NWA grading, which would otherwise produce a gap-graded mixture (Villareal & Crocker, 2007).

Note that Equation 2 provides a starting point to estimate of the PSLWA required to supply absorbed moisture to the concrete paste. The equation does not account for several issues related to autogenous shrinkage in concrete formulated with PSLWA including, but not limited to (ACI Committee 308; ACI Committee 213, 2013):

- Absorbed moisture loss from PSLWA from mixing, transportation and placement of the concrete there could be loss of some absorbed moisture from the aggregates.
- An insufficient spatial distribution of the lightweight aggregates within the concrete microstructure (Bentz & Snyder, 1999).
- Autogenous shrinkage from pozzolanic materials and calcium hydroxide rather than self-desiccation (Bentz D. P., 2007)
- Effects of other strains in concrete, such as drying shrinkage strains and thermal strains (ACI Committee 308; ACI Committee 213, 2013).

From Figure 3 to Figure 8, diagrams for mixture proportioning are provided. These Figures provide graphical representation of Equation 2 and Equation 3.

2.2.5 Proportioning Concerns

Providing too much water (overcuring) or insufficient water (undercuring) is also an important consideration. Overcuring may occur when water ponding or wet burlap is used to provide external curing to a concrete member proportioned with IC. Undercuring may occur when the water provided by IC is less than that recommended by Equation 2 and only partially maintains saturated conditions over time.

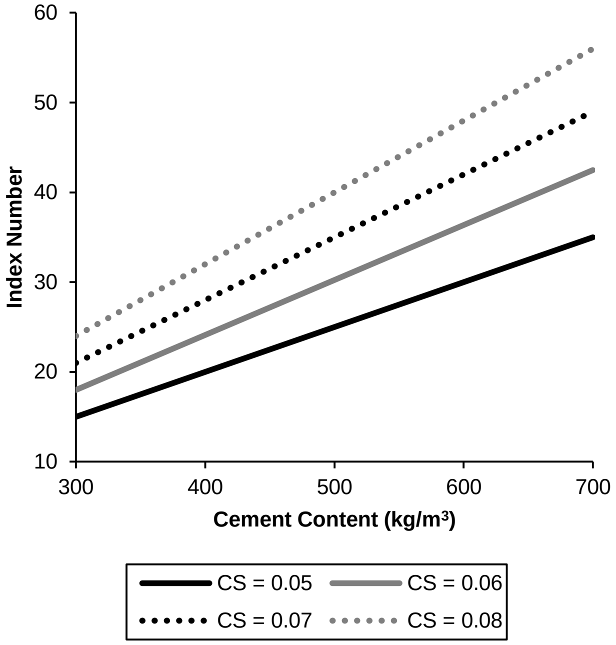

Figure 3 Chemical shrinkage of the mixture according to the cement content (kg/m^3). (Adapted from (ACI Committee 308; ACI Committee 213, 2013))

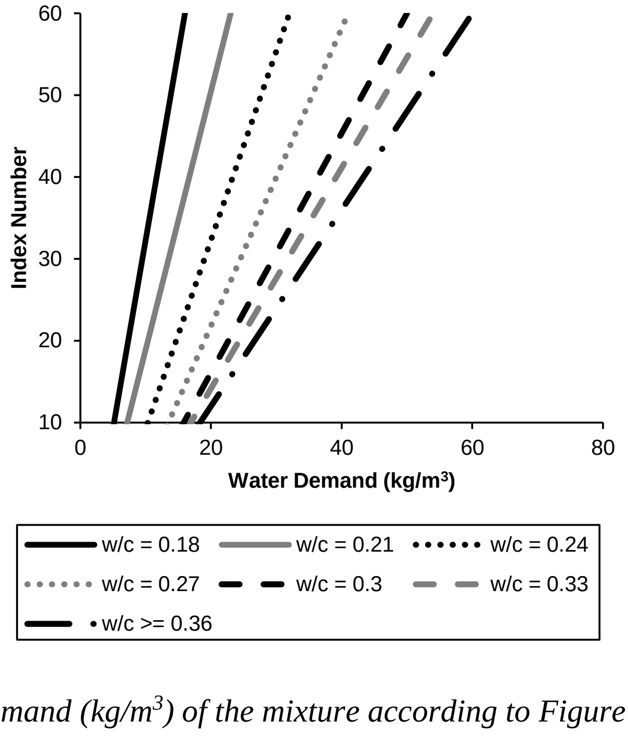

Figure 4 Water demand (kg/m^3) of the mixture according to Figure 3. (Adapted from (ACI Committee 308; ACI Committee 213, 2013))

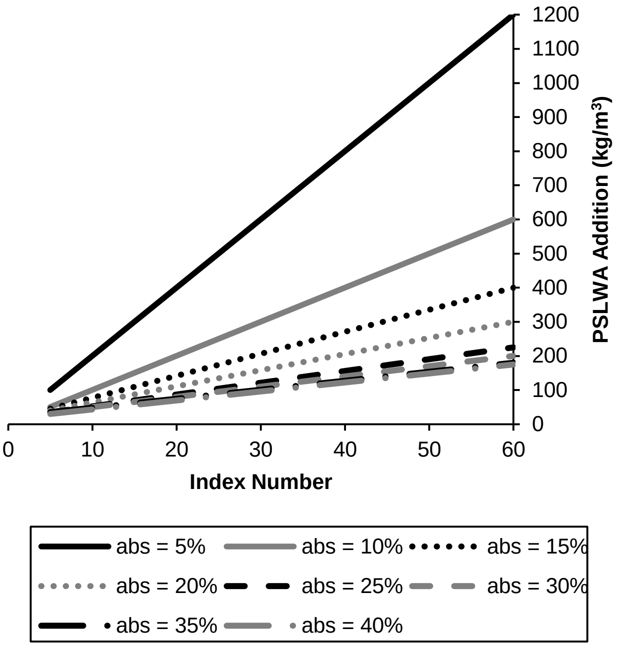

Figure 5 Recommended level of PSLWA (kg/m^3) dry mass basis) to be added to the concrete mixture according to Water Demand (see Figure 4) (Adapted from (ACI Committee 308; ACI Committee 213, 2013)).

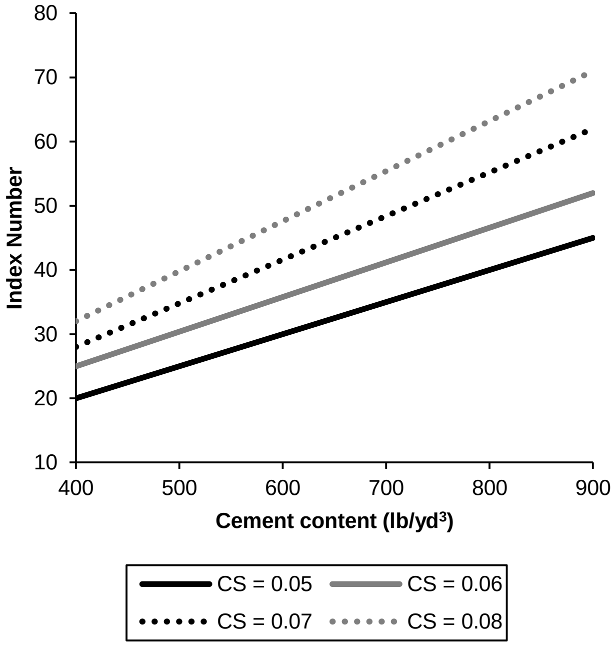

Figure 6 Chemical shrinkage of the mixture according to the cement content (lb/yd^3). (Adapted from (ACI Committee 308; ACI Committee 213, 2013))

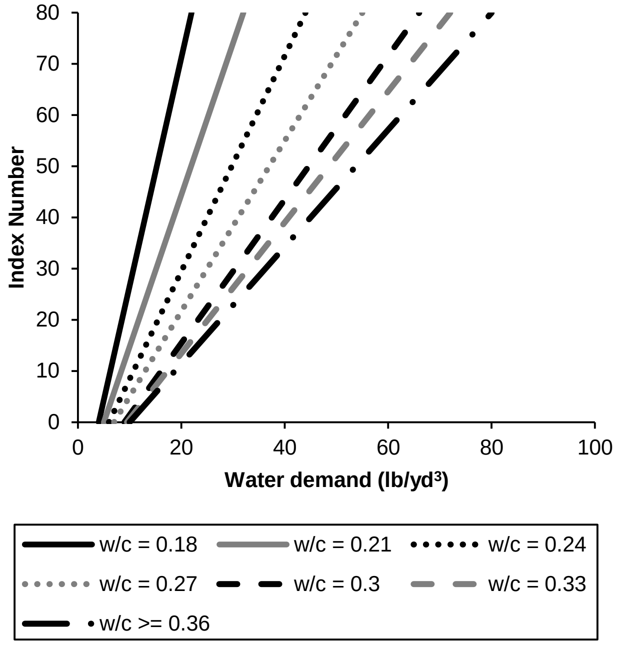

Figure 7 Water demand (lb/yd^3) of the mixture according to Figure 6. (Adapted from (ACI Committee 308; ACI Committee 213, 2013))

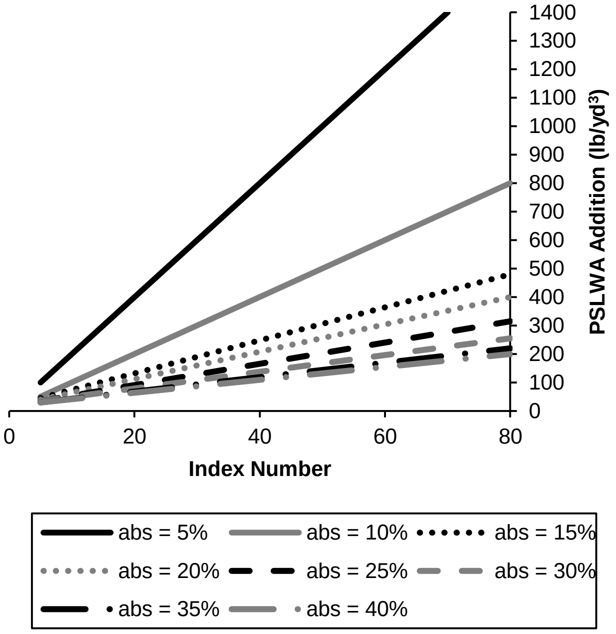

Figure 8 Recommended level of PSLWA (kg/m3) dry mass basis) to be added to the concrete mixture according to Water Demand (see Figure 3) (Adapted from (ACI Committee 308; ACI Committee 213, 2013)).

Often this is an issue when the IC water is not sufficiently distributed throughout the concrete microstructure. Initially, the water initially provided by IC fundamentally reduces the sizes of the pores within the hydrating cement past due to more complete hydration, leading to a greater relative humidity reduction and higher internal stress generation when these pores begin to empty.

Normally, an IC concrete mixture proportioned according to Equation 2 will have the required additional water in the PSLWA pores. If additional surface water is provided is sufficient for external curing, water in the pores of the PSLWA may remain in place rather than if it is hydrating the cement paste. If such specimen of concrete would be exposed to freezing conditions before this water migrates from the PSLWA pores, the concrete durability might be compromised (Bentz & Weiss, 2010).

2.2.6 Pre-wetting lightweight aggregate

Pre-saturating the LWA is critical for the internal curing procedure; but the process is not the same for all LWA. Aggregates with a sealed surface will require a longer amount of soaking time, preferably submerged in water. Those that have an open texture, or a crushed surface will absorb water faster and are usually pre-wetted by sprinkling with water in a stockpile. Sprinkling time can be controlled by the application rate of the water, ambient conditions and absorption of the lightweight aggregate (ACI Committee 308; ACI Committee 213, 2013).

If the LWA is not pre-wetted, early-age hydration and strength improvements are delayed and, in some cases, reduced. Autogenous shrinkage and creep can also increase if the aggregates are not at the required saturation level. From a field perspective the key to successful IC is to assure proper moisture conditioning of the lightweight aggregate to avoid variable unit weight, slump loss, pumpability and finishing issues (Villareal & Crocker, 2007).

The batching, mixing, transportation, placing, and finishing of internally cured concrete is not significantly different from any other common concrete practice. In batching, the lightweight aggregate and mixing water should be placed in the mixer first for further assurance that the lightweight aggregate is properly prewetted. When following guidelines outlined previously, the fresh concrete exhibits batching, mixing, transporting, placing and finishing characteristics that are like an equivalent conventional mixture without internal curing (ACI Committee 308; ACI Committee 213, 2013).

The absorption of water by the LWAs takes time. The period of time required for the LWAs to absorb their specific amount of water (different for each LWA) has been commonly set for 24 hours. To determine the volume of water absorbed as a function of time, Castro et al. (Castro, Keiser, Golias, & Weiss, 2011) conducted a “volumetric flask test”. In practice, ASTM C127-07 and ASTM C128-07 are commonly employed, although both test methods are not meant to test the absorption capability of lightweight aggregates. Equation 4 can be used to estimate the relative absorption (Castro, Keiser, Golias, & Weiss, 2011).

$$S = t^A$$

Equation 4 Relative Absorption Estimate

Where: S is the relative absorption, t is time in hours and a varies between 0.07 and 0.13 for times up to 48 hours.

Table 5 shows typical 24-hour absorption values for a variety of lightweight aggregates from North America, which range between 6% and 31%. Clearly from Equation 4 the amount of LWA required for IC is inversely proportional to its absorption (or desorption) capacity. Therefore, to provide the same amount of water for internal curing, LWA with desorption capacity of 30% will require only 1/3 of the mass of a different LWA with desorption capacity of 10%. These calculations assume the LWA provide adequate spatial distribution to rapidly provide water to a majority of the surrounding hydrating cement paste.

Table 5 Typical 24-hour Absorption Behavior of Expanded Shale Clay (1-3), Expanded Shale (4-12), and Slate (13-14) Aggregates available in North America (Castro, Keiser, Golias, & Weiss, 2011)

LWA#	**24-Hr Absorption (%)**
1	15.3
2	30.5
3	17.7
4	17.5
5	14.1
6	10
7	15.6
8	15
9	15.7
10	19.5
11	18.1
12	18.5
13	12.2
14	6

Saturated salt solutions have been used in several studies to control the relative humidity over PSLWAs to examine their mass loss or desorption (Bentz, Lura, & Roberts, 2005) (Radlinska, Rajabipour, Bucher, & al., 2008). Castro et al. (2011) employed dynamic vapor desorption in which the sample was placed in a highresolution balance in air stream within a carefully controlled relative humidity environment, to measure its desorption isotherm. It was found that approximately 90% of the 24-hour absorbed water is readily released at high relative humidities (> 93%) from nearly all LWAs currently produced in the U.S. (Radlinska, Rajabipour, Bucher, & al., 2008).

2.2.7 Laboratory Studies and Field Practices (2010-Present)

IC has captured the attention of many engineers in the last decade; however, this interest hasn't been the same in its efficiency, rather that the effectiveness (because this has been tested numerous times). Efficiency becomes relevant when considering possible limitation in the mechanical properties of concrete, which are derived from the increase in the number of pores within the mixture and the addition of internal curing agents. The success of IC heavily depends on the properties of the water reservoirs chosen. A good IC material should provide enough water at the right time. Important research studies are presented in Table 6.

Concrete mixtures that use Internal Curing as their curing method exhibit a higher degree of hydration and a lower autogenous shrinkage than those without. Many times it has been demonstrated that Internal Curing increases the effectiveness of the concrete, allows for a more efficient use of the cement and reduces the potential tendency to early cracking (Bentz, Geiker, & Jensen, 2002) (Bentz, Lura, & Roberts, 2005) (Bentz, M.R., & K.K., 2001) (Villareal & Crocker, 2007). Natural PSLWA show higher efficiency than artificial PSLWA in the matters of compressive strength, chloride ion permeability, and degree of hydration. Nevertheless, the autogenous shrinkage efficiency between both types of LWA hasn't been tested conclusively (Paul & Lopez, 2011).

In order to increase the performance of internal curing researchers have studied the effects of adding different materials to the concrete mixture in the hopes of achieving greater performance as a result. One of the laboratory studies that have been done regarding this increase in performance due to additional materials in the mixture is the development of High Volume Fly Ash (HVFA) concrete. The general approach for developing HVFA concrete is using a lower w/c ratio to offset the expected slower strength development. This is also in agreement with recent engineering tendencies of developing stronger and more durable concretes through the use of this technique and those concretes are called High Performance Concrete (De la Varga, Castro, Bentz, & Weiss, 2012).

To better utilize internal curing technology for durable concretes, Ya Wei et al. studied the microstructure and the desorption properties of sintered fly ash and expanded shale LWAs. With the increasing utilization of high performance concrete characterized by low water/cement ratios, the autogenous shrinkage and the early-age cracking become big concerns with regard to service life and appearance of structures. Ya Wei et al. used the Internal Curing Efficiency in their study to characterize the effectiveness of autogenous shrinkage mitigation, which relates to the PSLWA volume content (Wei, Xiang, & Zhang, 2014).

The benefits of using internal curing on the transport properties were assessed by Castro et al. by testing internally cured samples using water absorption test and electrical conductivity test. The total absorbed water is reduced when the level of internal curing increases, and it was known for the systems with a low w/c, but the results indicate that these benefits are extendible to systems with higher w/c. Electrical conductivity tests performed on sealed samples at early ages show a benefit in the use of internal curing in mortar systems containing low w/c, but at higher w/c the effect of the additional fluid in the system provided by the PSLWA can be observed. The effect of internal curing is proportionally larger in samples prepared with the highest w/c. It has been observed that the roughness (porosity) is reduced as the distance from the aggregate-paste interface increases (Castro J. , 2011).

Table 6 Important research on improving concrete performance using IC

Improving Characteristic	**Description**	**Reference**
IC can extend the service life of high-performance concrete bridge decks by more than 20 years	By reducing early-age cracking and providing a reduced chloride diffusion, IC adds 20 more years to usual bridge decks.	(Cusson, Lounis, & Daigle, 2010)
Water Absorption and Desorption	Natural LWAs possess higher water absorption and present a faster water release for IC, with better performance than artificial LWAs	(Paul & Lopez, 2011)
IC improves the performance of low w/c – low permeability concretes which require additional water to hydrate	Mixtures with IC show less water effectively lost than mixtures without it, maintaining better curing conditions for the cement paste	(Espinoza-Hijazin & Lopez, 2011)
LWA used in an oven-dry condition it can absorb water from the paste prior to set which will be returned to the system as IC water	By adjusting mixture proportions properly, absorbed water can be used by the aggregate before setting which provides IC benefits	(Castro, Keiser, Golias, & Weiss, 2011)
Cement replacement with fly ash to minimize potential reductions in early strength development	IC Mixtures with high volume of Fly Ash show additional benefits that permit broader applications: less shrinkage and less autogenous shrinkage.	(De la Varga, Castro, Bentz, & Weiss, 2012)
IC mixtures permit a larger use of fly ash and reduces early-age cracking when high early-age strength is needed	Testing was performed to observe IC effects on mechanical, shrinkage and hydration properties of HVFA mixtures for concrete pavements	(De La Varga, 2013)
IC concrete mixture can withstand a temperature change of over 30°C (54°F) before cracking.	Utilizing ASTM C1581 and a modified version of it (i.e. Dual Ring Test), autogenous shrinkage was monitored while applying changes in temperature to different concrete mixtures	(Schlitter, Bentz, & Weiss, 2013)

Table 6 continued

No autogenous shrinkage at the age 28 can be achieved with a specific ratio of PSLWA and particle size	Research concluded that 100% autogenous shrinkage mitigation can be achieved if the ratio of PSLWA and particle radius is about 1.1	(Wei, Xiang, & Zhang, 2014)
IC reduces significantly the effects of autogenous shrinkage of repair mortars	Two different materials were tested, and different IC agents were used. PSLWA was found to provide the greatest IC efficiency	(Bentz D. , Jones, Peltz, & Stutzman, 2015)
The addition of an IC agent produces retardation of the hydration reactions and reduces measured autogenous deformation	Two commercially available repair mortars were used. Compression cubes, shear slant testing, elastic modulus test, penetration test and more were performed.	(Bentz D. , Jones, Peltz, & Stutzman, 2015)
IC mixtures reduces lightweight concrete unit weight, and also increases their tensile strength	Investigations of PSWLA over burnt clay bricks as self-curing agents of concrete were carried out to evaluate mechanical properties	(Rashawan, Diab, & El-Fattah, 2016)
Pavement IC slabs possess lower stress-to-strength ratio and better cracking performance than standard mixtures slabs	Three test slabs were constructed to evaluate the performance of IC in pavement slabs. 3D Finite elements models were developed and calibrated for the test slabs	(Kim, Subgranon, Tia, & Bergin, 2016)

2.2.8 New Materials and Internal Curing Agents

In furtherance of maximizing the effect of internal curing, engineers have researched the use of new materials for concrete mixtures. They have gone through many different mixture proportions, interchanging materials in order to assess the efficiency of internal curing. Investigations regarding different types of lightweight aggregates, absorptive materials, additives and chemicals, their effects and properties and also the contribution of these to internal curing and their consequences on the concrete mixture. Table 7 shows a summary of important research on new IC agents.

One of the investigated materials is Fly-Ash. This is a by-product of coal combustion in power plants that can be used in concrete as a cement replacement. The amount of fly ash replacement for cement that is typically used in concrete pavements and transportations structures is limited by specifications to approximately 20-25% by mass; due to strength and de-ice scaling concerns. The replacement of cement with this material can contribute positively in improving the sustainability of the concrete construction industry in several ways (De la Varga, et al., 2014).

The use of High-Volume Fly Ash mixtures with low w/c ratio may be expected to improve performance in terms of reduced transport properties like water and ion penetrability. These properties depend on total porosity, pore size distribution, pore connectivity and pore tortuosity (property that relates to being twisted, having many turns). Internal curing elevates the rate of hydration at later ages, which refines the pore structure and reduces the transport of water and ions through the cement matrix at a given age (De la Varga, et al., 2014).

At 50% fly ash, most HVFA mixtures will exhibit a significant retardation in setting time and delays in finishing. In the study done by Bentz, Ferraris and De la Varga in 2010, these delays were linked both to retardation inherently caused by the Class C fly ash an increase in the required HRWRA (High Range Water Reducing Admixture) dosage. Calcium hydroxide or rapid set cement powder additions were found to reduce these setting times back to those exhibited by the control cement-only mixture, for the particular cements and fly ashes investigated (Bentz, Ferraris, De la Varga, Peltz, & Winpigler, 2010).

IC can be successfully employed with HVFA mixtures, dramatically reducing autogenous shrinkage, nonetheless with a concurrent slight decrease in compressive strength for the materials employed in this study. Moreover, IC will generally significantly increase the materials costs of the HVFA mixtures. From an economic standpoint, HVFA mixtures are cost competitive from a materials first cost basis.

When a life cycle analysis is considered and/or if carbon trading becomes a reality worldwide, the cost savings of HVFA mixtures may be even greater.

Another material that has been studied is the PSLWA produced from biomass-derived waste (bio-PSLWA). To be efficient as internal curing agents, these aggregates should rapidly absorb water when conditioned before concrete mixing. It has been confirmed that the internal curing performance of PSLWA depends critically on their microstructure: expanded-clay PSLWA, with coarse pore structure and well interconnected pores performed well, whereas natural zeolite aggregates, in spite of high absorption, didn’t release the absorbed water due to their extremely fine pore structure. The desorption behavior of the aggregates depends heavily on their pore size distribution (Ghourchian, Wyrzykowski, Lura, Shekarchi, & Ahmadi, 2013).

The use of bio-PSLWA from sugar cane bagasse fly ash as an internal curing agent for high performance concrete would allow converting agricultural wastes into a high-value product. Although the bio-PSLWA has water absorption and porosity in the range of lightweight aggregate that have been used for internal curing, until very recently only limited information on their microstructure and no information on desorption properties have been available. Lura et al investigated the properties of desorption of two different bio-PSLWA. IC obtained by the use of bio-PSLWA delays the development of self-desiccation and keeps the internal relative humidity high in the mortars, especially at the higher lightweight aggregate amounts (Lura, Wyrzykowski, Tang, & Lehmann, 2014).

Natural zeolite (clinoptilolite type) has been investigated. Zeolite is a natural porous aggregate with high absorption capacity (Ahmadi & Shekarchi, 2010). In some regions (i.e. Iran), zeolite is a highly available and relatively cheap lightweight aggregate to be used in concrete, since it can be found in easily accessible shallow deposits. The use of zeolite aggregate for internal curing is especially promising since it is a natural aggregate that needs basically no pretreatment respect to the artificial lightweight aggregates. Furthermore, its high water absorption suggests its application as internal curing reservoir (Ghourchian, Wyrzykowski, Lura, Shekarchi, & Ahmadi, 2013).

IC has been efficient when using slag in concrete. In recent studies, alkali activated slag has been selected to be used because it shows considerable promise as an environmentally friendly alternative to binders produced from ordinary Portland cement. The use of PSLWA with IC to mitigate shrinkage in slags activated by Na_2Co_3 solution and waterglass/NaOH solution has been investigated. Internal curing reduces the compressive strengths of mixtures using Na_2Co_3 and the waterglass solution. The decrease in strength observed with the incorporation of internal curing is due primarily to mechanical considerations: the lightweight aggregate is simply not as strong an aggregate as normal weight sand (Sakulich & Bentz, 2013).

Super absorbing polymers (SAP) are another type of internal curing agent. A substitute of lightweight aggregate, SAP aggregates provides additional curing water by creating an internal curing agent by gradually releasing absorbed water during the hydration process. These polymers can absorb very large quantities of water during concrete mixing (Hasholt, Jensen, Kovler, & Zhutovsky, 2012) (Craeye, Geirnaert, & De Schutter, 2011) (Trtik, 2010) (Zhutovsky & Kovler, 2013) (Wyrzykowski, Lura, Pesavento, & Gawin, 2012). Once the initial free water has been consumed by the hydration reactions, the water absorbed by the SAP will be gradually released. In this way, self-desiccation can be prevented, and autogenous shrinkage of concrete reduced. Nonetheless, due to this process of internal curing the mechanical properties of the high-performance concrete are negatively affected, mainly due to the addition of extra curing water (Wang, Helene, & Monteiro, 2006). In addition to the reduction in autogenous shrinkage, other benefits of adding SAP to a concrete can be named:

- The ability to obtain a higher ultimate degree of hydration of the cement due to the maintenance of a higher internal relative humidity, and thus a higher compressive strength at long term (Geiker, Bentz, & Jensen, 2004).
- The pores and air voids formed inside the matrix due to the SAP after drying can help in obtaining a frost resistance. Therefore, SAP act as an air entrainment agent and can protect the concrete against freeze/thaw cycles (Bentz & Jensen, 2004)

SAP have a very high ability to absorb water, sometimes even up to 500 times their own weight. The SAP is mixed into the concrete, after which they absorb part of the mixing water. During hydration and due to self-desiccation, this absorbed water can be released for further hydration, which makes it a good internal curing agent (Craeye, Geirnaert, & De Schutter, 2011).

Addition of SAP has been demonstrated by computer simulation and field tests to be successfully effective as an internal curing agent to prevent early-age cracking of bridge decks of high-performance concrete. Finite element calculations indicate that the normal observed cracking behavior of a bridge deck constructed in High Performance Concrete will be prevented due to the application of internal curing (Craeye, Geirnaert, & De Schutter, 2011).

In order to test the efficiency of SAP as internal curing agents, some researchers (Craeye, Geirnaert, & De Schutter, 2011) (Hasholt, Jensen, Kovler, &

Zhutovsky, 2012) have used simulations in computer software in order to predict certain properties. Some of these properties have been confirmed in recent studies (Wyrzykowski, Lura, Pesavento, & Gawin, 2012). Trtik reported that at the age of 20.5 hours approximately 90% if the absorbed water was released from the SAP to the cement paste (Trtik, 2010).

Table 7 Important research on new materials for IC

New Materials	**Description**	**Reference**
Fly Ash	HVFA mixtures with IC present a dramatic reduction of autogenous shrinkage, become cost competitive from a materials first cost basis	(De la Varga, et al., 2014)
Biomass Waste	Converts agricultural waste into an IC agent of high performance concrete, has water absorption and porosity in the range of PSLWA, delays development of self-desiccation and keeps internal RH high	(Ghourchian, Wyrzykowski, Lura, Shekarchi, & Ahmadi, 2013) (Lura, Wyrzykowski, Tang,
Natural Zeolite	Porous aggregate with high absorption capacity, highly available and relatively cheap in some regions, basically needs no treatment, environmentally friendly	(Ahmadi & Shekarchi, 2010) (Sakulich & Bentz, 2013)
Super Absorbing Polymers	Rapidly releases water during hydration process, absorbs very large quantities of water, prevent self-desiccation and reduces autogenous shrinkage, help with frost resistance, act as air entrainment agent,	(Trtik, 2010) (Craeye, Geirnaert, & De Schutter, 2011) (Wyrzykowski, Lura, Pesavento, & Gawin,
Recycled Concrete Aggregates	Low unit weights, increases generally inferior performance of RCA, similar drying shrinkage when used as 50% replacement, comparable performance in freeze-thaw, generally cheaper than normal	(Yildirim, Meyer, & Herfellner, 2015)
Recycled Fine Ceramic	With 30% replacement of natural fine aggregates present lower density of concrete, higher mechanical properties than conventional concrete, lower chloride ion penetration	(Gonzalez-Corominas & Etxeberria, 2014)
Rice Husk Ash	Does not significantly decrease compressive strength, reduces environmental pollution, comes from agricultural waste	(Nguyen & al., 2011)

Addition of SAP has a significant impact on the hydration behavior of cement pastes with low w/c. The main hydration peaks in the isothermal calorimeter are lower and appear earlier compared to the corresponding pastes with the same w/c ratio but without SAP. Water entrainment by means of SAP increases the degree of hydration at later times in a manner similar to a simple increase of the w/c (Justs, Wyrzykowski, Winnefeld, Bajare, & Lura, 2014).

2.2.9 DOT Practice of Internal Cured Concrete

Concrete pavement quality has been of utmost important for Departments of Transportation (DOT) in the United States. Many DOTs have researched IC and its numerous benefits in their respective regions. The benefits of IC are outstanding, and interest in IC research has escalated among DOTs in recent years. As stated before, IC improves mechanical properties and durability of concrete, making it a relevant technique for DOT and pavement construction. A summary of some of these projects can be seen in Table 8.

Ohio DOT observed significant differences in early-age cracking of high-performance bridge decks in northeast Ohio. These differences were attributed to the absorption of the coarse aggregates used in concrete pavement. Ohio DOT founded a research project focused on measuring the benefits of IC for pavement and overlay mixtures in the field. Different tests were performed in IC mixtures: workability, air content, unit weight, compressive strength, modulus of elasticity, freeze thaw and more. Reported results indicate that lightweight aggregate substitution improved both early and ultimate strength while reducing cracking tendency (Cleary & Delatte, 2008).

Utah DOT constructed four bridge decks located in northern Utah, two with conventional concrete and two with PSLWA. Laboratory testing showed that for the first 6 months following deck construction, both conventional and PSLWA concrete exhibited similar strength gain characteristic. In the field, a Schmidt rebound hammer test determined that PSLWA concrete was neither consistently stronger nor weaker than conventional concrete. Also, the conventional concrete mixture presented 4.6, 21.5, and 2.8 times more cracking than the IC concrete deck (PSLWA) at 5 months, 8 months and 1 year, respectively (Yaede, 2013) (Guthrie & Yaede, 2013).

New Jersey DOT and New York DOT have investigated IC as a method to reduce/eliminate cracking in concrete. New York DOT initiated research to demonstrate the potential of IC high performance concrete and has utilized the technology on several bridges throughout the state. Cracking was considered as the first step toward failure of the bridge deck, and IC mixtures showed advancements in cracking mitigation (Streeter, Wolve, & Vaughn, 2013). New Jersey DOT performed studies under Rutgers Center for Advanced Infrastructure and Transportation (CAIT) in order to utilize IC for cracking control and/or mitigation in new bridge decks construction (Szary & Roda, 2013).

Colorado DOT investigated 7 concrete mixtures which utilized IC techniques with different pre-wetted lightweight aggregates (LWA and SAP). IC mixtures improved autogenous shrinkage by providing swelling of the mixtures in early stages, minimized restrained shrinkage and showed a better drying shrinkage performance than the reference mixtures (Jones, 2014).

Indiana DOT constructed six bridge decks utilizing IC high performance concrete mixtures and compared them to a reference high performance concrete mixture. The study concluded that the difference in the mechanical properties of IC high performance concrete and the reference high performance concrete mixtures was not statistically significant. Furthermore, IC high performance concrete mixtures exhibited a reduction in early age shrinkage of 70 to 90% (Barrett, 2015).

Iowa DOT conducted several experiments with IC mixtures utilizing LWA and fly ash. The research concluded that at 20% and 30% LWA replacement, mechanical properties of concrete were not affected, statistically significantly speaking. These mixtures with IC proved to possess low potential for cracking according to the study. Live load testing was performed after the construction of an IC concrete bridge (with two sections, one for reference without IC and one with IC) immediately after it was opened to traffic, a year and approximately two years after. No significant differences were observed in the structural performance of the reference and IC sections of the bridge. For the IC section, the service life was estimated to be around 20 years longer than that of the reference section (Taylor, Hosteng, Wang, & Phares, 2016).

Following the success of other DOTs in the United States, Florida DOT initiated studies of IC in pavements in order to measure and quantify the behavior of IC pavements under realistic Florida conditions. Three slabs were constructed, two utilizing IC and one for reference. The results show that IC slabs did not possess observable cracks while the reference slab did. The stress-to-strength ratio between the three mixtures did not change significantly (Kim, Subgranon, Tia, & Bergin, 2016).

Table 8 Recent DOT IC research for IC in concrete

Department of Transportation	Relevant Observed Properties	Reference
Ohio DOT	Reported results indicate that lightweight aggregate substitution improved both early and ultimate strength while reducing cracking tendency	(Cleary & Delatte, 2008)
Utah DOT	PSLWA concrete was neither consistently stronger nor weaker than conventional concrete. Also, the conventional concrete mixture presented 4.6, 21.5, and 2.8 times more cracking than the IC concrete deck (PSLWA) at 5 months, 8 months and 1 year, respectively	(Yaede, 2013) (Guthrie & Yaede, 2013)
New York DOT	IC mixtures showed advancements in cracking mitigation due to reduced autogenous shrinkage	(Streeter, Wolve, & Vaughn, 2013)
New Jersey DOT	IC provides help in cracking control and/or mitigation in bridge decks construction utilizing different IC agents	(Szary & Roda, 2013)
Colorado DOT	IC mixtures improved autogenous shrinkage by providing swelling of the mixtures in early stages, minimized restrained shrinkage and showed a better drying shrinkage performance than the reference mixtures	(Jones, 2014)
Indiana DOT	Observed difference in the mechanical properties of IC high performance concrete and the reference high performance concrete mixtures was not statistically significant. IC high performance concrete mixtures exhibited a reduction in early age shrinkage of 70 to 90%	(Barrett, 2015)
Iowa DOT	No significant differences were observed in the structural performance of the reference and IC sections of instrumented bridge. The service life of the IC mixtures was estimated to be around 20 years longer than that of the reference mixture	(Taylor, Hosteng, Wang, & Phares, 2016)
Florida DOT	Three slabs were constructed, two utilizing IC and one for reference. The results show that IC slabs did not possess observable cracks while the reference slab did. The stress-to-strength ratio between the three mixtures did not change significantly	(Kim, Subgranon, Tia, & Bergin, 2016)
North Carolina DOT	Observed reductions in autogenous shrinkage using IC ranged from 30% to 56% depending on the type of LWA used. Fresh concrete properties were observed to be similar to control concrete. IC compressive strength met required specifications from the DOT. Lower moduli of elasticity were recorded as well, which could aid in reducing cracking at early ages	(Leach, 2017)

North Carolina DOT was reporting issues of early-age cracking of bridge decks along the state. These were most likely caused of high cementitious material content and low water-to-cement ratios of concrete mixtures utilized. The DOT initiated research to develop a standard to support the application of IC techniques in future highway infrastructure projects. Observed reductions in autogenous shrinkage using IC ranged from 30% to 56% depending on the type of LWA used. Fresh concrete properties were observed to be similar to control concrete. IC compressive strength met required specifications from the DOT. Lower moduli of elasticity were recorded as well, which could aid in reducing cracking at early ages (Leach, 2017).

2.2.10 Conclusions

It is safe to say that as of 2017, IC has been researched to a point in which engineers can start utilizing it as a proportioning and mixture design method in many different types of construction around the world. Many researchers have investigated properties, effects, materials, performance, and most of the time IC is considered a good, viable option. IC contributes in a great way to increase the sustainability of concrete infrastructure. The two main goals of IC: increasing hydration to a maximum and decreasing self-desiccation to a minimum. In IC, the aggregates are not considered to be inert; rather they play an integral role in the development of the paste microstructure, fundamentally in the hydration of the concrete paste. Low w/c ratio concrete mixtures have been increasingly promoted for use in civil engineering infrastructure due to potential improvements in strength and durability. One of the disadvantages of using these is that they are susceptible to early-age cracking caused by autogenous shrinkage. To counter these effects there are many methods, one of them is IC. With it, the PSLWA will supply water to counteract the effect of self-desiccation after the initial pore structure of the paste has formed. Internal curing is one of the most appealing techniques of concrete construction nowadays. It shows great promise for field applications, especially in high performance concrete mixture design.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the testing matrix and materials utilized in this research are described, which include ASTM tests such as Compression Strength, Elastic Modulus, Split Tension, Drying Shrinkage, Penetration Test, Shrinkage Ring Test, Compression Creep, Autogenous Shrinkage, and Freeze Thaw. The chapter will also include material descriptions for OPC, CSA, Silica Fume, Proprietary Mixtures, Normal weight aggregates (NWA), Lightweight Aggregates and admixtures. 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.

3.2 Selected Tests for Research

3.2.1 Compressive Strength

Compressive strength was evaluated in accordance with the specifications of ASTM C39. At least, three 4×8 in. cylindrical concrete specimens or three 2 in.

concrete cubes were tested for each mixture at a specified age. Cylinders were capped with neoprene caps in accordance with the specifications of ASTM C39 prior to testing, as seen in Figure 9.

Figure 9 Cylinder in the compressive strength test with neoprene caps

3.2.2 Static Modulus of Elasticity

The static modulus of elasticity was evaluated in accordance with the specifications of ASTM C469. At least three 4×8 in. cylindrical concrete specimens were tested for each mixture. Concrete specimens were tested at 4 hours. Each cylinder was fitted with an axial compressometer (Figure 10) 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.

3.2.3 Splitting Tensile Strength

Splitting tensile strength was evaluated in accordance with the specifications of ASTM C496. At least three 4×8 in. cylindrical specimens were tested for each mixture. The age at testing was 4 hours. The test setup is shown in Figure 11. Splitting tensile strength is known to underestimate the tensile strength of concrete compared to direct tension or flexural testing (Metha & Monteiro, 2006) (Olufunke, 2014).

3.2.4 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 4 hours and measured using a standard-length comparator (Figure 12). 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 10 Compressometer for determination of modulus of elasticity

Figure 11 Splitting tensile test

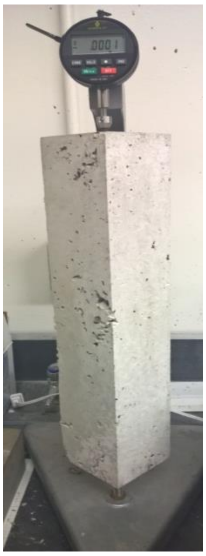

Figure 12 Length comparator for Drying Shrinkage

3.2.5 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 various needles at different times until each mixture reached final set. Typical set up for this test is shown in Figure 13.

3.2.6 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 Figure 14. Testing typically begins at 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.

Figure 13 Setting time test

Figure 14 Restrained shrinkage ring test

3.2.7 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 Figure 15 and loaded to 40% of their ultimate compressive strength, starting at 48 hours. Length change was monitored at the measuring locations depicted in Figure 16 using the strain gauge shown in Figure 17. Measurements were taken until the length change measurement stabilized or until 120 days.

3.2.8 Freeze Thaw

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

Figure 15 Creep frame

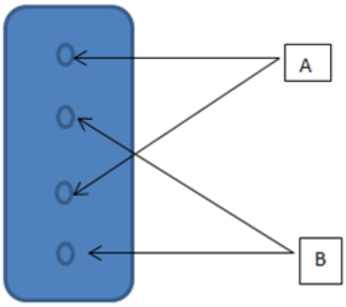

Figure 16 Reference measurement locations

Figure 17 Creep strain gauge

3.2.9 Autogenous Shrinkage

Autogenous shrinkage was measured in accordance with the specifications of ASTM C1698 beginning at the time of final set (as determined by penetration resistance in accordance with the specifications of ASTM C 403) and using 3 replicate specimens per mixture. Mixtures were prepared by sieving the concrete into a mortar version so that they satisfied ASTM C1698. Testing apparatus can be seen in Figure 18.

Figure 18 Autogenous shrinkage apparatus

3.2.10 Maturity Test

The maturity of the concrete is a method which can be used to predict the in-place strength of hardening concrete based on its thermal history. Two 4×8 in insulated foam cylinders were used for each mixture. The thermal history of the mixtures was recorded utilizing thermocouples (Type K) and a data logging device REED SD-947. Setup utilized for recording the thermal history of the mixture can be shown in Figure 19.

Figure 19 Thermal history setup

3.3 Mixing Procedure

The mixing procedure is given as follows:

1. Rinse the mixer with water;
2. Remove any excess (puddled) water from the mixer; the mixer should be damp, not wet;
3. Add coarse and fine aggregate to mixer and about ¼ of the mix water;
4. Mix for 1-2 minutes;
5. Start adding the cement and water to the mixer as it is mixing (cement is added using a scoop and some of the water is added after every 2 scoops of cement);
6. After all the cement and water has been added, add the air entrainment admixture (AEA);

7. Mix for 1-2 minutes;
8. If it the mixture has a low slump, add the HRWR and let it mix for about 1 minute;
9. Turn the mixer off for 3 minutes;
10. Restart the mixer, add the accelerator, and mix for 2 minutes;
11. Check slump, unit weight, air content, and temperature; and
12. Cast specimens

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

3.4 Materials

3.4.1 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 Figure 20 and Figure 21, respectively. Normalweight coarse aggregate was crushed limestone with specific gravity 2.7, unit weight 105 lb/ft^3, and nominal maximum particle size 3/4 in. Normalweight fine aggregate was natural quartz sand with specific gravity 2.65, unit weight 110 lb/ft^3, and fineness modulus 3.45.

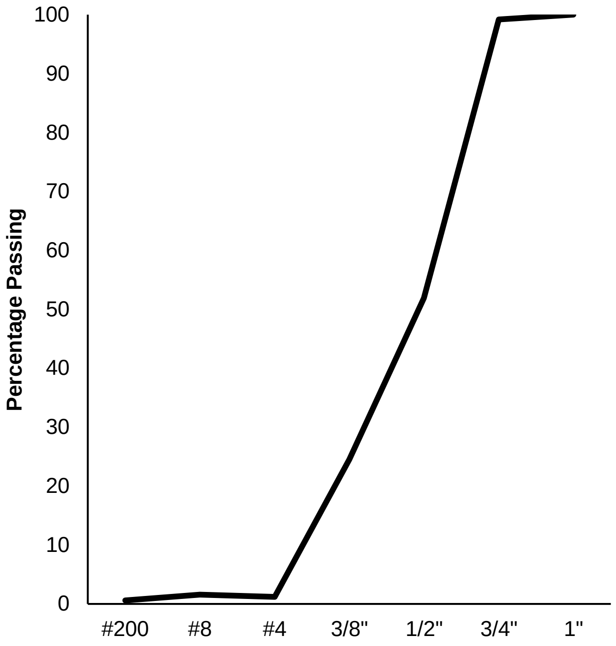

Figure 20 Normal weight coarse aggregate gradation

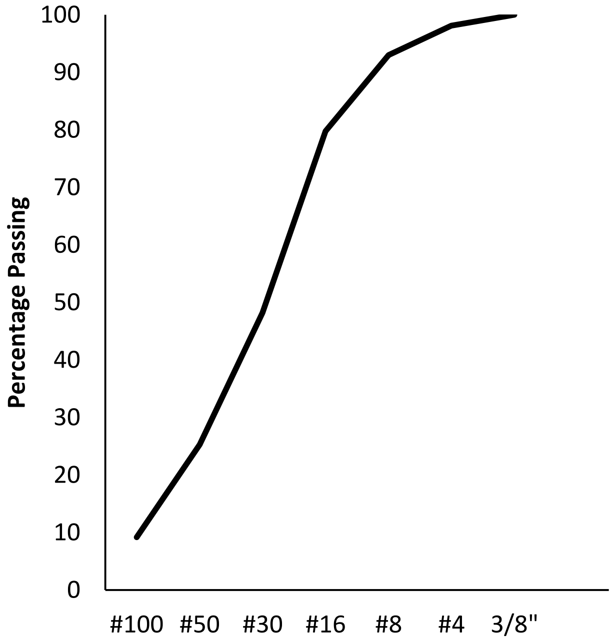

Figure 21 Normal weight fine aggregate gradation

3.4.2 Lightweight Aggregate

Lightweight coarse aggregate (LWA) was expanded shale with specific gravity 1.73, unit weight 65 lb/ft^3, and nominal maximum particle size 0.5 in. Lightweight fine aggregate was expanded shale with specific gravity 1.81, unit weight 55 lb/ft^3, and fineness modulus 3.12. Lightweight aggregates were presaturated by soaking for 24 h and air-drying to saturated surface dry (SSD) condition. Gradation for LWA are presented in Figure 22 and Figure 23. Lightweight aggregate was proportioned utilizing the Expanded Shale, Clay and Slate Institute (ESCSI) internal curing calculator (ESCSI, 2012).

3.4.3 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.

3.4.4 Type III Portland Cement

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

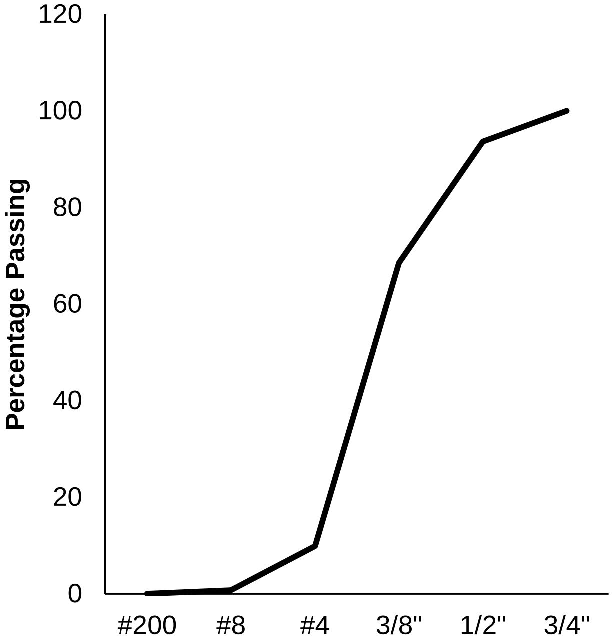

Figure 22 Lightweight coarse aggregate gradation

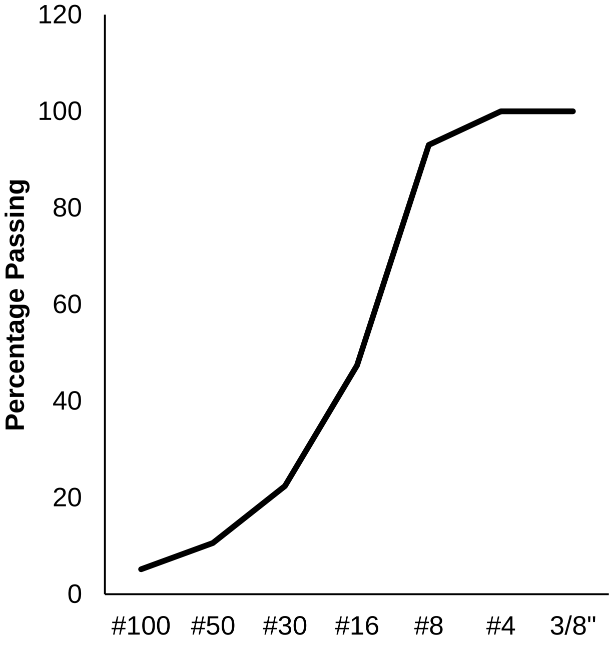

Figure 23 Lightweight fine gradation

3.4.5 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.

3.4.6 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 9.

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.

3.5 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 (Figure 24). In addition, 5 states participated and responded that they did not usually make use of concrete pavement (Figure 25). 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. The list of survey questions can be found in Appendix A: Full Depth Pavement Repair Questionnaire, at the end of this dissertation.

Table 9 Summary of proprietary repair media

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

3.6 Experimental Procedure

The proprietary mixtures and two phases of non-proprietary mixtures were subjected to different testing matrices according to the need to investigate properties and the amount of material that could be bought or obtained depending on the budget for the project. These testing matrices are shown in Table 10.

Due to limited availability of proprietary mixtures (P1, P2, and P3), a more complete testing program was impossible to follow. In addition to the 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 (Mixture proportions for OPC are presented in Table 11), and calcium sulfoaluminate (CSA) cement (Mixture proportions for CSA are presented in Table 12).

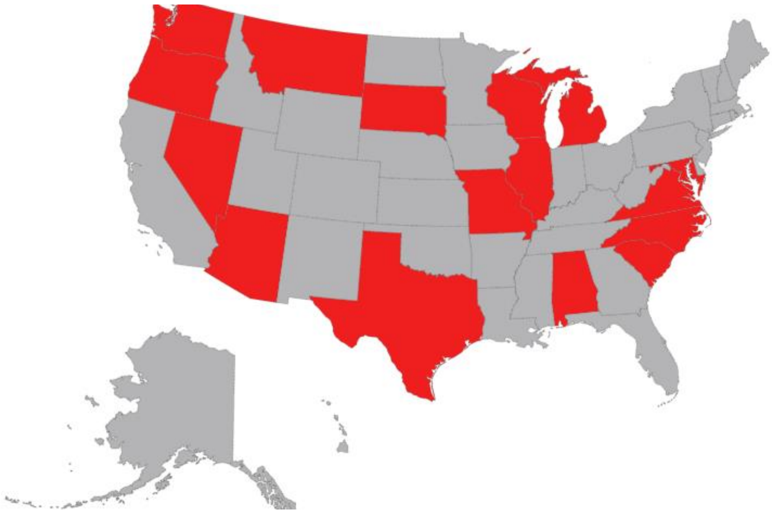

Figure 24 Representation of survey respondents by state with concrete pavement

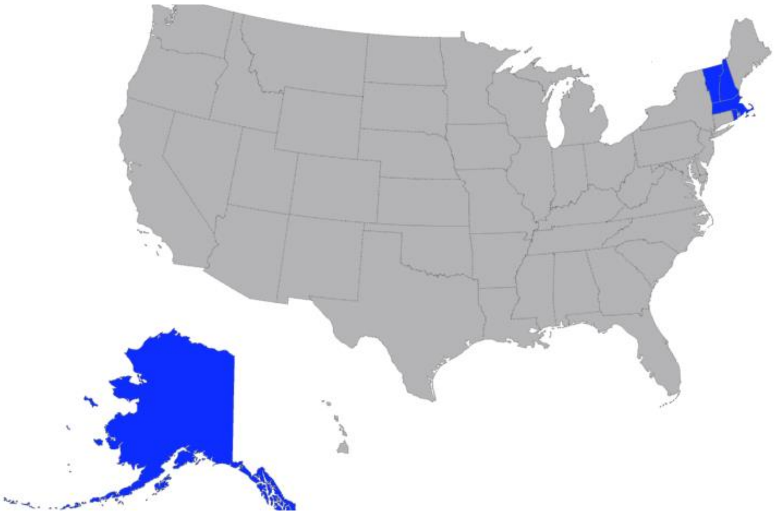

Figure 25 Representation of survey respondents by state without concrete pavement

Table 10 Testing matrices for different phases

Proprietary Mixtures Testing Matrix		
ID	**Code**	Age of Specimens
Compressive Strength	ASTM C39	4 h, 24 h
Splitting Tensile Strength	ASTM C496	4 h
Setting Time	ASTM C403	0 h
Elastic Modulus	ASTM C469	4 h
Drying Shrinkage	ASTM C157	From 4 h to 7 d
Phase I Mixtures Testing Matrix		
ID	Code	Age of Specimens
Compressive Strength	ASTM C39	4 h, 6 h, 24 h, 7 d
Phase II Mixtures Testing Matrix		
ID	Code	Age of Specimens
Compressive Strength	ASTM C39	4 h, 6 h, 24 h, 7 d
Elastic Modulus	ASTM C469	4 h
Splitting Tensile Strength	ASTM C496	4 h
Setting Time	ASTM C403	0 h
Drying Shrinkage	ASTM C157	From Final Set
Restrained Shrinkage	ASTM C1581	4 h
Freeze Thaw	ASTM C666	4 h
Creep	ASTM C512	1 d
Autogenous Shrinkage	ASTM C1698	From Final Set
Set Time Mixtures Testing Matrix		
Setting Time	ASTM C403	0 h
Compressive Strength	ASTM C39	12 h, 24 h, 3 d, 7 d, 28 d
Drying Shrinkage	ASTM C157	From Final Set
Autogenous Shrinkage	ASTM C1698	From Final Set

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

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

Table 12 Mixture proportions for Phase I CSA repair media

Components	**Mixture 1**	**Mixture 2**	**Mixture 3**
Cement (lb/yd^3)	850	850	850
Water (lb/yd^3)	213	297.5	297.5
Coarse Agg (lb/yd^3)	1787	1300	1400
Fine Agg (lb/yd^3)	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

Table 13 presents mixture proportions for the eight concrete mixtures evaluated in this study. Mixtures based on CSA cement are denoted ‘CSA’. Those based on Portland cement are denoted ‘OPC’. Some Portland cement mixtures contain 20–30% silica fume by mass of cementitious material. These are denoted ‘SF20’ or ‘SF30’, respectively. Mixtures containing presaturated lightweight aggregate (PSLWA) for internal curing are denoted ‘IC’ for those containing presaturated lightweight coarse aggregate and ‘ICF’ for those containing both fine and coarse PSLWA. The paste volume was kept constant between mixtures. All mixtures included glenium high range water reducing admixture—25.5 fl oz/cwt for CSA based mixtures and 15 fl oz/cwt for Portland cement-based mixtures. Portland cement-based mixtures included 150 fl oz/cwt calcium chloride accelerator. The water-to-cementitious materials ratio (*w/cm*) was 0.30 for all mixtures.

Table 13 Phase II Mixture proportions

Material	Units	CSA	CSA IC	CSA ICF	OPC1	OPC IC	OPC SF20	OPC SF30 IC	OPC SF30 ICF
OPC	lb/yd^3				950	950	735	630	630
CSA	lb/yd^3	800	800	800					
SF	lb/yd^3						185	270	270
Water	lb/yd^3	240	240	240	290	290	275	270	270
NWA Coarse	lb/yd^3	1700		1700	1600		1600		1600
NWA Fines	lb/yd^3	1450			1400		1400		
LWA Coarse	lb/yd^3		1095			1030		1030	
LW Fines	lb/yd^3		940	940		905		905	905

Next, preliminary mixtures were designed to improve the previously obtained workability times of Phase II CSA mixtures. Based on previous research, the following admixtures were selected as preliminary: sugar, gypsum, boric acid, zinc oxide, citric oxide, and acetic acid. Coca-Cola was also tested as a preliminary admixture because of empirical evidence of its retarding properties in the Dominican Republic. From the aforementioned admixtures, 41 mixtures were designed for the Set time testing matrix utilizing Citric Acid (CA), Boric Acid (BA), Sugar (SU) and Coca-Cola (Coke), denoted in each mixture. Internal curing (IC) with PSLWA was also considered for the mixtures, also denoted in each mixture. Three different w/c were considered for these mixtures: 0.4, 0.5 and 0.6, denoted in each mixture. The admixture weight was assigned as a percentage of cement weight. Mixture proportions can be seen in Table 14 (all units are lb/yd^3).

Table 14 Set Time Mixture proportions

ID	CSA	Water	NWA Fines	Admixture
B0.4Ctrl	1200	480	2200	
B0.4CA0.125	1200	480	2200	1.5
B0.4CA0.25	1200	480	2200	3
B0.4CA0.5	1200	480	2200	6
B0.4CA0.7	1200	480	2200	8.4
B0.4CA3	1200	480	2200	36
B0.4BA0.125	1200	480	2200	1.5
B0.4BA0.25	1200	480	2200	3
B0.4BA0.3	1200	480	2200	3.6
B0.4BA0.4	1200	480	2200	4.8
B0.4BA0.5	1200	480	2200	6
B0.4SU0.125	1200	480	2200	1.5
B0.4SU1	1200	480	2200	12
B0.4SU15	1200	480	2200	180
B0.4Coke1	1200	480	2200	12
B0.4Coke15	1200	480	2200	180
B0.4IC	1200	480	1450	
B0.5Ctrl	1057	528.5	2200	
B0.5CA0.125	1057	528.5	2200	1.5
B0.5CA0.25	1057	528.5	2200	3
B0.5CA0.5	1057	528.5	2200	6
B0.5CA0.7	1057	528.5	2200	8.4
B0.5CA3	1057	528.5	2200	36
B0.5BA0.125	1057	528.5	2200	1.5
B0.5BA0.25	1057	528.5	2200	3
B0.5BA0.3	1057	528.5	2200	3.6
B0.5BA0.4	1057	528.5	2200	4.8
B0.5BA0.5	1057	528.5	2200	6
B0.5IC	1057	528.5	1450	
B0.6Ctrl	943	565.8	2200	
B0.6CA0.125	943	565.8	2200	1.5
B0.6CA0.25	943	565.8	2200	3
B0.6CA0.5	943	565.8	2200	6
B0.6CA0.7	943	565.8	2200	8.4
B0.6CA3	943	565.8	2200	36
B0.6BA0.125	943	565.8	2200	1.5
B0.6BA0.25	943	565.8	2200	3
B0.6BA0.3	943	565.8	2200	3.6
B0.6BA0.4	943	565.8	2200	4.8
B0.6BA0.5	943	565.8	2200	6
B0.6IC	943	565.8	1450	

CHAPTER 4

RAPID CONCRETE REPAIR PROPERTIES FOR DIFFERENT MIXTURES

4.1 Introduction

Structural deterioration represents a significant challenge for the concrete industry. Rapid hydration and high early strength Portland cement and calcium sulfoaluminate (CSA) concretes are commonly used as rapid set repair media. Ordinary Portland Cement (OPC) has been extensively studied and has been used commonly for repairs in the past. Admixtures have been used to increase OPC mechanical properties to the level of rapid set repair media. Silica Fume (SF) increases compressive strength of OPC mixture while reducing cement content and maintaining mixture design parameters. CSA cements due to their rapid hydration, high early strength and shrinkage reducing properties have been used for rapid repair media as well. Internal curing is a process by which the hydration of cement continues because of the availability of internal water, not part of the mixing water, which lies within internal curing agents (i.e., pre-saturated lightweight aggregates, super absorbent polymers, etc.).

As state Departments of Transportation (DOTs) face pressure to limit the impact of maintenance on the travelling public, the use of rapid pavement repair media is increasingly prevalent in the field. Several recent publications discuss application, benefits, and drawbacks of rapid repair media (Bizzozero, Gosselin, & Scrivener, 2014) (Poole & Sims, 2016) (Winnefeld & Lothenbach, 2010) (Qian, You, Wang, Wang, & Jia, 2014) (Zuniga, 2013) (Ramseyer & Bescher, 2014). Rapid repair media may be based on type III high early strength portland cement, with or without chemical accelerators, and possibly including supplementary cementitious materials like silica fume (Won, Kim, Lee, Lee, & Park, 2011) (Moffatt & Thomas, 2017). Many formulations are based on calcium sulfoaluminate CSA cement, which offers extremely rapid strength development even without the use of chemical accelerators (Beretka, Sherman, Marroccoli, Pompo, & Valenti, 1997) (Glasser & Zhang, 2001) (Juenger, Winnefeld, Provis, & Ideker, 2011). Proprietary formulations are common.

Anecdotal evidence gathered from interviews of Utah DOT (UDOT) personnel suggest the propensity for early-age cracking of CSA repair media in the field. Cracks typically form in the longitudinal direction after 10–15 d (Maguire, Thomas, Quezada, & Szary, 2015). This anecdotal evidence is, however, in direct opposition to previously published results suggesting that CSA cements exhibit almost no shrinkage (Bizzozero, Gosselin, & Scrivener, 2014) (Kaufmann, Winnefeld, & Lothenbach, 2016). Despite potential issues with volume stability and cracking, CSA based repair media are in common use in the field because of the tremendous benefit offered in terms of rapid strength development and excellent mechanical strength. Other benefits offered by CSA include reduced environmental impact, and excellent durability performance (Thomas, Maguire, Sorensen, & Quezada, 2018) (Juenger, Winnefeld, Provis, & Ideker, 2011) (Damtoft, Lukasik, Herfort, Sorrentino, & Gartner, 2008) (Trauchessec, Mechling, Lecomte, Roux, & Le Rolland, 2015).

Internal curing has been often demonstrated as a means of improving volume stability by providing internal reservoirs of water to offset the effects of internal desiccation and drying (Bentz D. , Jones, Peltz, & Stutzman, 2015) (Bentz D. , Jones, Peltz, & Stutzman, 2015) (Paul & Lopez, 2011) (Wei, Xiang, & Zhang, 2014). This is traditionally provided by replacement of normalweight aggregates with presaturated lightweight expanded clay or shale aggregates. More recently, this has been performed using presaturated super-absorbent polymers (Craeye, Geirnaert, & Schutter, Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks, 2011) (Justs, Wyrzykowski, Bajare, & Lura, 2015). The intent of this chapter is to investigate whether internal curing with presaturated lightweight aggregate can improve the volume stability of CSA pavement repair media, and—in doing so—prolong the time to cracking in laboratory tests. The results presented in this chapter will be of interest to researchers and practitioners alike and will be of immediate use in the field.

4.2 Results and Discussion

4.2.1 DOT Survey

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.

Figure 26 shows the DOT responses to Question 1 which asked the agencies what environmental zone, according to the dominant weather condition of the local area, the state DOT operated in. Question 2 asked the agency to rank the DOT’s current routine for Full Depth Pavement repair from 1 (being the worst) to 5 (being the best). Results are shown in Figure 27. Question 3 asked the agency what the life expectancy of their full depth pavement repairs is. Responses are presented in Figure 28.

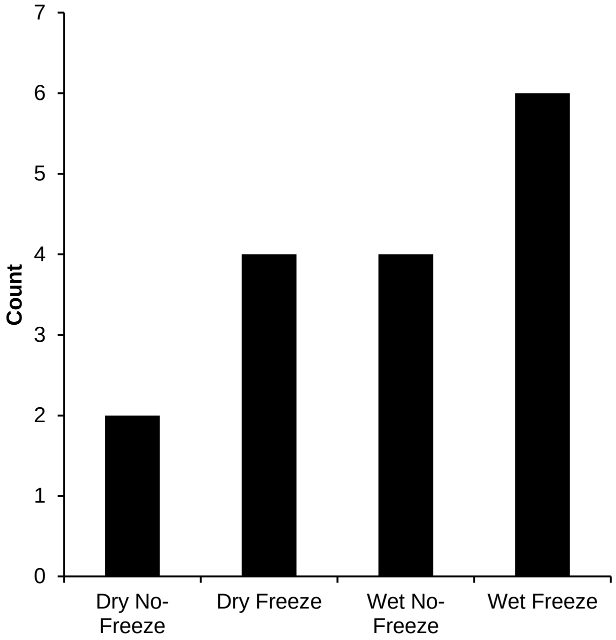

Figure 26 Results of survey question #1 (Environmental Zone)

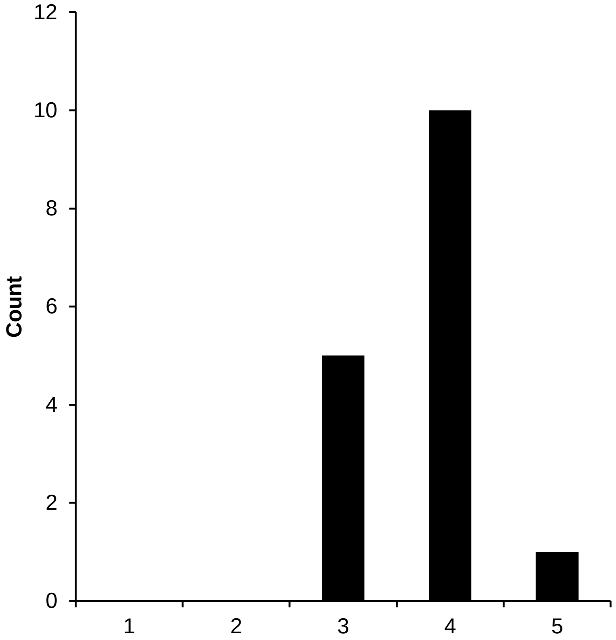

Figure 27 Results of survey question #2 (Repair Rating)

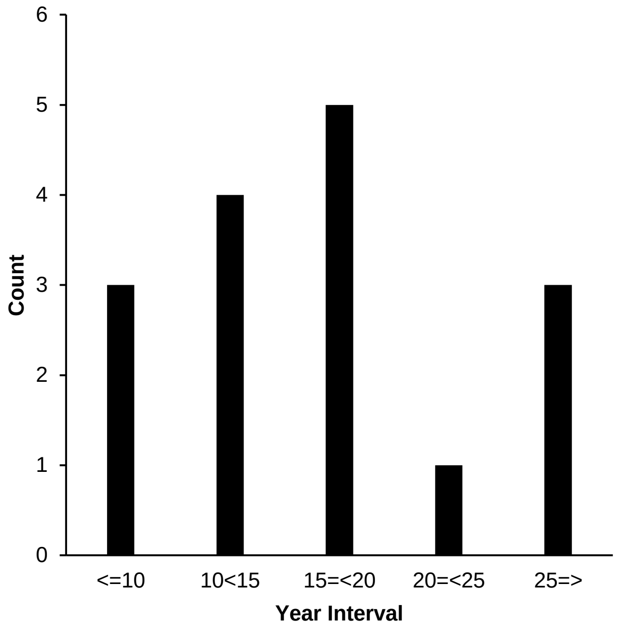

Figure 28 Results of survey question #3

Question 4 asked how long the agency's typical full depth pavement repair lasts (in years). Responses are shown in Figure 29 Question 5 asked agency employees, contractors, or both if they utilized Full Depth Pavement Repair. Responses are presented in Figure 30. Question 6 asked DOTs to specify how soon repaired areas re-opened to traffic. Answers obtained were mostly ranges of time, so two histograms were made, one with the earliest times and one with the latest times (see Figure 31 and Figure 32). Question 7 asked what the criteria were for full depth pavement repairs to open to traffic (X strength, X time, etc.). Two histograms were plotted for this question. Figure 33 shows the minimum strength prior to opening and Figure 34 shows the minimum wait time before opening. Question 8 asked what the material or practice was which performed the best for the DOT. The recorded answers were categorized (see Table 15) and plotted as seen in Figure 35.

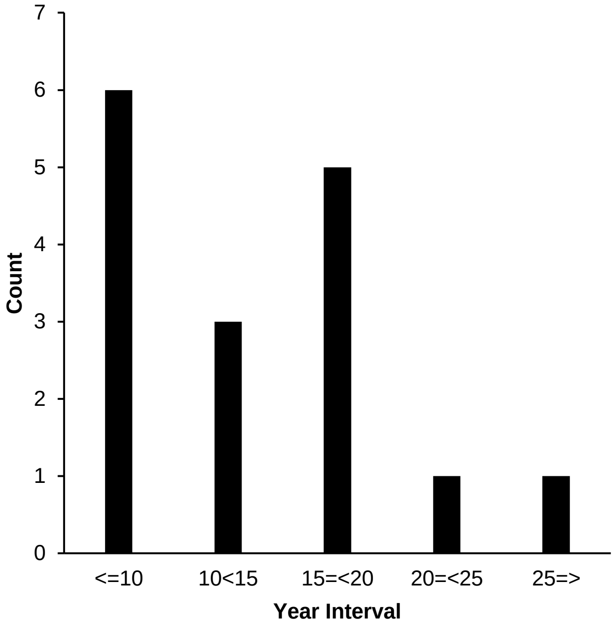

Figure 29 Results of survey question #4

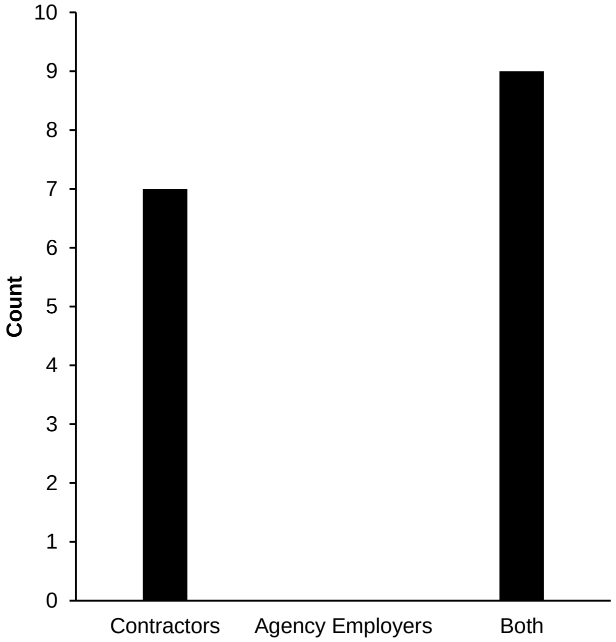

Figure 30 Results of survey question #5

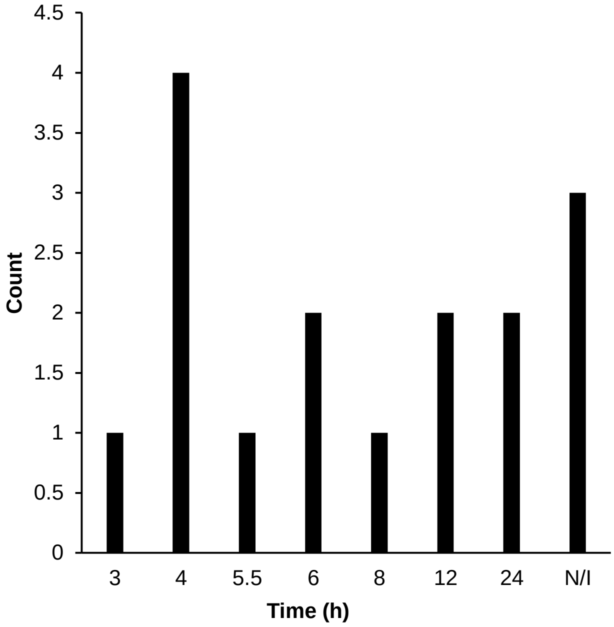

Figure 31 Results of survey question #6 Earliest Times (Note N/I = Not Important)

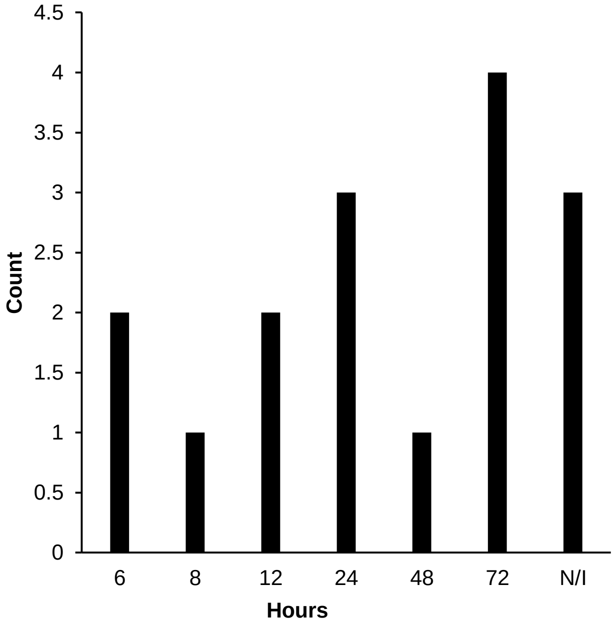

Figure 32 Results of survey question #6 Latest Times (Note N/I = Not Important)

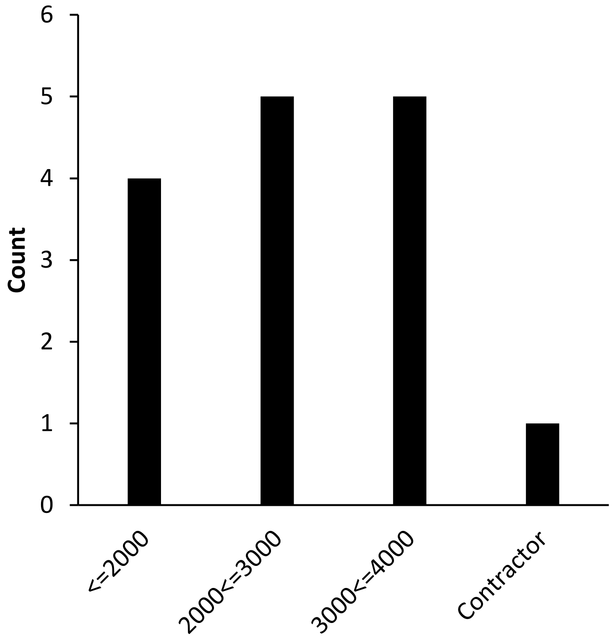

Figure 33 Results of survey question #7 Minimum Strength (Contractor means the Min. Strength is left to the Contractors decision)

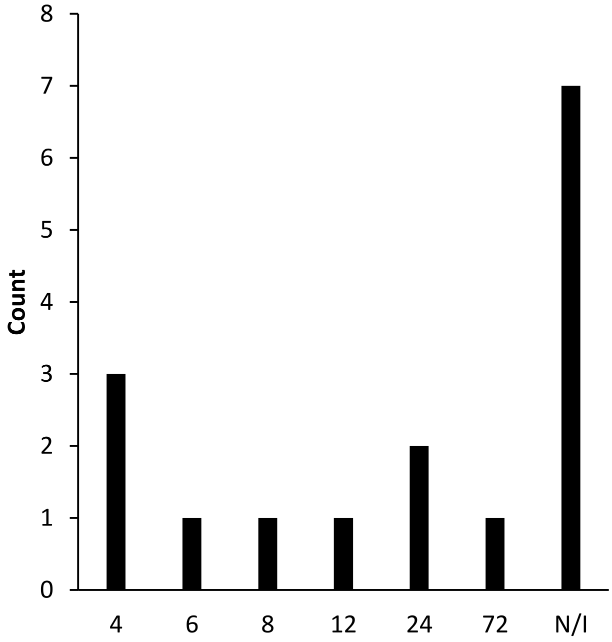

Figure 34 Results of survey question #7 Minimum Time before Opening

Table 15 Responses and Categories for Question #8

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

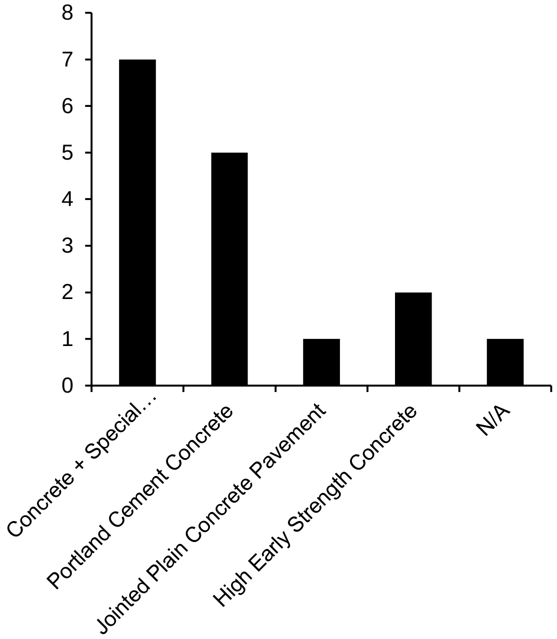

Figure 35 Results of survey question #8

Table 16 Responses and Categories for Question #9

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

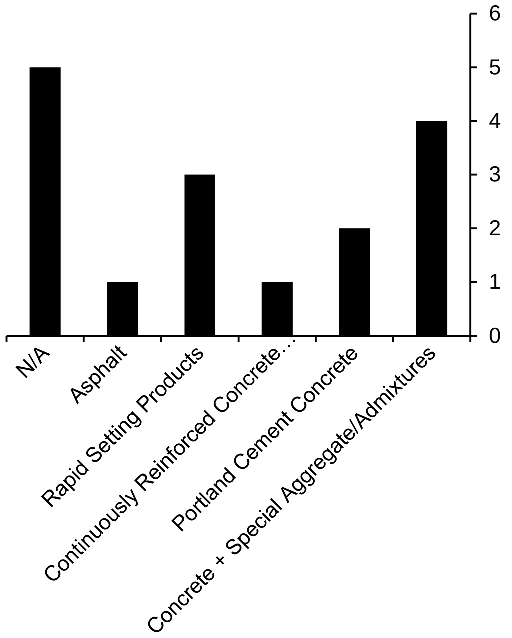

Figure 36 Results of survey question #9

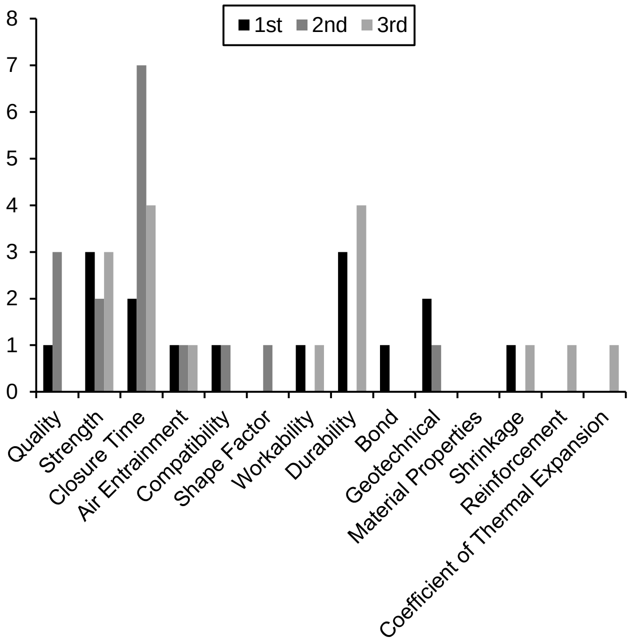

Figure 37 Results of survey question #10 (1st Priority, 2nd Priority and 3rd Priority)

Question 9 asked what material or practice performed the worst for the DOT. The recorded answers were categorized (see Table 16) and plotted in Figure 36. Question 10 asked DOTs to select their top three criteria when performing a concrete repair mixture. The most selected criterion was Closure Time (see Figure 37).

After recording the results from each question, Table 17 was obtained via Statistical Analysis Software (SAS) University Edition.

Numerical Variables:

- ID: Represents each different state.
- rate: Represents answers to Question #2
- expect: Represents answers to Question #3 (in years)
- actual: Represents answers to Question #4 (in years)
- optime1 and optime2: Represent answers to Question #6 (in hours)

- opstr and optimes: Represent answers to Question #7 (in psi and in hours respectively)
- money: Represents answers to Question #11 (in US dollars)

Analyzing the relationship table (Table 17), it is safe to assume that there is a significant relationship between opstr and optime1, meaning that one can be the predictor of the other. Therefore, those DOTs that indicate time to opening is important also feel, high strength at opening is important. Also, there is a very significant relationship between money and optimes which indicates that both variables are strongly related under the significance level of 5%. The answers to rate (rating a DOT gives to their repairs 1-5) are not strongly related to expect (expected life for a repair) or actual (actual life for a repair). A DOTs quality assessment of their repairs in unrelated to the actual performance. DOTs may need a more objective way to evaluate pavement performance.

4.2.2 Proprietary Mixtures

Compressive strength was tested from each mixture at 4 hours and 24 hours and the average was plotted in the bar graph as shown in Figure 38. P2 obtained the highest compressive strength at 4 hours and 24 hours with approximately 5,900 psi and 7,300 psi, respectively. The average Modulus of Elasticity of each mixture can be seen in Figure 39. P2 obtained the highest Modulus among all proprietary mixtures at 4,100 ksi at 4 hours. The average splitting tensile strength of each proprietary mixture is plotted as shown in Figure 40.

Table 17 Pearson Relationship Matrix between the numerical variables obtained in the survey

Pearson Relationship Coefficients, N = 16									
Prob > |r| under H0: Rho=0									
	ID	rate	expect	actual	optime1	optime2	opstr	optimes	money
ID	1	0.2425	0.0462	0.0468	0.2948	0.0153	0.007	0.1874	0.1608
		0.3654	0.865	0.8631	0.2677	0.9549	0.9794	0.4871	0.5518
rate	0.2425	1	0.3584	0.2728	0.1970	0.2580	0.1124	0.2463	0.1471
	0.3654		0.1728	0.3066	0.4645	0.3346	0.6785	0.3578	0.5866
expect	0.0462	0.3584	1	0.4074	0.2655	0.0188	0.0851	0.0526	0.1108
	0.865	0.1728		0.1172	0.3203	0.9449	0.7538	0.8465	0.6827
actual	0.0468	0.2728	0.4074	1	0.0498	0.2067	0.2670	0.0044	0.1369
	0.8631	0.3066	0.1172		0.8545	0.4424	0.3173	0.9869	0.6131
optime1	0.2941	0.1970	0.2655	0.0498	1	0.2560	0.3457	0.0161	0.1947
	0.2677	0.4645	0.3203	0.8545		0.3385	0.1896	0.9526	0.4698
optime2	0.0153	0.2580	0.0188	0.2067	0.2560	1	0.0634	0.3248	0.0806
	0.9549	0.3346	0.9449	0.4424	0.3385		0.8153	0.2196	0.7665
opstr	0.0070	0.1124	0.0851	0.2670	0.3457	0.0634	1	0.0007	0.1748
	0.9794	0.6785	0.7538	0.3173	0.1896	0.8153		0.9978	0.5171
optimes	0.1874	0.2463	0.0526	0.0044	.01617	0.3248	0.0007	1	0.5482
	0.4871	0.3578	0.8465	0.9869	0.9526	0.2196	0.9978		0.0279
money	0.1608	0.1471	0.1108	0.1369	0.1947	0.0806	0.174	0.5482	1
	0.5518	0.5866	0.6827	0.6131	0.4698	0.7665	0.5171	0.0279	

P1 attained the highest split tension at approximately 280 psi at 4 hours. Figure 4.4 shows drying shrinkage strain on each proprietary mixture. It is important to note that these measurements do not indicate that the proprietary materials have stopped shrinking. P1 obtained the highest drying shrinkage at the end of the measurements. Initial and final setting times for proprietary repair media are shown in

Figure 42. The fastest setting repair medium was P3, with initial and final setting times of 9 and 22 minutes, respectively. The slowest setting medium was P2, with initial and final setting times of 50 and 65 minutes.

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

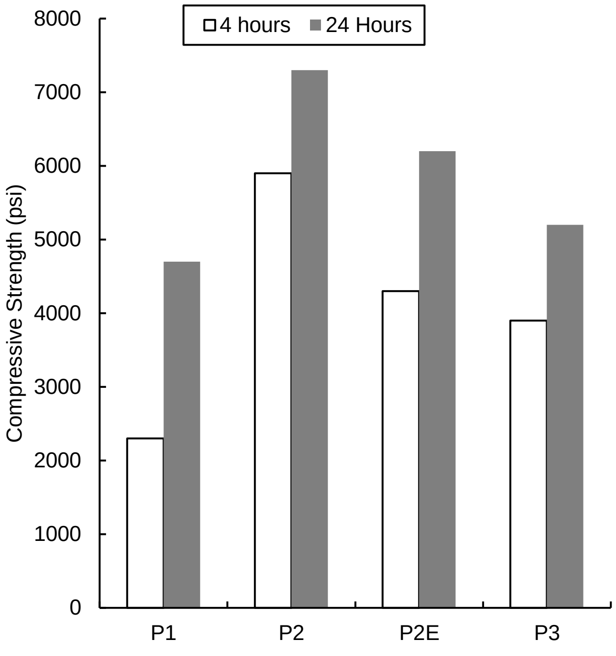

Figure 38 Compressive strength of proprietary materials

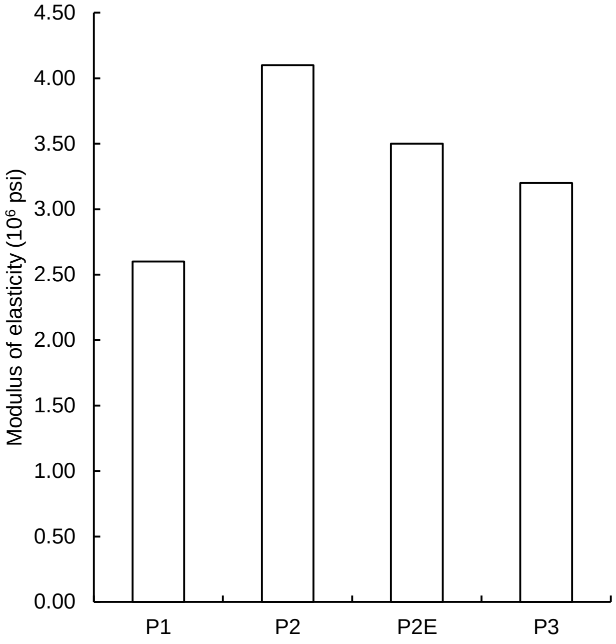

Figure 39 Modulus of elasticity of proprietary materials (age = 4 hours)

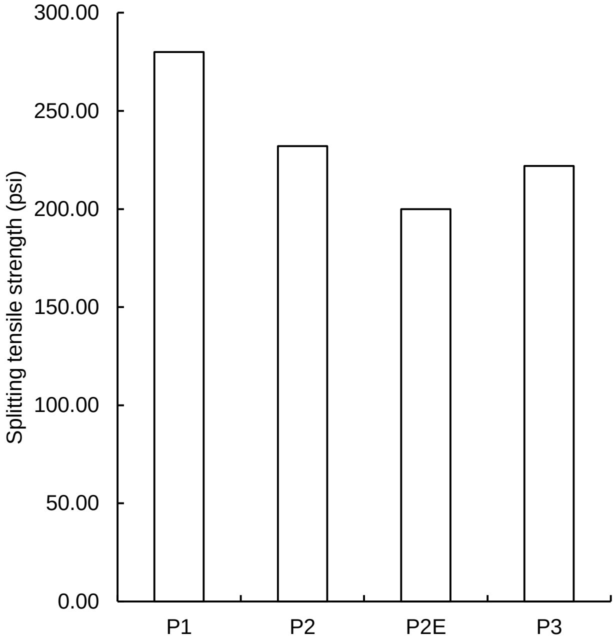

Figure 40 Splitting tensile strength of proprietary materials (age = 4 hours)

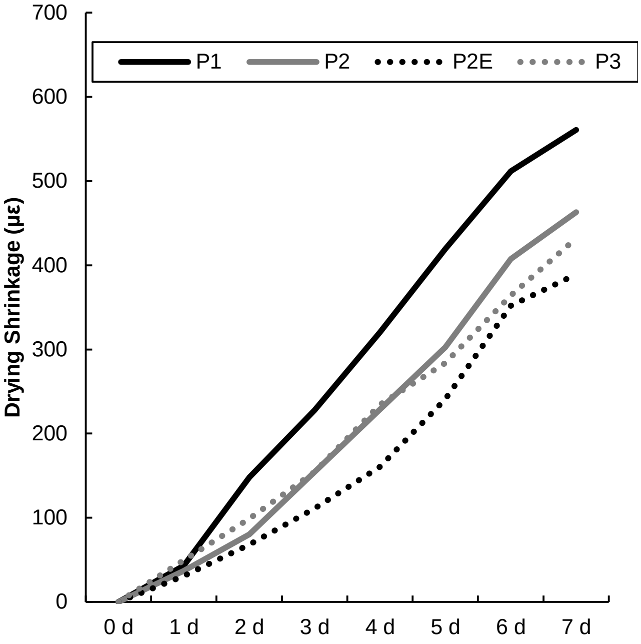

Figure 41 Drying Shrinkage Strain for proprietary materials

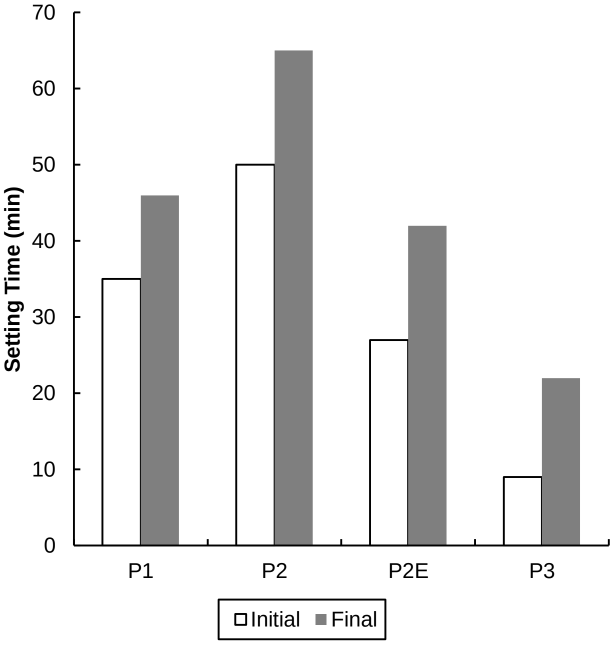

Figure 42 Initial and Final setting times of proprietary materials

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

P3 had the lowest workability time of all the mixtures tested (9 minutes for initial setting), which may have been caused by temperature, although the mixture was made in the temperature range specified by the manufacturer. Table 4.1 presents a summary of the tests performed on the proprietary mixtures. Table 18 lists the results of tests performed on the proprietary products side-by-side for comparison.

4.2.3 Phase I

Figure 43 contains compressive strengths of mixtures with type II/V cement. Typically, type II/V cements do not gain strength rapidly. Mixture 3 had the highest 4-hour compressive strength observed at about 2,100 psi. Mixtures 4 and 5 with more accelerator failed to gain more strength than Mixtures 2 and 3 (at 4 h) and this is different from what has been observed throughout the study (more accelerator equals higher early compressive strength). The unknown water content of the accelerator may be affecting Mixtures 4 and 5 by compromising their strength gain. The CSA mixture results are presented in Figure 44. These mixtures had strengths in excess of 7,000 psi at 4 hours, and the cement content used in these mixtures was greater than recommended by the manufacturer. This was done to do a one-to-one comparison to the other mixtures. Type III OPC mixtures compressive strengths are presented in Figure 45.

Table 18 Summary of Test Results for Phase I Proprietary Products

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

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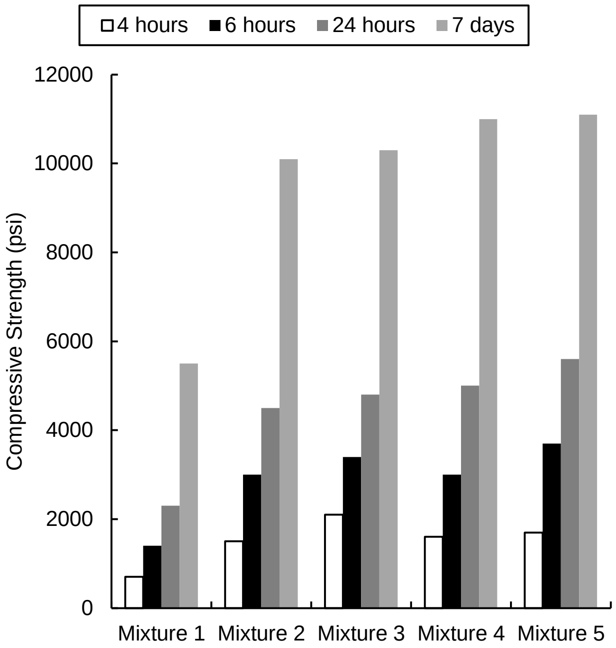

Figure 43 Phase I Type II/V Compressive Strengths

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

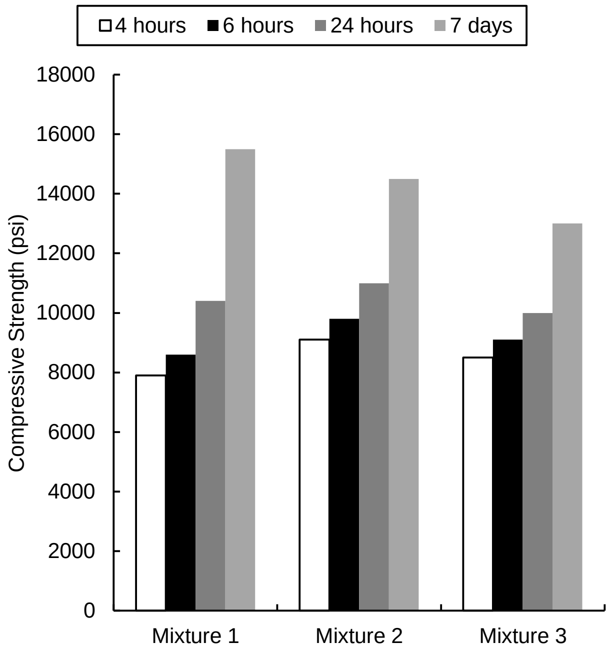

Figure 44 Phase I CSA Compressive Strengths

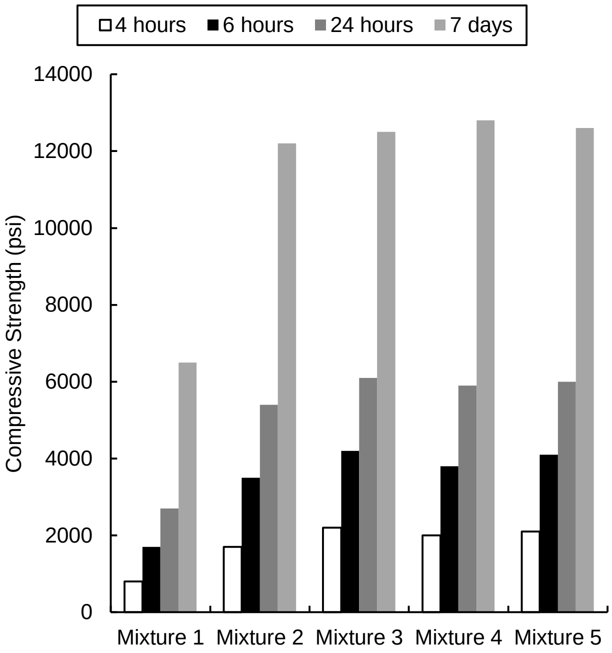

Figure 45 Phase I Type III Compressive Strengths

Based on the above results, Type II/V was discarded due to Type III mixtures obtaining between 10% and 25% more compressive strength when compared at same ages. Mixtures 3, 4 and Mixture 5 were selected for continued study, including PSLWA full and partial replacement (IC), Silica Fume replacement, and investigation into durability and dimensional stability, similar to the tests performed on the proprietary materials.

4.2.4 Phase II

The initial and final setting times for the Phase II mixtures are presented in Figure 46. The CSA reach initial set under 15 min (CSA1, CSAIC, and CSAICF, with 9, 16, 13 min, respectively). Internal curing extends the initial setting time of CSA mixtures significantly—by 40% with only coarse PSLWA and by 70% with fine and coarse PSLWA. OPC mixtures reached initial set between 27 and 38 min. From previous research, the setting time for full CSA concrete mixtures has been determined to be around 5 minutes and has been extended to 45 minutes or more utilizing admixtures (Ioannou, Reig, Paine, & Quillin, 2014) (Glasser & Zhang, 2001). Internal curing extended the initial setting time by about ten percent. The inclusion of silica fume accelerated the initial setting time of OPC by about ten percent. A combination of 30% silica fume and internal curing with only coarse PSLWA resulted in similar setting times to OPC with neither PSLWA or silica fume. The same mixture with both fine and coarse PSLWA exhibited the shortest setting time of all mixtures. The longer setting times exhibited by the OPC mixtures could be reduced by increasing the dosage of accelerator, but this reveals one of the primary benefits of CSA for use as rapid repair materials. CSA cements set much more quickly than neat OPC, and OPC requires the use of high dosages of accelerators to approach the rapid setting behavior of CSA. Additionally, the delay between initial and final setting times is much shorter for CSA than for OPC, meaning that once CSA begins to set it sets very quickly (on average, 11 minutes after initial set). Once OPC begins to set, it remains in the intermediate phase for relatively longer (around 30 min on average).

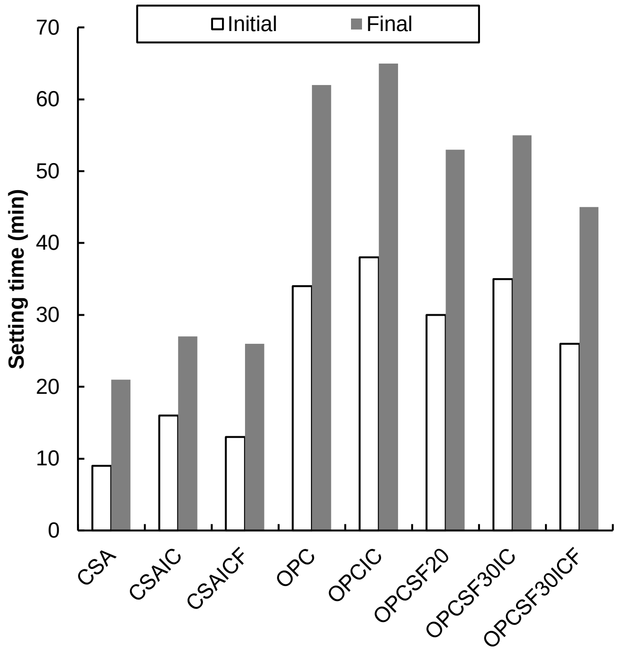

Figure 46 Initial and final setting times of Phase II non-proprietary mixtures

Compressive strength results are shown in Figure 47. Compressive strength was evaluated at [4 h, 6 h, 24 h and 7 d]. CSA mixtures exhibited the highest strength despite *w/cm* being constant between all mixtures. Without internal curing, the compressive strength was about 8 ksi after 4 h and over 14 ksi at 7 d. As expect, internal curing reduced the compressive strength significantly—by about 2 ksi with coarse PSLWA and by more than 3 ksi with both fine and coarse PSLWA. CSA concrete mixtures have been found to obtain more than 5,000 psi of strength at 6 hours, and more than 8,000 psi at 7 days in previous research (Péra & Ambroise, 2004) (Ioannou, Reig, Paine, & Quillin, 2014).

OPC concrete exhibited significantly lower strength. Without internal curing the strength was about 2 ksi at 4 h and approached 10 ksi at 7 d. Again, internal curing reduced compressive strength, this time by about 500 psi. Inclusion of silica fume improved the compressive strength of OPC mixtures. The addition of 20% silica fume improved the compressive strength to about 3 ksi at 4 h and 10.5 ksi at 7 d. Internal curing with coarse PSLWA only reduced the compressive strength by a few hundred psi, and internal curing with both fine and coarse PSLWA actually improved the strength at all ages.

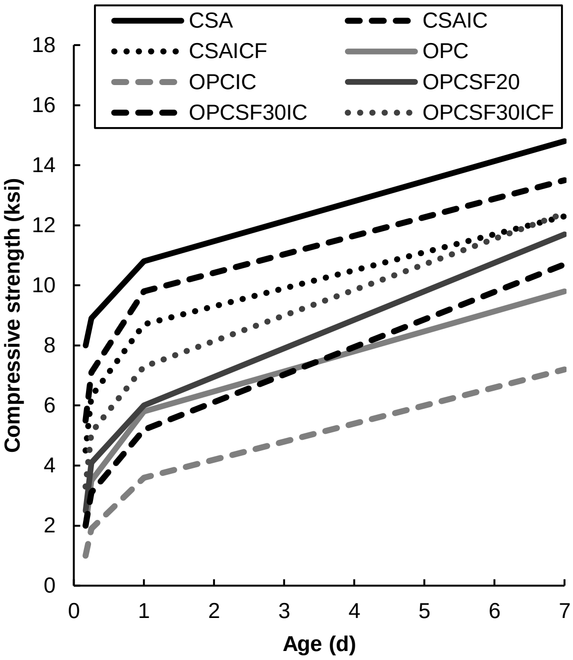

Figure 47 Compressive strength development of Phase II non-proprietary mixtures

Static moduli of elasticity are shown in Figure 48, and splitting tensile strength results are shown in Figure 49. Both properties were only measured at 4 hours. In general, the results followed the same trend as compressive strength; CSA mixtures exhibited improved mechanical performance, and the internal curing with PSLWA resulted in an across-the-board reduction in mechanical performance. Silica fume improved the performance of OPC-based mixtures by a small margin. Donza et al. obtained static moduli for CSA concrete mixtures as high as 5.6 x 10^6 psi (at 28 d) and split tensile strength as high as 565 psi (at 28 d), and Beshr and Almusallam obtained static moduli for OPC mixtures as high as 4.2 x 10^6 psi (at 28 d) and split tensile strength as high as 544 psi (at 14 d) (Donza, Cabrera, & Irassar, 2002) (2003). These results were obtained at older ages, and thus are expected to be higher than the results of this study. The difference in modulus of elasticity between CSA- and OPC-based mixtures was, however, far more significant than the difference in splitting tensile strengths. This will be the subject of ongoing research.

Autogenous shrinkage results are presented in Figure 50, where time $t = 0$ reflects the time of final set, as reported in Figure 46. Without internal curing, CSA exhibited rapid autogenous shrinkage within the first 8 hours, reaching about 300 με and remaining approximately constant thereafter. When internally cured with coarse PSLWA, the mixture exhibited very early age expansion reaching about 50 με within the first hour, after which the mixture began to shrink. The resulting shrinkage was significantly reduced—reaching about 100 με within two hours and increasing only slightly thereafter. Internal curing with both fine and coarse PSLWA resulted in early-age expansion near 300 με at 2 h, shrinking rapidly to a shrinkage strain of about 100 με after 8 hours and shrinking gradually to an ultimate shrinkage strain of about 150 με thereafter. CSA concrete mixtures have been found to obtain as high as 300 με and OPC concrete mixtures, as high as 600 με of autogenous shrinkage in previous research (Guan, Gao, Sun, Won, & Ge, 2016).

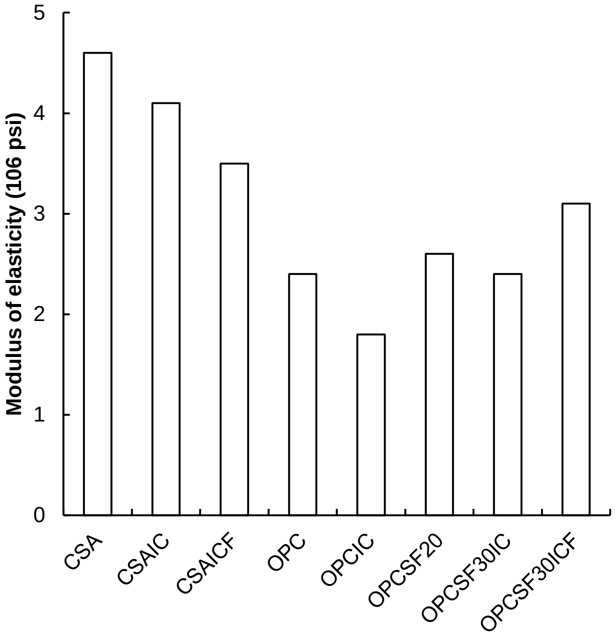

Figure 48 Static modulus of elasticity (at 4 hours) of Phase II non-proprietary mixtures

Similar behavior was observed for OPC-based mixtures with and without silica fume. The shrinkage was slightly lower for OPC than for CSA, and the inclusion of silica fume further reduced the autogenous shrinkage. As with CSA-based mixtures, internal curing resulted in slight early-age expansion and tempered the later-age shrinkage. Internally cured OPC without silica fume and with only coarse PSLWA exhibited the lowest ultimate shrinkage, near 100 με at 48 h. Internal curing effects have been observed in previous research as well (Bentz D. , Jones, Peltz, & Stutzman, 2015).

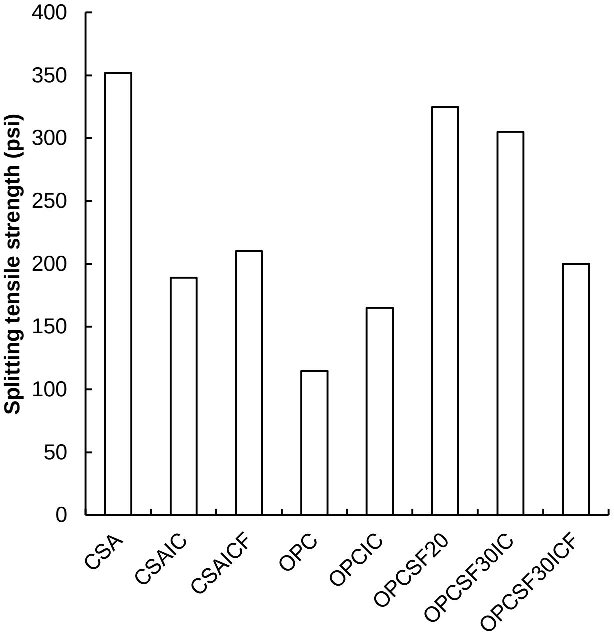

Figure 49 Splitting tensile strength (at 4 hours) of Phase II non-proprietary mixtures

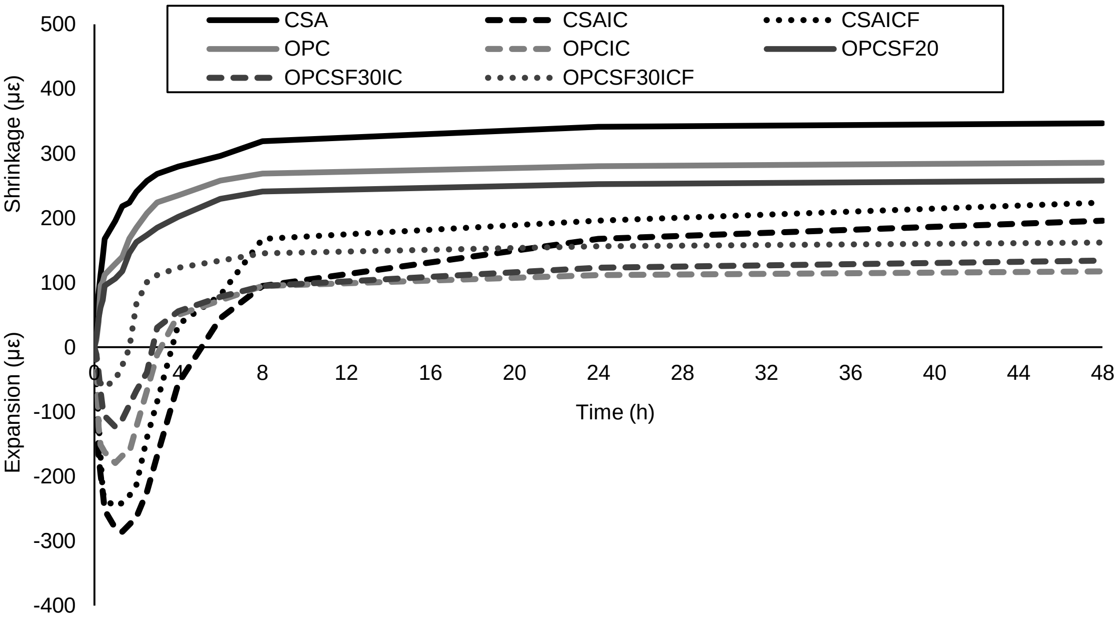

Figure 50 Autogenous shrinkage of Phase II non-proprietary mixtures

Drying shrinkage results are presented in Figure 51, where time $t = 0$ is 24 h after final set. CSA mixtures exhibited lower drying shrinkage than OPC, and internal curing reduced the drying shrinkage even further. However, internal curing of OPC mixtures reduced the drying shrinkage well below that of any CSA mixture—internally cured or otherwise. Inclusion of silica fume in OPC mixtures increased the drying shrinkage, but internal curing was effective in reducing that shrinkage. Even the least volume-stable mixtures exhibited drying shrinkage of less than 700 με in 35 d. Bescher observed between 550 and 990 με during drying shrinkage tests of several rapid set concretes at 7 days.

Figure 52 reports time to cracking under the restrained ring shrinkage test. CSA mixtures cracked in about 13 d. This behavior was the impetus for this study—CSA mixtures have a tendency to crack at an early age in the field. Internal curing with coarse PSLWA extended cracking to about 21 d; internal curing with fine and coarse PSLWA was less effective, extending cracking to about 17 d. Interestingly, the same trend was observed in the shrinkage data, suggesting that internal curing may be more effective at preventing cracking of CSA repair media when only coarse PSLWA is used. This will be the subject of continued investigation.

CSA mixtures did not crack until 35 d, and internal curing extended that to 45 d. Inclusion of silica fume reduced the time to cracking, but OPC mixtures including silica fume still performed better than CSA mixtures. Yatagan also reported between 5 and 12 d to first crack in shrinkage rings for different types of rapid set cement concrete mixtures (2015).

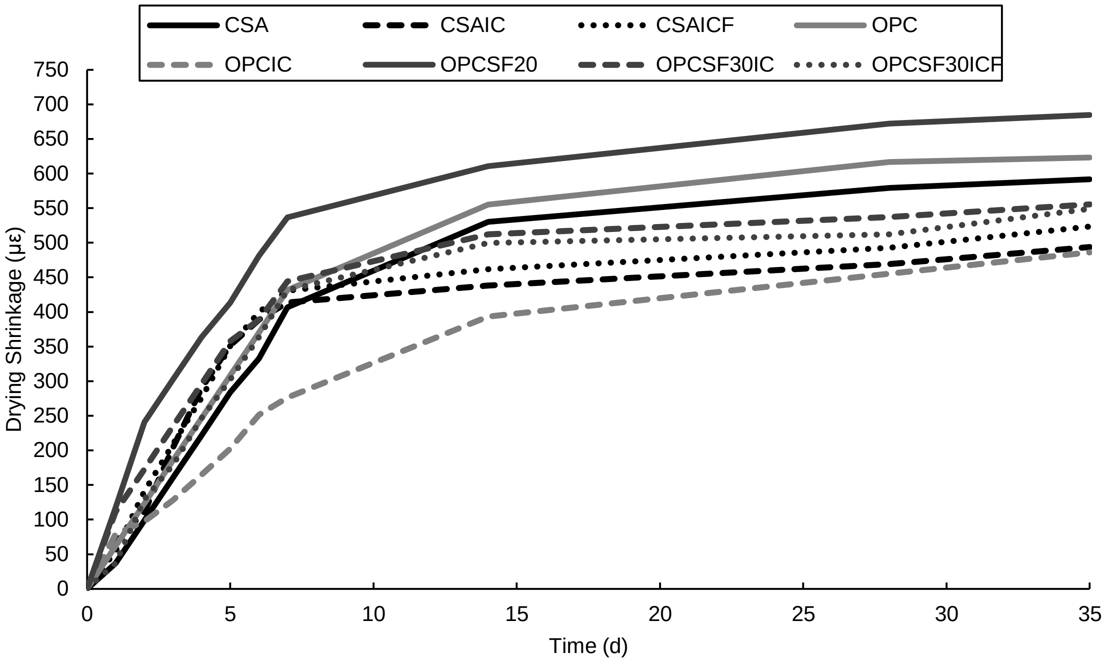

Figure 51 Drying shrinkage of Phase II non-proprietary mixtures

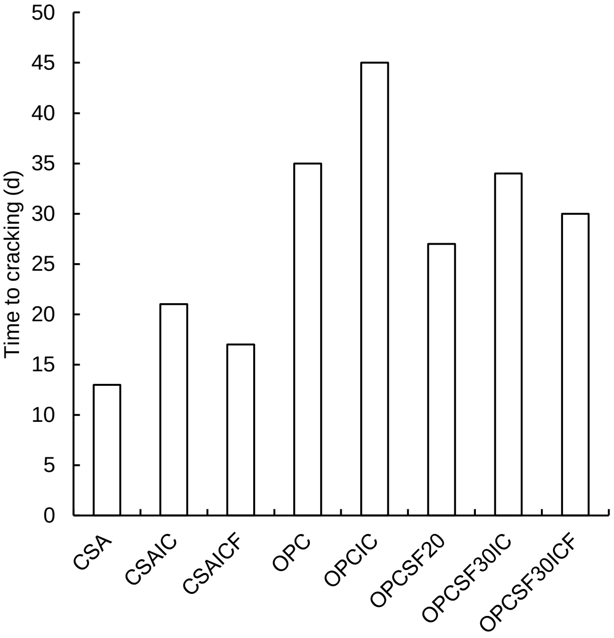

Figure 52 Time to cracking under restrained ring shrinkage test of Phase II non-proprietary mixtures

Furthermore, Yang et al also reported cracking at 12 d and in some cases no cracking within 24 d for rapid set pre-packaged concrete mixtures (Yang, Brown, Huddleston, & Seger, 2016) Unfortunately, these results show the limitations of internal curing in preventing early-age cracking of CSA repair media. CSA mixtures, internally cured or otherwise, cracked in less than half the time of OPC mixtures and more than 1.5 times faster than OPC mixtures with partial silica fume replacement. This is a major limitation of CSA for use in repair media; despite the tremendous advantages related to improved strength and rapid strength development, CSA repair media struggle with early-age volume stability and cracking, both in the laboratory and in the field.

Figure 53 shows total deformation of the repair media. Following elastic deformation OPC repair media creeped about 300 με in 120 days. Internal curing (OPCIC) did not significantly change ultimate creep, when compared to the control. Inclusion of silica fume in OPC repair media reduced the creep to about 25 με (OPCSF20), and 50 με for OPCSF30I, but a large reduction of 90 με for OPCSF30ICF. Creep deformation in CSA repair media was extremely low with an ultimate value near 50 με for the CSA mixture and increased to 70 με for CSAIC and 60 με for CSAICF. Most of this deformation occurred in the first few days. Vincent (2003) obtained similar results with his research regarding the lightweight aggregate mixtures. The effect of PSLWA addition to the repair media seems to be opposite for CSA and OPC. Increasing creep behavior is beneficial for repair media as it will mitigate propensity for cracking, however, the aforementioned improvements in shrinkage volume stability with only coarse PSLWA far outweigh the minor changes in creep deformation observed here. Mass retained values for the Phase II mixtures are presented in Table 19. Similar mass retained values have been presented by Ozyildirim (2009) for concretes with similar constituents. There was almost no observable difference in mass retained in the Phase II mixtures subjected to Freeze Thaw.

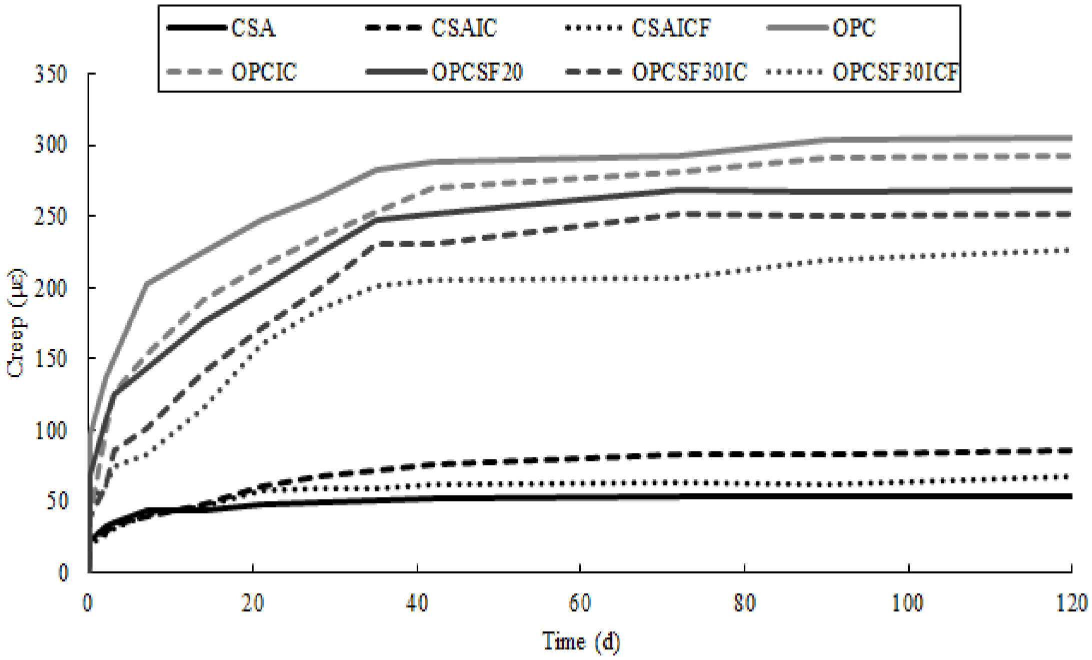

Figure 53 Creep deformation of Phase II non-proprietary mixtures

Table 19 Mass retained after 300 cycles of freezing and thawing of Phase II non-proprietary mixtures

Test	Unit	CSA1	OPC SF20	OPC1	OPC IC	OPC SF30 IC	CSA IC	CSA ICF	OPC SF30 ICF
Mass Retained	%	96	94	95	94	94	98	97	95

4.2.5 Statistical Analysis of Phase II Results

Based on the results, statistical analysis was performed on the mixtures. This analysis was meant to determine any relationships between materials used and the structural properties of each mixture. A confidence level of 95% was utilized and p-values lower than 0.05 were considered with a statistically significant relationship.

Utilizing the Pearson Correlation Coefficient Procedure (shown in Appendix B), the survey results could be analyzed and the following relationships between variables were found:

- Initial and Final setting time are extremely dependent on the type of cement used (<.0001), water content (0.0007), amount of accelerant (0.0006).
- Compressive strength is related with initial and final setting with a p-value of 0.0040 and 0.005 respectively.
- Drying Shrinkage is significantly dependent on the amount of water used in the mixture, the percentage of entrained air (0.0240), initial and setting time (0.0227).
- Elastic Modulus is not dependent on the amount (0.5235) nor type (0.5773) of aggregates used per mixture; however, it is extremely dependent on the amount (0.0013) and type of cement used (0.0025).
- Mass retained in Freeze Thaw is significantly dependent on the Compressive Strength values obtained at 24 hours (0.0393) and 7 days (0.049).
- Creep Coefficient is close to being significantly dependent on the amount of entrained air (0.095) and the unit weight of the mixture (0.0627).

4.3 Conclusions

This chapter was focused on the investigation of the setting time, mechanical properties, and volume stability of CSA and OPC repair media for concrete pavements. CSA repair media exhibit improved compressive strength, tensile strength, modulus of elasticity, and rate of strength development over Type III OPC repair media, even with the inclusion of high dosages of accelerators and silica fume. This suggests improved performance as rapid pavement repair media.

However, the volume stability of CSA mixtures, as evidenced by autogenous shrinkage, drying shrinkage, and restrained shrinkage cracking, is comparably worse than that of OPC with or without silica fume. Internal curing of CSA mixtures with PSLWA tends to improve volume stability at the expense of mechanical strength, and also retards the setting time.

Paradoxically, internal curing of CSA repair media with coarse PSLWA resulted in better volume stability and mechanical properties than internal curing with fine and coarse PSLWA, although the retarding effect was less significant in the former than in the latter. These results show significant promise for internally cured CSA repair media, but also highlight several shortcomings of the material. Specifically, the time to cracking of CSA repair media under restrained shrinkage is less than half that of OPC repair media. Finally, the creep deformation in CSA repair media is a mere fraction of that in OPC repair media, regardless of internal curing.

CHAPTER 5

RETARDING SET TIME OF CSA MIXTURES

5.1 Introduction

The rapid setting nature of CSA cement is beneficial for repair applications but precludes its use in routine precast or ready-mix operations. Based on existing literature (Samson, Phelipot-Mardelé, & Lanos, 2015) (Champenois, 2015) (Atthakorn, Somchai, Chantana, & Yothin, 2014) (Thanongsak, Yoshika, Supab, & Arnon, 2015) (Gediminas, Xiangming, Castro-Gomes, Huang, & Saafi, 2015), this Chapter focuses on utilizing citric acid, boric acid, sugar and Coca-Cola as admixtures for rapid repair media which could effectively retard the hydration in CSA cement and extend setting times to within the workable range for these operations. The results of 41 mixtures proportioned for the set time testing matrix are presented in the following section.

Temperature history was recorded for the mixtures as well. Due to time constraints, both sugar and Coca-Cola were only tested at a water to cement ratio of 0.4 and the maturity test was not performed in these mixtures. Previous research in maturity (Carino N. , 1984) (Carino & Tank, 1992) (Kim, Moon, & Eo, 1998), has demonstrated that this method is capable of estimating concrete compressive strength. Civil engineers have accurately estimated the compressive strength of OPC mixtures (Jin, Seung, Choi, & Yeon, 2017) (Perry, Fusiek, Niewczas, Rubert, & McAlorum, 2017), nevertheless, little has been researched about maturity of CSA. If the maturity method can accurately predict compressive strength for CSA mixtures, it will be beneficial for rapid concrete repair. Wireless monitoring of the temperature of concrete repairs could be performed with CSA which would let the contractor know the compressive strength of the repairs, leading to earlier opening times, thus reducing costs and waiting times.

5.2 Results

5.2.1 Setting Times

The initial and final setting times for the mixtures containing CA are presented in Figure 54. At a water to cement ratio of 0.4, the CA mixtures reached initial set as low as 20 min (at 0.125% of CA addition) and as high as 200 min (at 3% of CA addition). When the water to cement ratio is 0.5, the CA mixtures reached initial set as low as 18 min (at 0.125% of CA addition) and as high as 210 min (at 3% of CA addition). Moreover, when the water to cement ratio is 0.6, the CA mixtures achieved initial set as low as 24 min (at 0.125% of CA addition) and as high as 245 min (at 3% of CA addition).

The initial and final setting times for the mixtures containing BA are presented in Figure 55. At a water to cement ratio of 0.4, the BA mixtures reached initial set as low as 36 min (at 0.125% of BA addition) and as high as 224 min (at 0.5% of BA addition). When the water to cement ratio is 0.5, the BA mixtures reached initial set as low as 20 min (at 0.125% of BA addition) and as high as 263 min (at 0.5% of BA addition). Furthermore, when the water to cement ratio is 0.6, the BA mixtures achieved initial set as low as 21 min (at 0.125% of BA addition) and as high as 275 min (at 0.5% of BA addition).

The initial and final setting times for the mixtures containing SU and Coke are presented in Figure 56. At a water to cement ratio of 0.4, the SU mixtures reached initial set as low as 8 min (at 0.1% of SU addition) which was lower than B0.4Ctrl (12 min), and as high as 30 min (at 15% of SU addition). Additionally, the Coke mixtures reached initial set as low as 11 min (at 1% of Coke addition) which was close to B0.4Ctrl (12 min) and as high as 97 min (at 15% of Coke addition).

The initial and final setting times for the mixtures with IC are presented in Figure 57. At a water to cement ratio of 0.4, the IC mixture reached initial set around 15 min, three minutes higher than the control. When the water to cement ratio is 0.5, the IC mixture reached initial set around 20 min, a seven-minute increase from the control. Furthermore, when the water to cement ratio is 0.6, the IC mixture achieved initial set around 22 min, a ten-minute increase from the control.

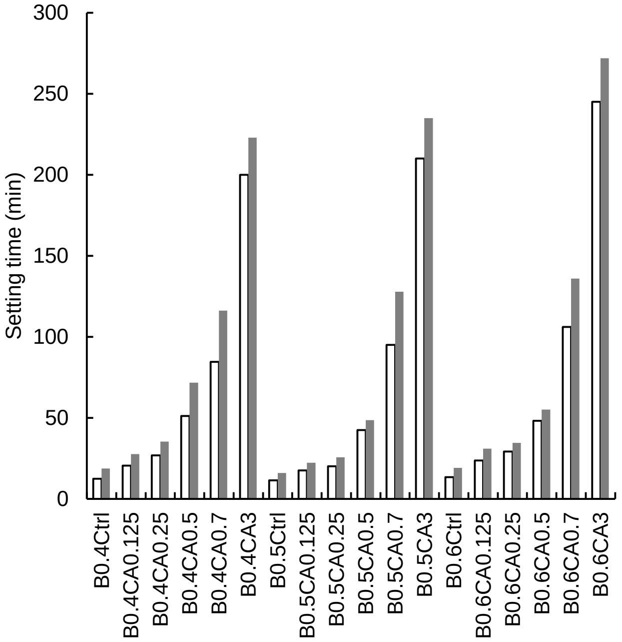

Figure 54 Setting times of CA mixtures

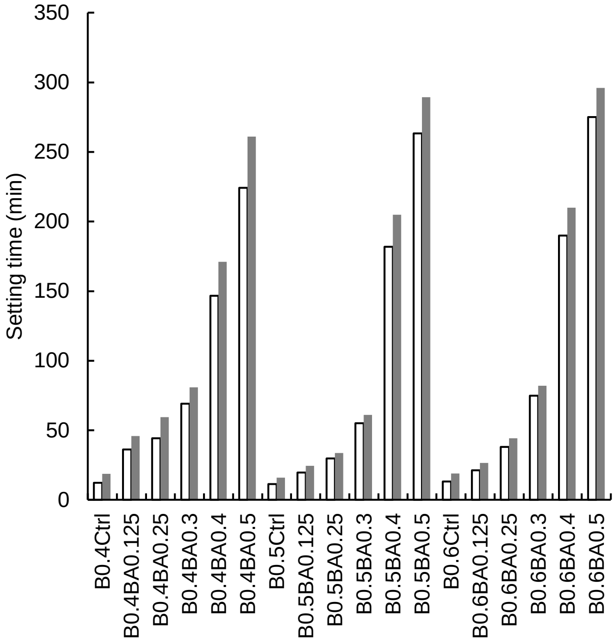

Figure 55 Setting times of BA mixtures

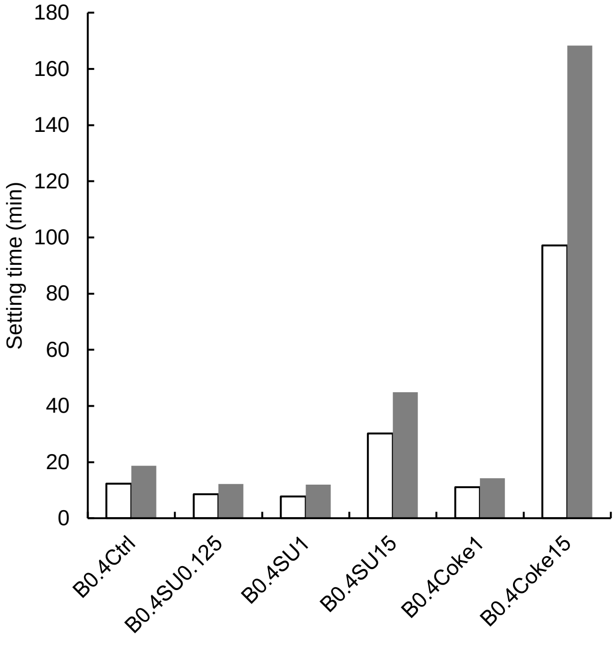

Figure 56 Setting times of SU and Coke mixtures

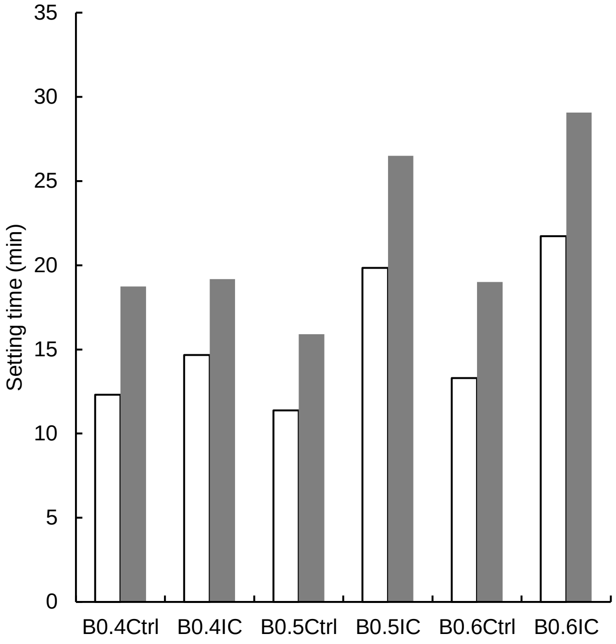

Figure 57 Setting times of IC mixtures

5.2.2 Compressive Strength Development

Compressive strength results are shown from Figure 58 to Figure 65. Compressive strength was evaluated at [12 h, 24 h, 3 d, 7 d and 28 d]. CA mixtures (at W/C = 0.4) exhibited losses in compressive strength between 13% (0.125% CA at 12 h) and around 60% (3% CA at 12 h) compared to the control, and between 9% (0.125% CA at 28 d) and around 40% (3% CA at 28 d). CA mixtures (at W/C = 0.5) obtained losses in compressive strength between 5% (0.125% CA at 12 h) and around 65% (3% CA at 12 h) compared to the control, and between 4% (0.125% CA at 28 d) and around 37% (3% CA at 28 d). CA mixtures (at W/C = 0.6) presented losses in compressive strength between 9% (0.125% CA at 12 h) and around 70% (3% CA at 12 h) compared to the control, and between 8% (0.125% CA at 28 d) and around 44% (3% CA at 28 d).

BA mixtures (at W/C = 0.4) produced losses in compressive strength between 7% (0.125% BA at 12 h) and around 20% (3% BA at 12 h) compared to the control, and between 8% (0.125% BA at 28 d) and around 18% (0.5% BA at 28 d). BA mixtures (at W/C = 0.5) exhibited losses in compressive strength between 8% (0.125% BA at 12 h) and around 30% (0.5% BA at 12 h) compared to the control, and between 4% (0.125% BA at 28 d) and around 27% (0.5% BA at 28 d). BA mixtures (at W/C = 0.6) displayed losses in compressive strength between 30% (0.125% BA at 12 h) and around 50% (0.5% BA at 12 h) compared to the control, and between 20% (0.125% BA at 28 d) and around 40% (0.5% BA at 28 d).

SU mixtures showed losses in compressive strength between 1% (0.125% SU at 12 h) and around 78% (15% SU at 12 h) compared to the control, and between 12% (1% SU at 28 d) and around 67% (15% SU at 28 d). Coke mixtures presented losses in compressive strength between 15% (1% Coke at 12 h) and around 45% (15% Coke at 12 h) compared to the control, and between 21% (1% Coke at 28 d) and around 67% (15% Coke at 28 d). IC mixtures exhibited losses in compressive strength at 12 h around 15% (W/C = 0.4), 16% (W/C = 0.5) and 18% (W/C = 0.6). Additionally, IC mixtures exhibited losses in compressive strength at 28 d around 10% (W/C = 0.4), 14% (W/C = 0.5) and 9% (W/C = 0.6).

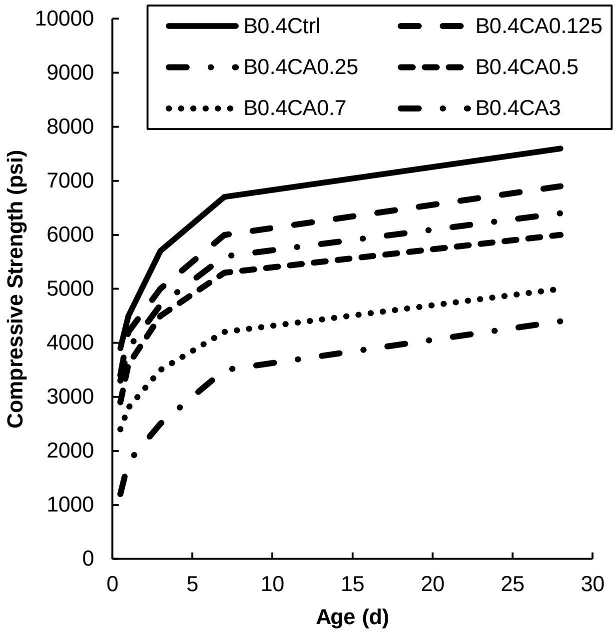

Figure 58 Compressive Strength of CA mixtures (w/c = 0.4)

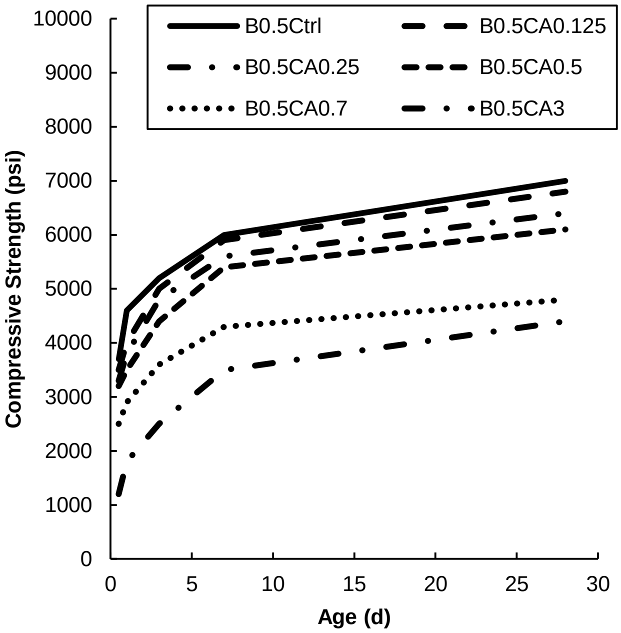

Figure 59 Compressive Strength of CA mixtures (w/c = 0.5)

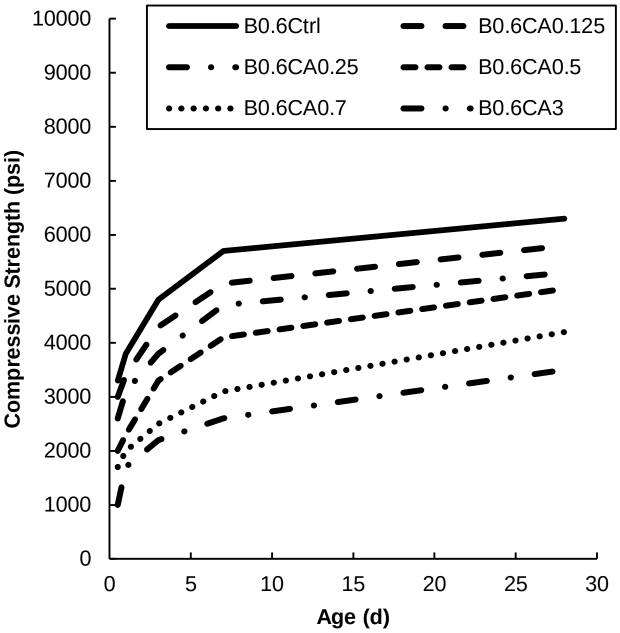

Figure 60 Compressive Strength of CA mixtures (w/c = 0.6)

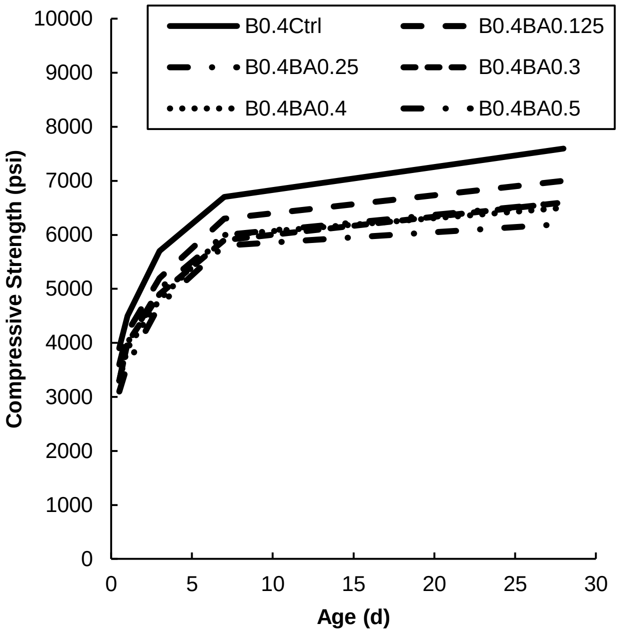

Figure 61 Compressive Strength of BA mixtures (w/c = 0.4)

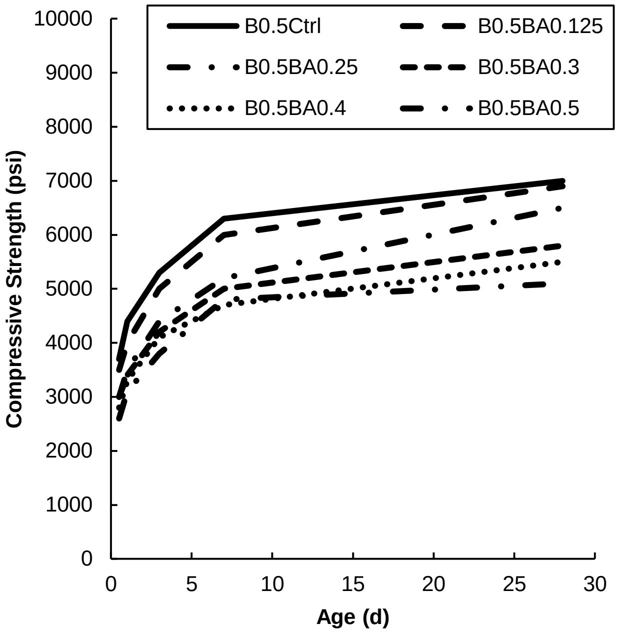

Figure 62 Compressive Strength of BA mixtures (w/c = 0.5)

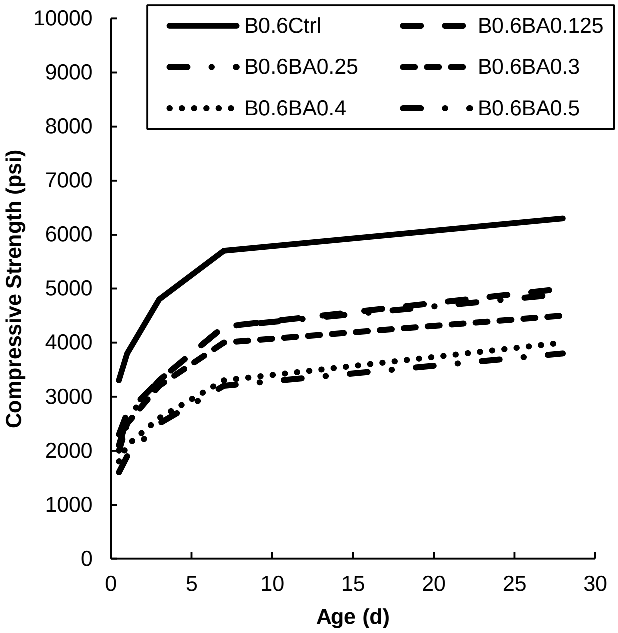

Figure 63 Compressive Strength of BA mixtures (w/c = 0.6)

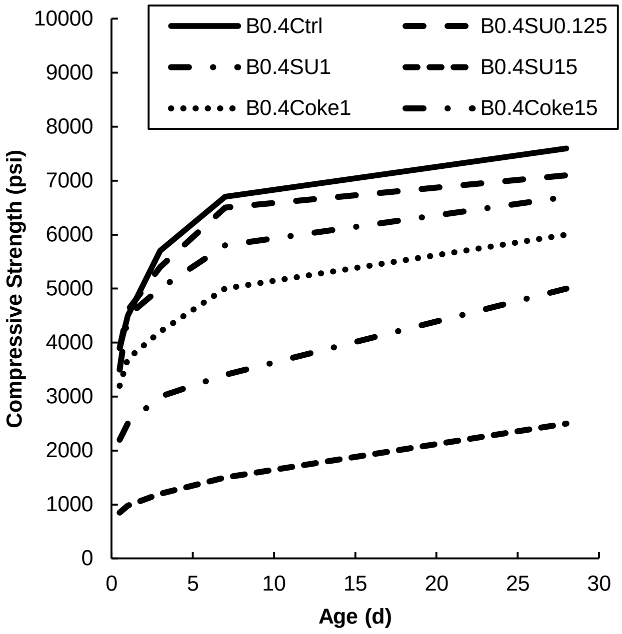

Figure 64 Compressive Strength of SU and Coke mixtures

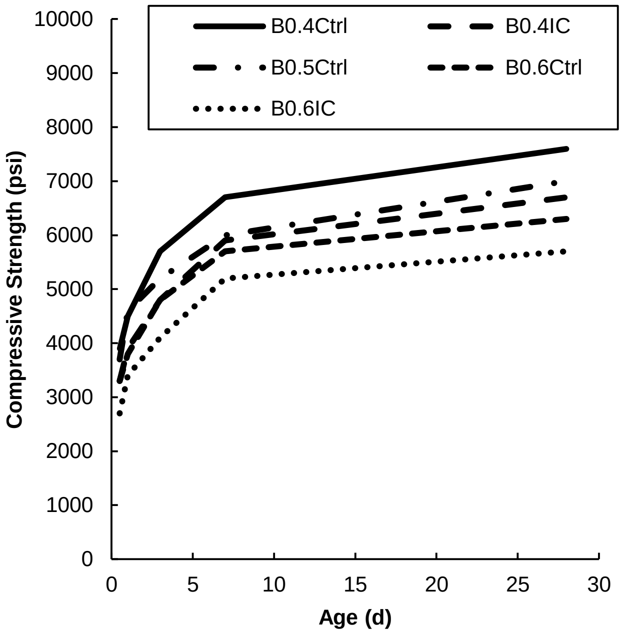

Figure 65 Compressive Strength of IC mixtures

5.2.3 Thermal History

Thermal history (in degrees Celsius) was measured for each mixture (see from Figure 66 to Figure 72). Mortar reaction produces heat, and with thermal history of the mixtures, it can be determined if a reaction produces more heat (faster reaction) or less heat (slower reaction). Temperature peaks for the CA mixtures were reduced compared to the control for each water to cement ratio. For CA mixtures (at any given w/c), the temperature peak occurred under 40 °C, whereas, the control obtained a temperature peak at 45 °C. Furthermore, the time at which the mixtures reached their temperature peak stayed relatively the same (between 0.4 and 0.5 d). B0.4Ctrl had the steepest temperature increase (ascending branch) until it reached its peak. In addition, as the concentration of CA was increasing, the temperature of the mixture increased at a lower rate (see Figure 66). When the water to cement ratio increased to 0.5 or 0.6, the mixtures' peak did not change significantly (less than 10%), however, a shift of the temperature peak location was observed: around 0.56 d for w/c = 0.5 and around 0.74 d for w/c = 0.6. (see Figure 67 and Figure 68). After a cooling period of 2 days, the temperature of the mixtures stayed mostly constant as they became the ambient temperature. For BA mixtures (at any given w/c), the temperature peak occurred under 36 °C, whereas, the control obtained a temperature peak at 45 °C (as shown from Figure 69 to Figure 71). However, the time at which the mixtures reached their temperature peak increased relatively to the control (0.58 d at w/c = 0.4, 0.61 d at w/c = 0.5 and 0.78 at w/c = 0.6). IC mixtures (at any given w/c) presented a shift of the temperature peak location relative to the control mixtures (see Figure 72) from 0.5 d to 0.57 d (at w/c = 0.4), from 0.56 d to 0.62 d (at w/c = 0.5) and from 0.73 d to 0.77 d (at w/c = 0.6).

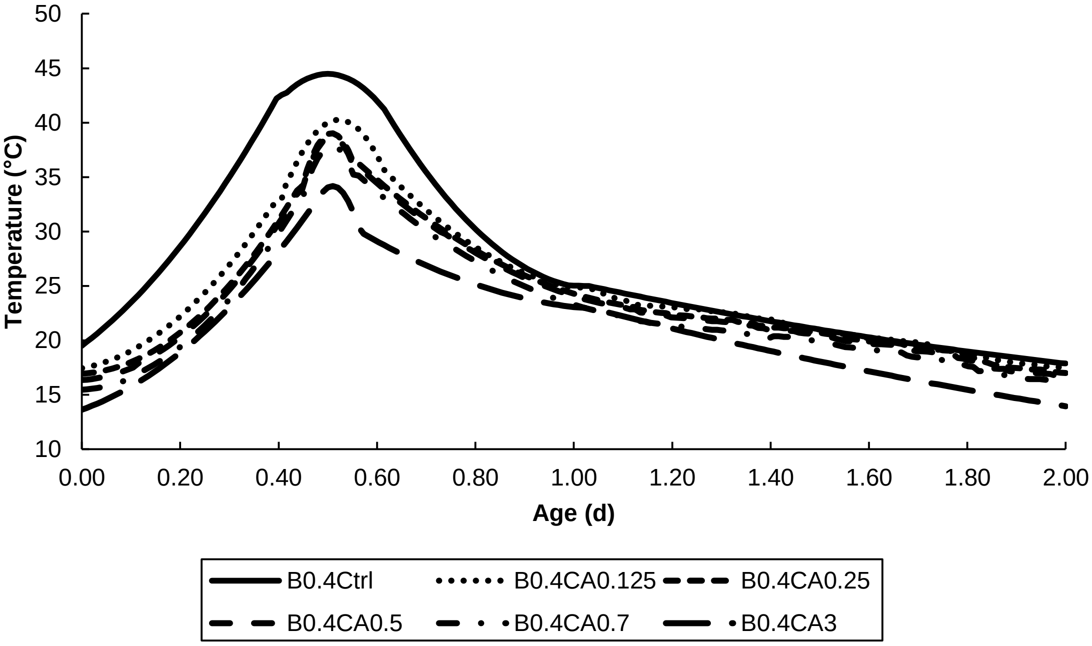

Figure 66 Thermal history of CA mixtures (w/c = 0.4)

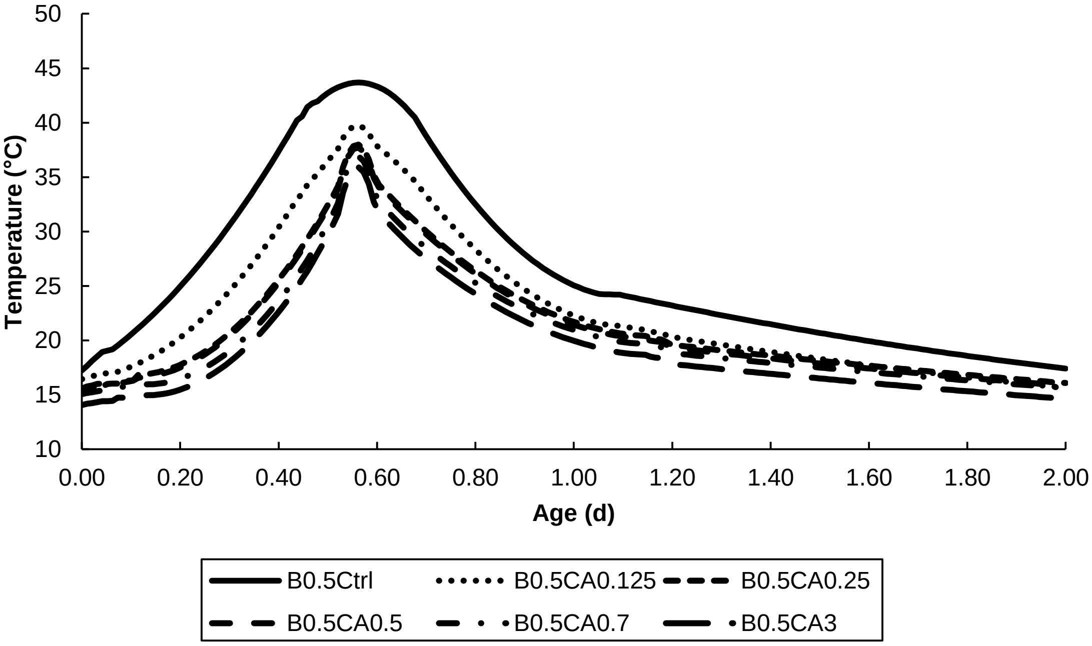

Figure 67 Thermal history of CA mixtures (w/c = 0.5)

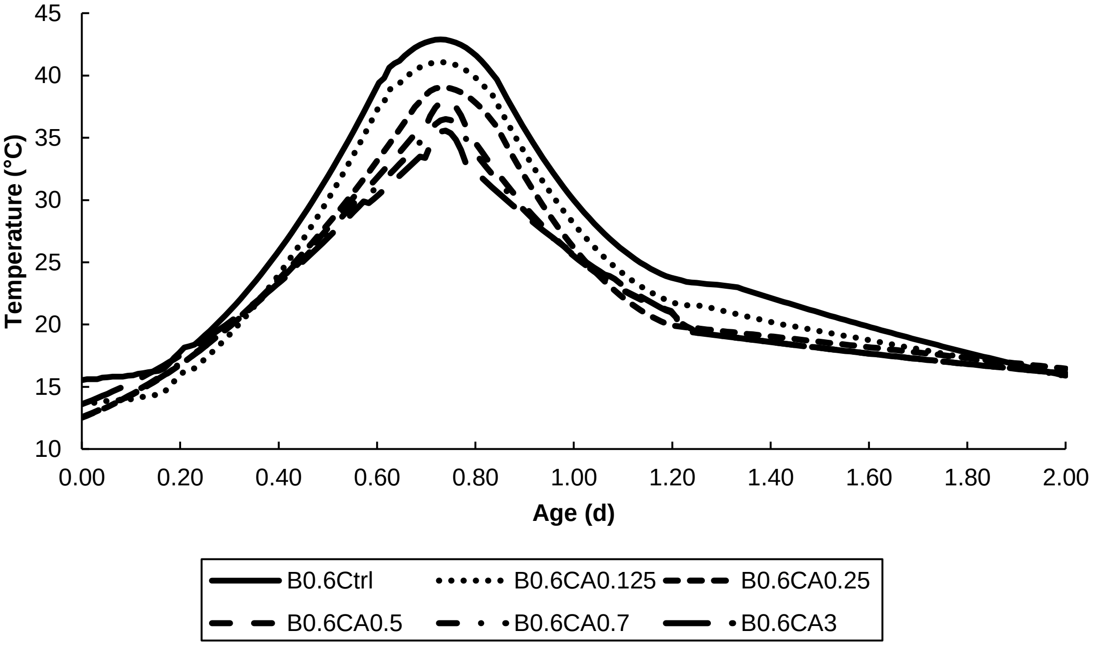

Figure 68 Thermal history of CA mixtures (w/c = 0.6)

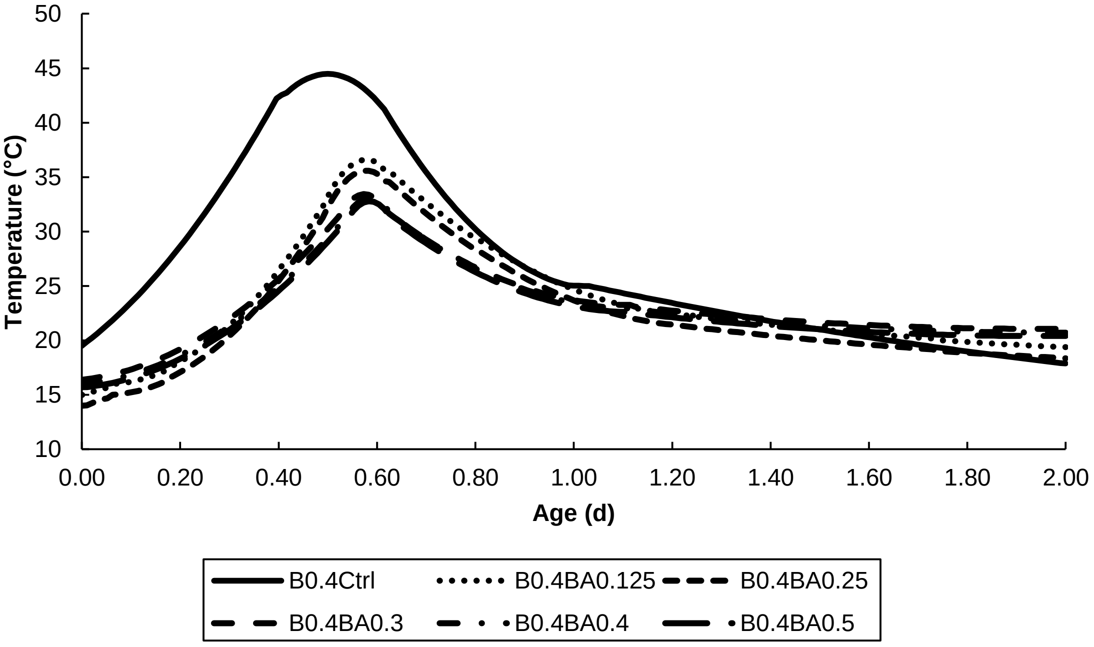

Figure 69 Thermal history of BA mixtures (w/c = 0.4)

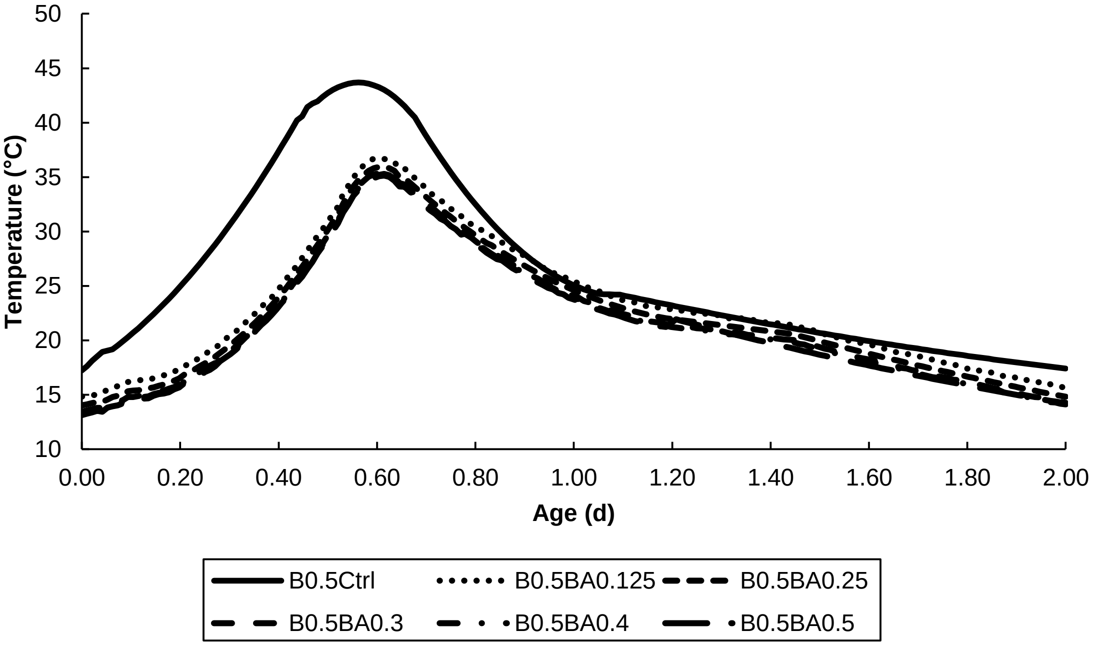

Figure 70 Thermal history of BA mixtures (w/c = 0.5)

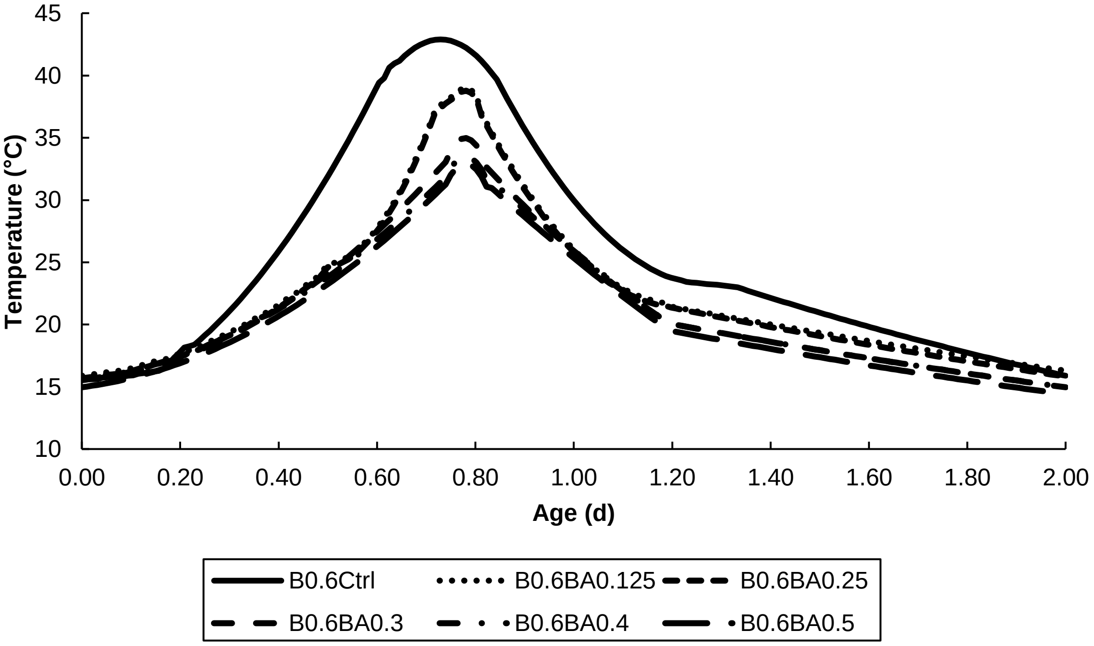

Figure 71 Thermal history of BA mixtures (w/c = 0.6)

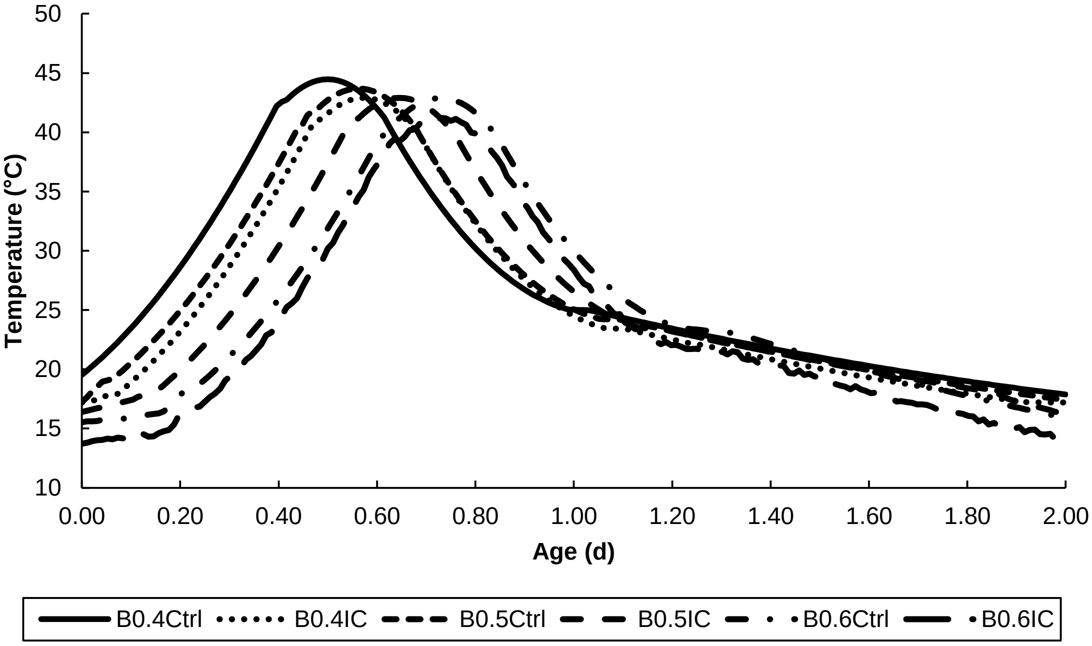

Figure 72 Thermal history of IC mixtures

A possible relationship between compressive strength and the thermal history temperature peaks was investigated. From Figure 73 to Figure 76, these variables were plotted against each other and a linear regression was calculated for each case. From the figures, an apparent linear relationship exists between compressive strength and max temperature of the mixtures. This relationship has been seen in the literature before (Carino N. , 1984). Compressive strength is related to the set time, which is affected by the heat generation of the hydration reaction of concrete. Following this, it is safe to say that also compressive strength is related to the maximum temperature produced by the hydration reaction of the mixture. Observing this, it is possible to say that this relationship could be utilized to predict compressive strength of CSA mixtures utilizing their thermal history. Furthermore, this may enable current thermal sensors to be used with CSA, extending their benefits to this material, providing more control over the compressive strength development of rapid repair media.

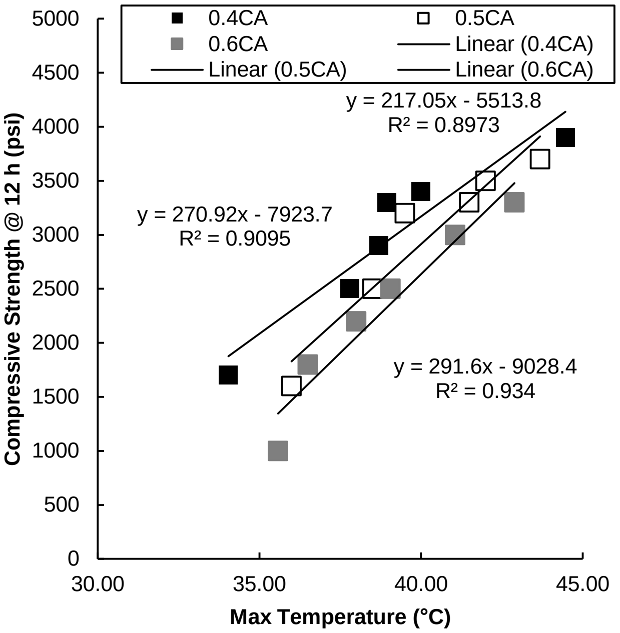

Figure 73 Relationship between compressive strength at 12 h and max temperature for CA mixtures

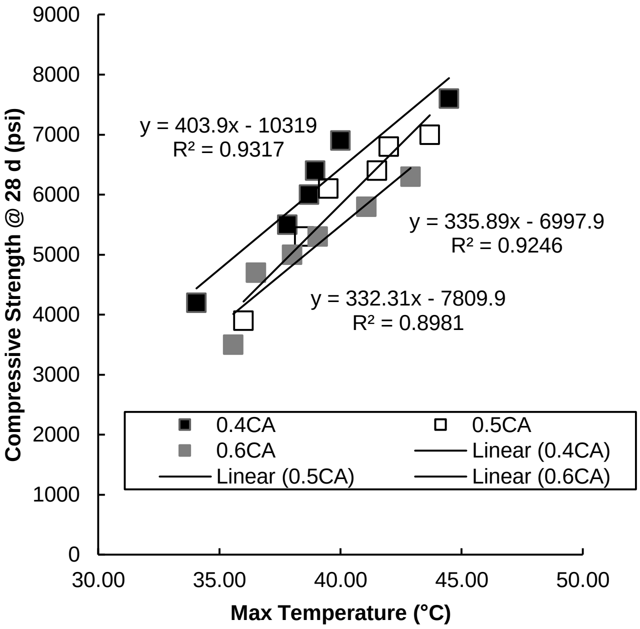

Figure 74 Relationship between compressive strength at 28 d and max temperature for CA mixtures

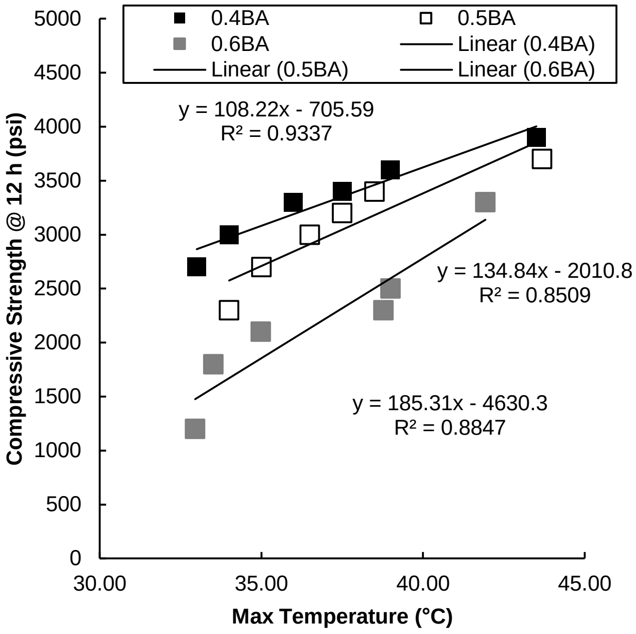

Figure 75 Relationship between compressive strength at 12 h and max temperature for BA mixtures

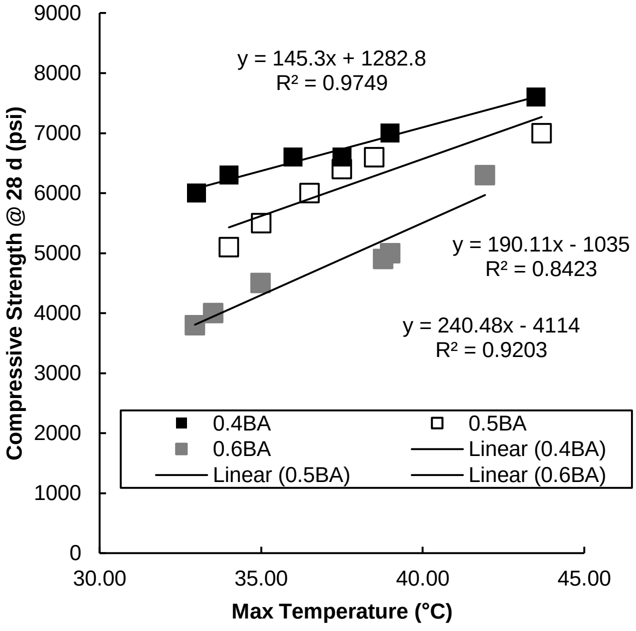

Figure 76 Relationship between compressive strength at 28 d and max temperature for BA mixtures

5.3 Discussion

5.3.1 Setting Time

CA presented an effective retardation of the setting time of CSA with respect to the control. CA retarding capabilities have been observed in the past (Velazco, Almanza, Cortés, Escobedo, & Escalante-Garcia, 2014) (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016) (Hu & Ma, 2017), and are consistent with the obtained results. CA is known to not crystallize as other salts; however, it does complex with the Ca^{2+} ions produced in the hydration process, potentially lowering its concentration in the pore solution which slows down the formation of ettringite, thus, retarding the hardening of the cement paste (Kurdowski, 2014). Figure 54 shows that setting times seem to have a linear relationship proportional to CA concentration in the mixtures. Additionally, a linear regression of the results show that CA concentration can be a predictor of initial set time of a CSA mixture with a p-value of 7.18×10^{-12} (statistically significant) and the model has an R Square value of 0.95 (shown in Figure 77). The linear regression shown in Figure 77 is limited by the 3% dosage of CA, since increments after that percentage were not considered for this dissertation. More dosages may reveal other trends besides linear which is presented. Additionally, a multiple linear regression was considered utilizing CA concentration and water to cement ratio as predictor of initial setting time. Nevertheless, water to cement ratio obtained a p-value of 0.25 and was not considered statistically significant. CSA possesses short setting times which can prove to be a hassle on the field. With the utilization of CA, setting times could be longer, allowing for work crews to utilize CSA instead of OPC with high dosages of admixtures. Normally, CSA is not recommended to be utilized in a concrete truck, because of its fast setting time. Utilizing CA as part of the mixture, could allow CSA to be transported in a normal concrete truck, instead of a special volumetric truck used to transport concrete materials and mix them on the field.

With BA, it was noticeable that when increasing the water to cement ratio, the initial setting time was shortened. This could be due to more water in the mixture diluting the admixture and thus, reducing its effect. The presence of BA has been observed to produce a retardation in ettringite formation, because it reacts with water before Klein's salt at higher speeds, interfering with the nucleation of ettringite (Kurdowski, 2014). However, at higher concentrations of BA (0.5%), this effect was not observed. The amount of borate ions that are in the mixture have been observed to influence the way BA reacts with water and the hydration products it makes (Poellmann, Auer, Kuzel, & Wenda, 1993). Furthermore, it has been observed that the reduction of the initial pH of the mixture by acids prevents a dissolution of the mineral components of the reaction, thus, inhibiting clinker dissolution or the precipitation of hydration products, such as ettringite (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016).

Previous research had investigated BA retarding capabilities (Champenois, 2015) (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016) (Hu & Ma, 2017), and their results are consistent with Figure 55. These results show that setting times might be related to BA dosage in the mixtures.

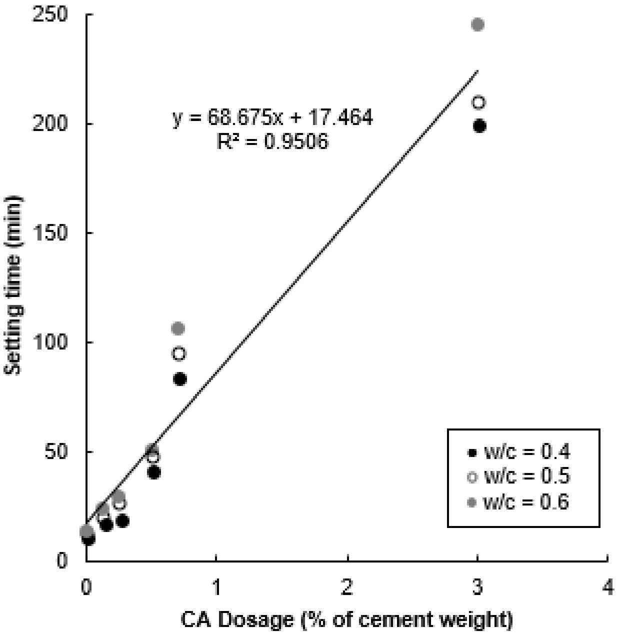

Figure 77 Linear regression of CA mixtures (w/c = 0.4 is black, w/c = 0.5 is white, w/c = 0.6 is gray)

Moreover, a linear regression of the results show that BA concentration could be a predictor of set time of a CSA mixture with a p-value of 1.00x10^{-6}, however, the model has an R Square value of 0.80 (shown in Figure 78), which means that this model does not completely explain the variability in the observed. The figure also shows us that a negative setting time value is obtained at dosages lower than 0.1% which is impossible. Nevertheless, dosage of BA is a predictor of statistical significance due to its p-value. An exponential regression was also considered (see Figure 79). It is important to note that this exponential regression is still a linear regression obtained after transforming the setting times into natural logarithm form and performing a standard linear regression. This model obtained an R Square value of 0.95, which is higher than the previous linear regression. Figure 79 presents a model that is valid only until 0.5% dosage of BA. Dosages past this value were not considered in this dissertation, thus the validity of the model is comprehended between 0% and 0.5% of BA. The model suggests that the retarding effect of dosage of BA is higher than the observed retarding effect for CA, implying that the lower dosages of BA have a more potent retarding effect that those of CA.

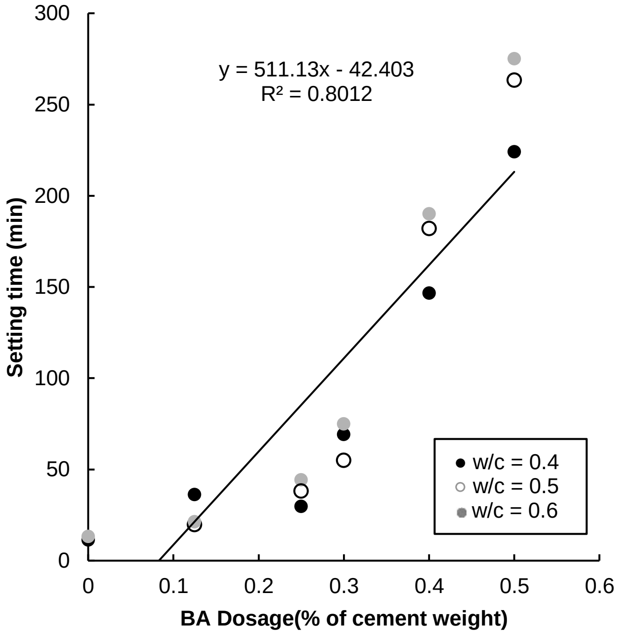

Figure 78 Linear regression of BA mixtures

The addition of low dosages of SU and Coke were detrimental to the setting times, lowering them below the control mixture. SU has been shown to complex calcium ions the same way CA and BA do, which influences the speed of nucleation and growth of ettringite (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016), thus making sense that SU also retards the setting of concrete. Since Coke has high quantities of SU, at lower concentrations their effects were similar. Nevertheless, Coke is also composed of water and phosphoric acid. Previous experiments with BA and CA determined that both acids had significant retarding set time properties, as well as the literature which suggests that acids lower the pH of the cement hydration reaction, thus affecting the speed of the reaction (Champenois, 2015) (Kurdowski, 2014), thus suggesting the phosphoric acid may also have a similar effect. More experimentation with phosphoric acid should be performed to assess its effects.

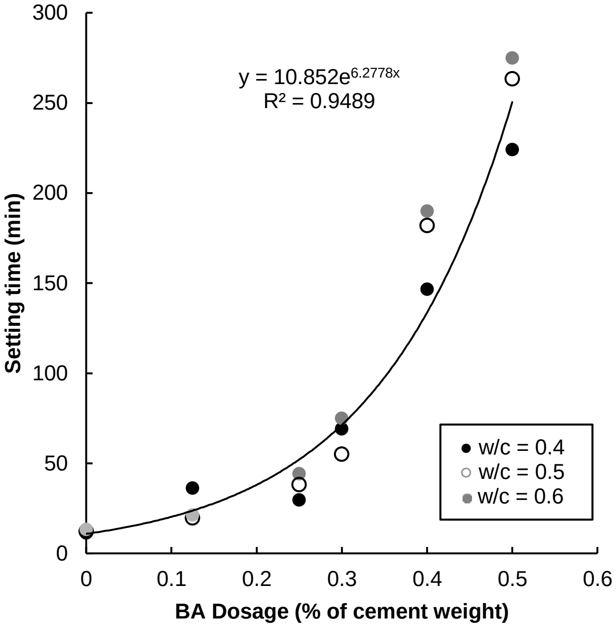

Figure 79 Exponential Regression of BA mixtures

Apparently, IC acts beneficially towards an increase in setting times. IC provides additional water for curing. It has been observed that an increase in water content delays setting time by allowing for a longer induction period of hydration (Pang, 2015). It is possible that part of the water intended for internal curing, is being absorbed by the cement paste and used to extend hydration, thus, presenting an increase in setting time. The previously observed benefits of internal curing in volume stability of repair concrete make internal curing a tool to retard the setting time of

CSA used as rapid repair media. For future research, measurements of the effect of IC mixtures plus the previous evaluated admixtures should be considered.

5.3.2 Compressive Strength Development

Compressive strength development is critical for rapid repair media. In the previous section, it was determined that the admixtures produced a retardation in setting times. It was also observed that the mixtures presented losses in compressive strength with respect to the control. These losses in strength are determined by the production of ettringite in the hydration process. As mentioned before, the admixtures temper with the speed of the ettringite production during the hydration process, thus affecting not only the set time of the mixture, but also its compressive strength development. These losses affect the ability of the mixtures to be used as rapid repair media. Frequently, rapid repair media needs to meet certain compressive strength requirements at a specified time. Due to the relationship between ettringite formation, setting time and compressive strength established by previous research (Kurdowski, 2014) (Velazco, Almanza, Cortés, Escobedo, & Escalante-Garcia, 2014) (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016), it is possible that a relationship between the dosage of the admixtures and the observed compressive strength can be determined. This allows for careful consideration when proportioning rapid repair media utilizing the selected admixtures and could provide more insight in predicting compressive strengths in the field. Compressive strength results are consistent with previous research utilizing retarding admixtures (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016) (Burris & Kurtis, 2018).

Compressive strength and setting times were evaluated to determine the existence of any relationship. Compressive strength at 12 h and 28 d were plotted against initial setting time values and an exponential regression was obtained (see Figure 80 to Figure 83). Initial setting time was a strong predictor of compressive strength at 12 h for both CA and BA mixtures with R values between 0.94 to 0.99. Furthermore, initial setting time was also a strong predictor of compressive strength at 28 d for CA mixtures (R values between 0.92 and 0.98) and for BA mixtures (R values between 0.89 and 0.96). The regression models suggest that there is a statistically significant relationship between set time and compressive strength. This is important because set time testing may be able to predict compressive strength at a given age for retarded CSA mixtures. CSA is normally utilized as rapid repair media, thus, knowing at what age certain strength level is obtained, is important, and if determined by the set time of the mixture, the need to pour concrete cylinders for compressive strength may be reduced. It is important to note that from Figure 80 to Figure 83, even though a linear effect is observed, the regression may indicate that there will be a compressive strength when set time is 0, which is impossible. The model also implies that there might be a set time value in which strength will be close to 0, which is not entirely impossible. Large setting times would mean that the concrete mixture never sets, thus, never attaining any compressive strength. However, large setting times were not investigated in this research and thus this assumption cannot be validated by the data. The models hold true to set times between the minimum and maximum observed and are only valid within this range.

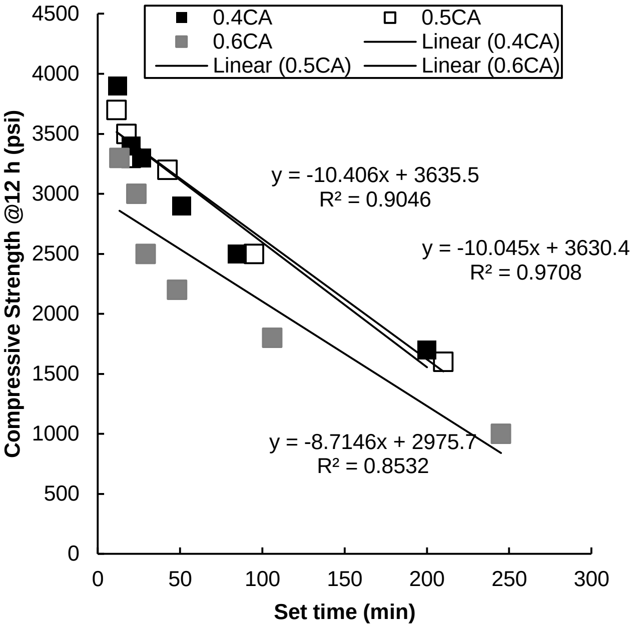

Figure 80 Compressive strength of CA mixtures (12 h) vs setting time

Compressive strength was also plotted against dosage of the admixtures (for CA and BA) as presented from Figure 84 to Figure 87. The relationship between CA at any w/c and compressive strength at 12 h and 28 d was seen to be more exponential than linear (R values from 0.92 to 0.98). Most likely, this is due to CA having a mixture with 3% dosage, extending the data points far into the x axis. Without this 3% dosage, the relationship is pretty much linear for CA as well. The exponential relationship implies that after a certain dosage, the admixture will probably stop reducing the compressive strength of the mixture significantly and at higher dosages the obtained compressive strength will be close to 0. However, CA dosages higher than 3% were not tested, thus, this assumption cannot be validated by the obtained data. This model is only valid for the observed dosages and the values between them (see Figure 84 and Figure 85).

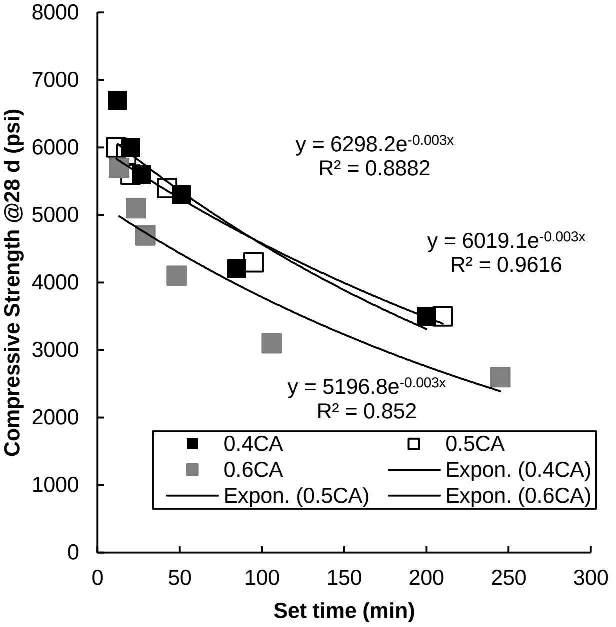

Figure 81 Compressive strength of CA mixtures (28 d) vs setting time

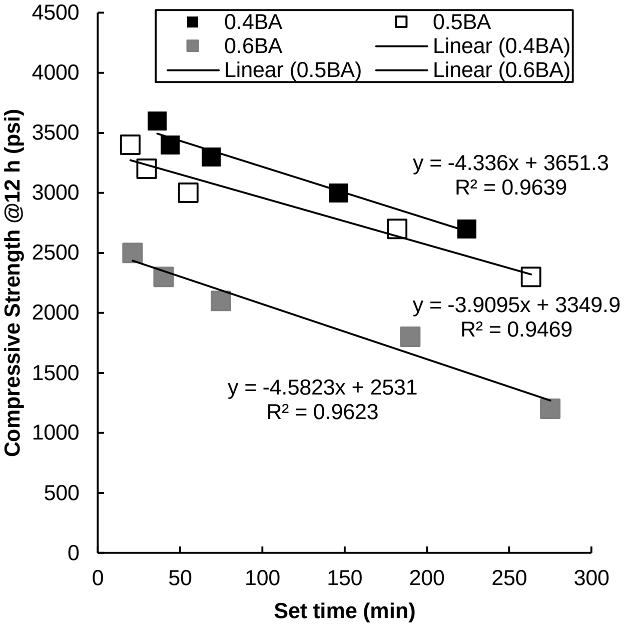

Figure 82 Compressive strength of BA mixtures (12 h) vs setting time

On the other hand, the relationship between BA dosage and compressive strength at 12 h and 28 d was mostly linear (R values between 0.92 and 0.98) (see Figure 86 and Figure 87). It is important to note that the linear regression suggests that higher dosages of BA will proportionally reduce the compressive strength of the mixtures and that at a high enough dosage of BA the compressive strength of the mixture will be equal to 0. These assumptions have not been verified by the data at hand. These models are only valid for the observed dosages and values between them.

Compressive strength development shows that for SU at lower dosages (0.125% and 1%), the strength gain of CSA is not affected (around 10% compressive strength loss at any age). Lower dosages of sugar seem to have little effect in compressive strength development, whereas higher dosages (15%) greatly affect the compressive strength (around 75% overall loss of compressive strength).

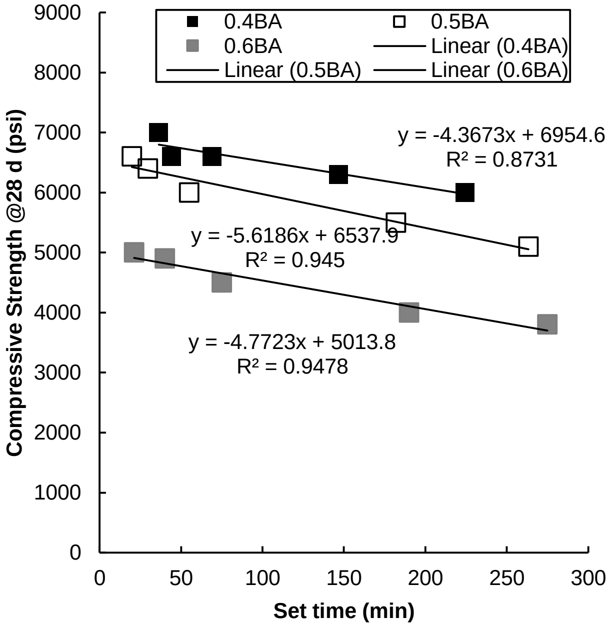

Figure 83 Compressive strength of BA mixtures (28 d) vs setting time

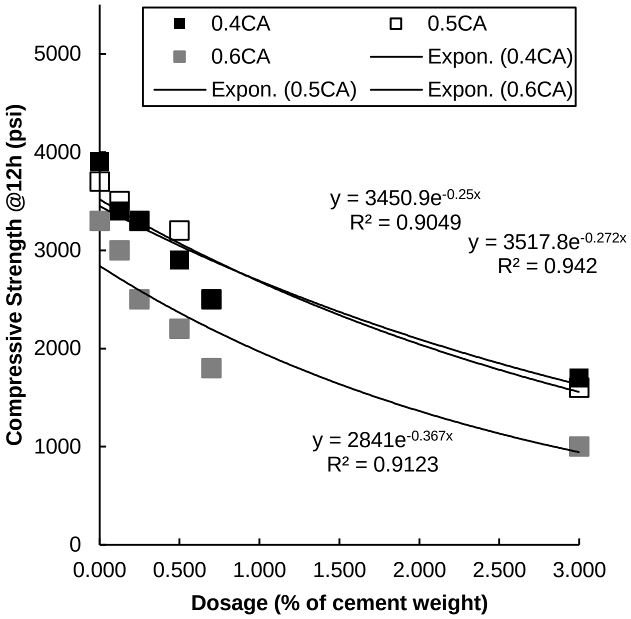

Figure 84 Relationship between compressive strength at 12 h and dosage for CA mixtures

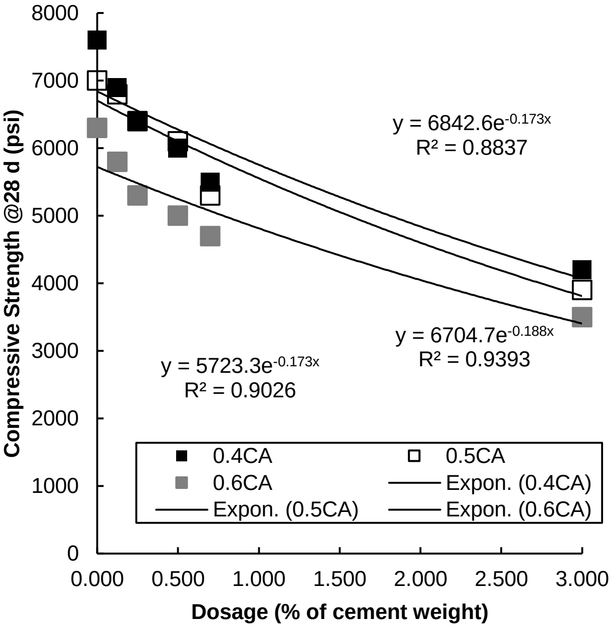

Figure 85 Relationship between compressive strength at 28 d and dosage for CA mixtures

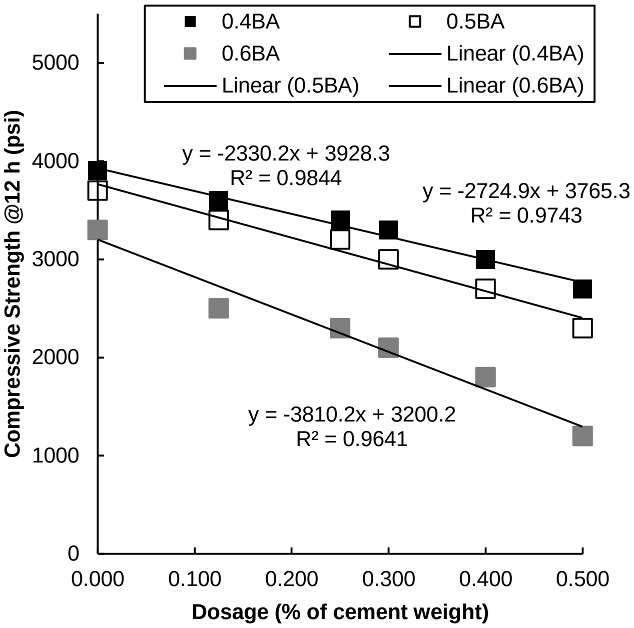

Figure 86 Relationship between compressive strength at 12 h and dosage for BA mixtures

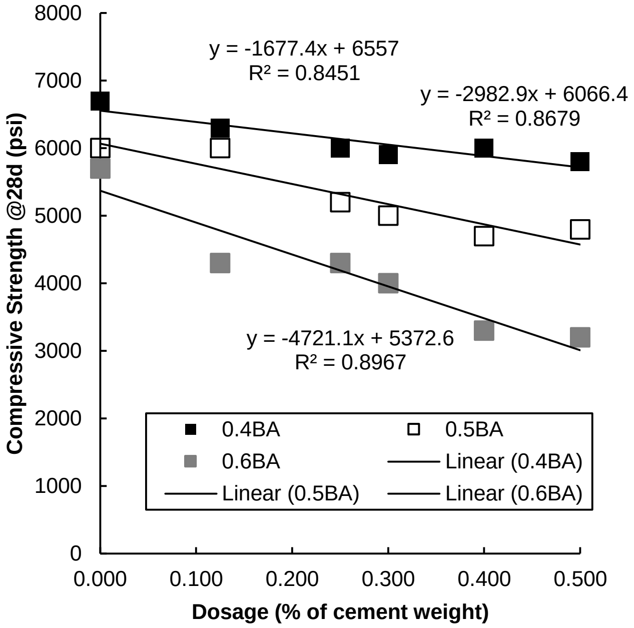

Figure 87 Relationship between compressive strength at 28 d and dosage for BA mixtures

As explained before, the chemical composition of SU inhibits the formation of ettringite and delays the hardening of the concrete. This effect seems to affect the total production of ettringite at higher dosages, evidenced by the low compressive strength development during the observed ages (see Figure 64)

Coke showed a similar behavior to SU, which was expected due to Coke being composed in part by sugar. At 1% Coke presented overall losses of 20% at all observed ages and, at 15%, around 40% at all observed ages. As mentioned before, Coke has a proprietary composition and little is known about the chemicals that make Coke. However, phosphoric acid and sugar are known components and have been studied before to influence cement hydration (Zajac, Skocek, Bullerjahn, & Ben Haha, 2016). It is possible that the different effects observed by SU (table sugar) and Coke indicate that Coke may use a different type of sugar or that the effects of phosphoric acid influence the total effect table sugar has on the mixture. To observe these effects X-ray Diffraction (XRD) could be utilized to study the structure, composition, and physical properties of the mixture. This would allow to determine which materials are present at a given time in the mixture and if they are being transformed faster or slower, thus, revealing more data about the retardation of the hydration process.

IC also proved to reduce the mortar compressive strength at all ages as observed in Chapter 3. For this dissertation, only full IC replacement was proportioned, thus, it is natural for the mixtures to present losses in strength due to LWA being utilized (which possess less compressive strength than NW aggregates). For future research, measurements of the effect of different IC proportions (PSLWA fines with NW coarse aggregates, vice-versa, or different combinations) should be evaluated. In addition, the previous evaluated admixtures with PSLWA replacement should be considered as well. All the admixtures in this Chapter produced losses in compressive strength compared to the control mixtures. In Chapter 3 it was found that initial and final setting times could be predictors of compressive strength, thus, this behavior of the mixtures is expected. In practice, careful consideration must be given to the admixtures to utilize or how internal curing is effectively incorporated into mixture proportion, as these two may have a negative effect in compressive strength development.

5.3.3 Temperature Peak Shifts and Reductions

The introduction of chemical retarders affected the thermal history of the mixtures. The literature states that modifications to the hydration process at early ages influence the properties of the mixture (Bizzozero, Gosselin, & Scrivener, 2014) (Beretka, Sherman, Marroccoli, Pompo, & Valenti, 1997) (Kurdowski, 2014) (Chaunsali & Mondal, 2016). With this in mind, it is safe to say that the retarders have some effect in the properties of the mixtures. CA and BA mixtures exhibited small shifts prolonging the time at which maximum temperature was reached. This is consistent with the literature which observed that CA and BA delayed the formation of ettringite which releases the highest amount of heat for the CSA cement mixtures (Kurdowski, 2014) (Chaunsali & Mondal, 2016) (Hu & Ma, 2017). In CA mixtures, these shifts (from 30 min to 2 h) mean that ettringite is being produced later than the control, so the hardening process is retarded (consistent with the observed retarded setting times and lower compressive strengths for CA and BA mixtures).

It is observable that BA reduces the speed of the mortar reaction more than CA, as the concentration of BA increased, the reaction occurred around 5 h later than the control. BA was observed to be a more effective retarder of set time, and this data is consistent as BA delays the formation of ettringite more than CA. In IC mixtures, a shift in the temperature peak location was observed. The peak moved around 2 h for all IC mixtures. Possibly, the water on the surface of the aggregates was not dried enough and part of the water was utilized by the chemical reaction. If this had occurred, more water would have been available for hydration, inducing a longer dormant period, until the formation of ettringite began. Moreover, this was consistent with the observed extended setting time for IC, CA and BA.

These shifts are important because they help validate the results obtained in set time and compressive strength development. Peaks occurring at later times mean that the hydration was prolonged and that he setting time was extended. In practice, monitoring the temperature of poured concrete may be utilized to predict its set time without the need of the penetration test.

Also, in the thermal history data, it can be observed that the admixtures reduced the mixtures' peak (releasing less heat, which could mean that less ettringite was produced). CA mixtures exhibited peak temperature losses up to 20%. BA mixtures showed losses of peak temperature up to 30%. This could be related to a loss in strength gain, as the compressive strength of the mixtures was reduced compared to the control (which is also related with set time). Cusson and Hoogeveen obtained similar results utilizing high-performance mortar mixtures, IC and commercial retarders (Cusson & Hoogeveen, 2008). With less ettringite production, the early-age strength of the mixtures is reduced, and this is consistent with the observed values of compressive strength. B0.4IC presented losses up to 3% and B0.5IC and B0.6IC showed elevated temperatures up to 1%. IC mixtures presented less compressive strength than the controls, which leads to believe that less ettringite was produced (and it would make sense because of the observed retarded setting times for IC mixtures). However, this cannot be said with certainty because of the different aggregates utilized in the controls and the IC mixtures. For future research, control mixtures with lightweight aggregates (without internal curing) should be tested to observe the difference.

Statistical analysis was performed to look for a relationship between set time and the time at which the maximum temperature occurs. It is interesting to note that there is a logarithmic relationship between initial setting time and the time at which the maximum temperature occurs (R values between 0.8554 and 0.9908) for both CA and BA mixtures (see Figure 88 and Figure 89). This data seems to be accurate as some sort of relationship had to exist between these two variables, because the literature has proved that an alteration of the hydration process at early ages influences compressive strength development and leads to a possible reduction of strength (Kurdowski, 2014), which was observed when utilizing the chemical admixtures as retarders. These regressions seem to reach a certain time value when set time is 0. As mentioned before, there wouldn’t be a realistic situation in which set time would be 0, so these regressions are only valid for the set times measured and the values between them. Optimizing these regressions could help civil engineering develop ways to determine setting time of the mixtures by measuring their thermal history. This could corroborate previous analyses in which set time was a predictor of compressive strength, which would mean that maximum temperature time could also be a predictor of compressive strength. Nevertheless, this was tested and the obtained R values were not significant (under 0.85) for results obtained in this dissertation.

Even so, if compressive strength could be determined based of thermal history of the mixtures (or maturity), civil engineers would be able to determine compressive strength of mixtures in a construction project without the need to cast separate cylinders per concrete truck arriving on the field. This would help to reduce laboratory costs and save time, as engineers would not have to wait for testing results to arrive on site, rather, they would measure the temperature of the mixture and find out if the construction is ready to progress to the next steps.

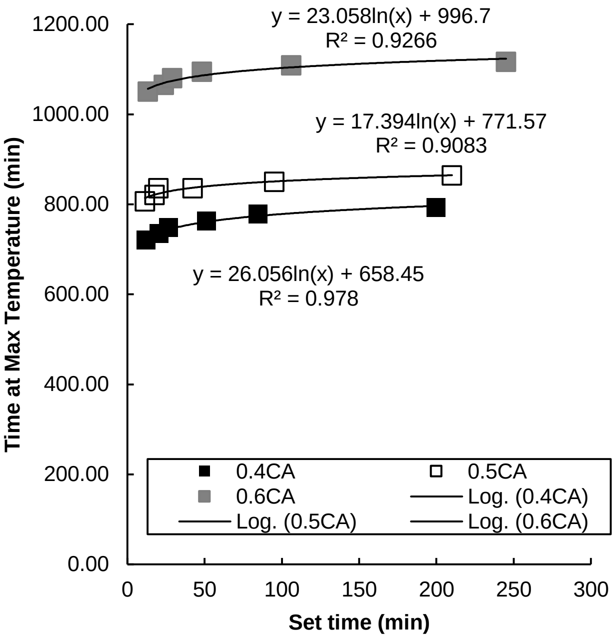

Figure 88 Time at max temperature of CA mixtures

5.3.4 Maturity

Maturity for the mixtures is presented from Figure 90 to Figure 96. These plots represent a cumulative temperature progress (°C times d vs age (d)) of the mortar mixtures, as the maturity is the integral of the thermal history over time. From the previous presented figures, it is safe to say that reactions are happening at a slower rate after CA or BA are utilized. Ultimate maturity for each mixture is the last value observed from Figure 90 to Figure 96.

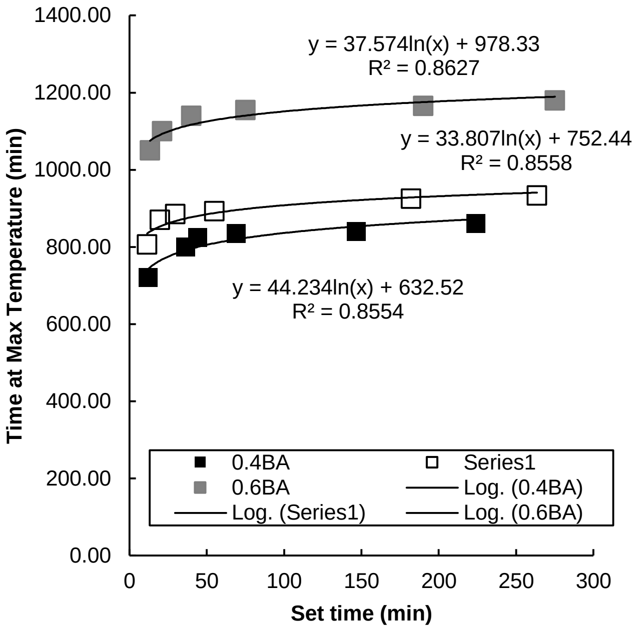

Figure 89 Time at max temperature of BA mixtures

From the previous section, thermal history suggests that the total heat of hydration from the mixtures has been affected by CA and BA, thus, reducing the ultimate maturity of the mixtures. Consequently, when the ultimate maturity is reduced, a loss in compressive strength is to be expected due to less released heat during the hydration process (Kurdowski, 2014). This effect was consistent in the mixtures as they exhibited less compressive strength than the control mixtures at all ages.

From maturity data, it can be observed that for CA mixtures, at water to cement ratio of 0.4, by 2 d, at any given concentration of CA, the mixtures ultimate maturities were under 10% difference of their respective control maturity. For water to cement ratio of 0.5 and 0.6 (see Figure 91 and Figure 92), this difference increased up to 40%. The reduction observed in ultimate maturity reveals that the cumulative temperature is reduced in the hydration process of the concrete by the retarders.

An opposite trend was observed for the BA mixtures. At water to cement ratios of 0.4, mixtures' maturities were under 60% difference of their respective control maturity. When water to cement ratio was 0.5 and 0.6, this difference decreased to 20% and 35%, respectively (see Figure 94 and Figure 95). BA significantly affected the maturity of the mixtures at a lower w/c. As mentioned previously, a reduction in ultimate maturity may lead to a reduction in compressive strength, due to the delay in the formation of ettringite and a lower total production of heat, which is observed when the peaks are shifted in the thermal history of the mixtures.

The aforementioned reduction in compressive strength was observed in previous sections and is consistent with the lower ultimate maturities obtained by the mixtures with CA and BA (for a lower compressive strength, a lower maturity is observed). For the IC mixtures (at any given w/c), the observed maturity at 2d was less than a 10% difference of their respective control mixture (shown in Figure 96). This means that even though IC shifts the peak of temperature for the mixture, at the seemingly end of the reaction (2 d), they obtain similar maturity values.

Consequently, the IC mixtures did not present a significant loss in strength (around 10%), which would be consistent with the observed maturity values (when maturity does not vary significantly, compressive strength should not vary as well). The loss in strength is also consistent with previous experiments with internal curing in Chapter 4.

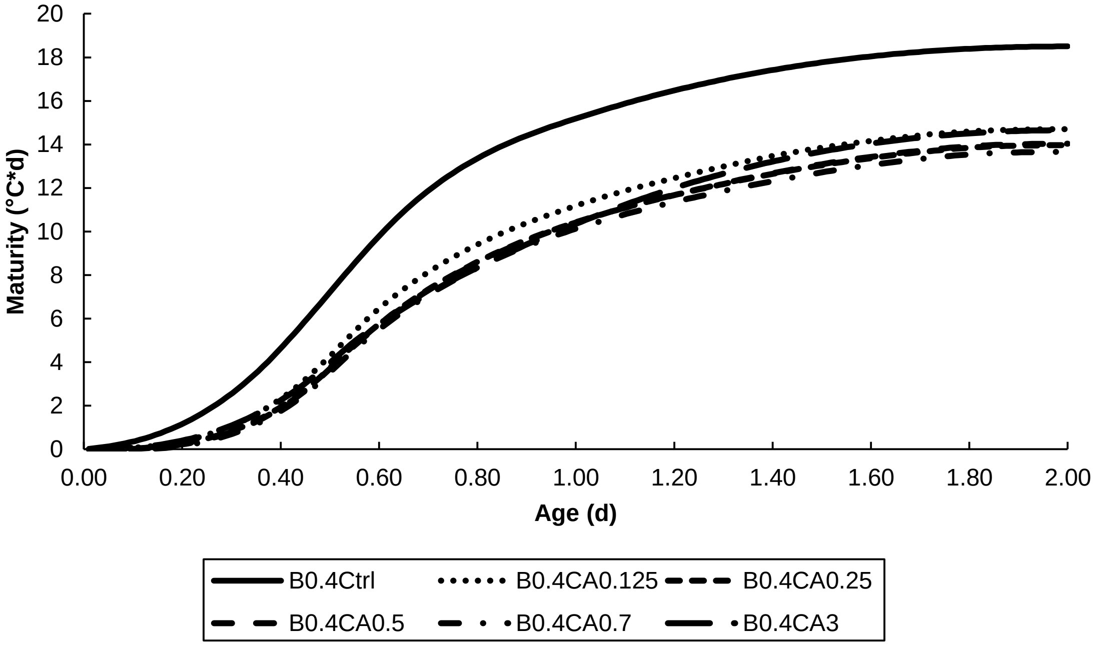

Figure 90 Maturity of CA mixtures (w/c = 0.4)

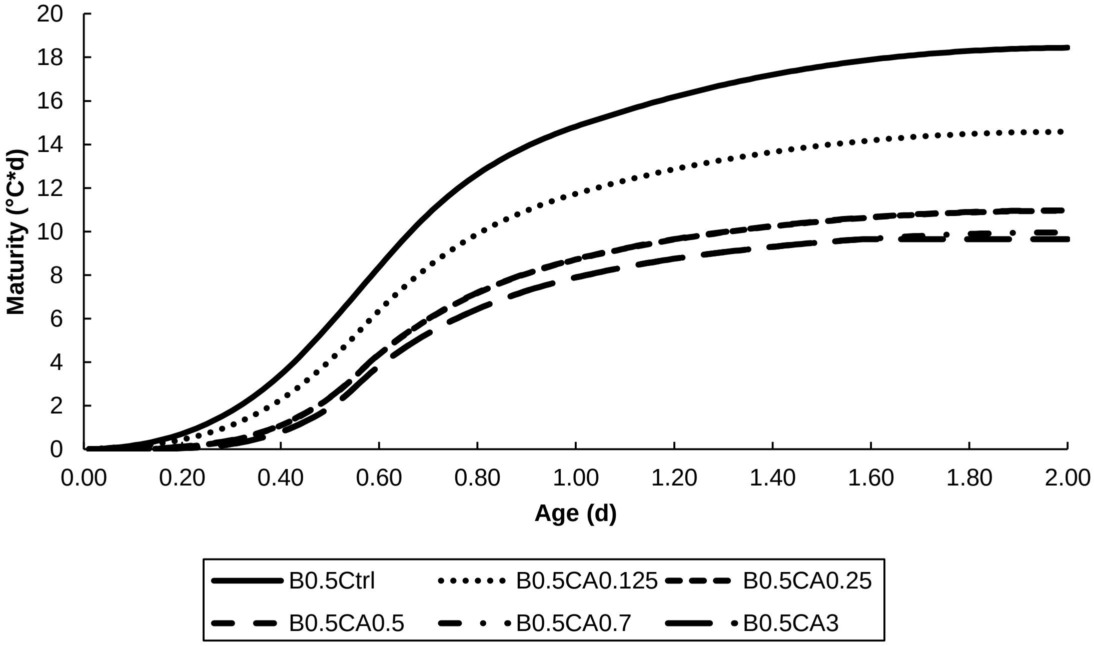

Figure 91 Maturity of CA mixtures (w/c = 0.5)

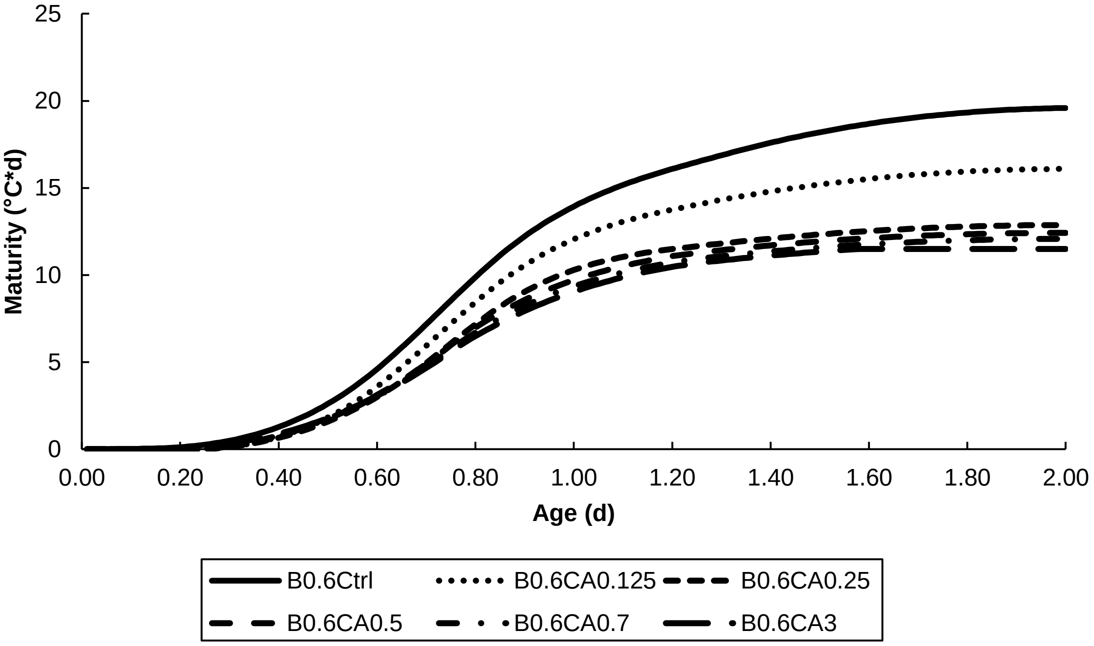

Figure 92 Maturity of CA mixtures (w/c = 0.6)

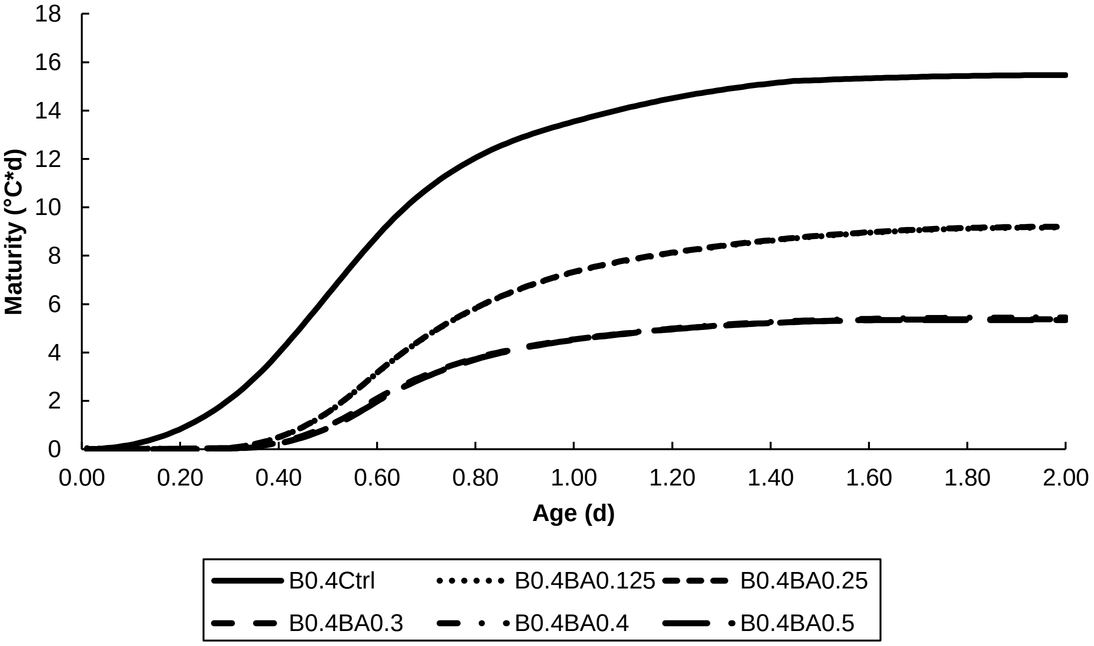

Figure 93 Maturity of BA mixtures (w/c = 0.4)

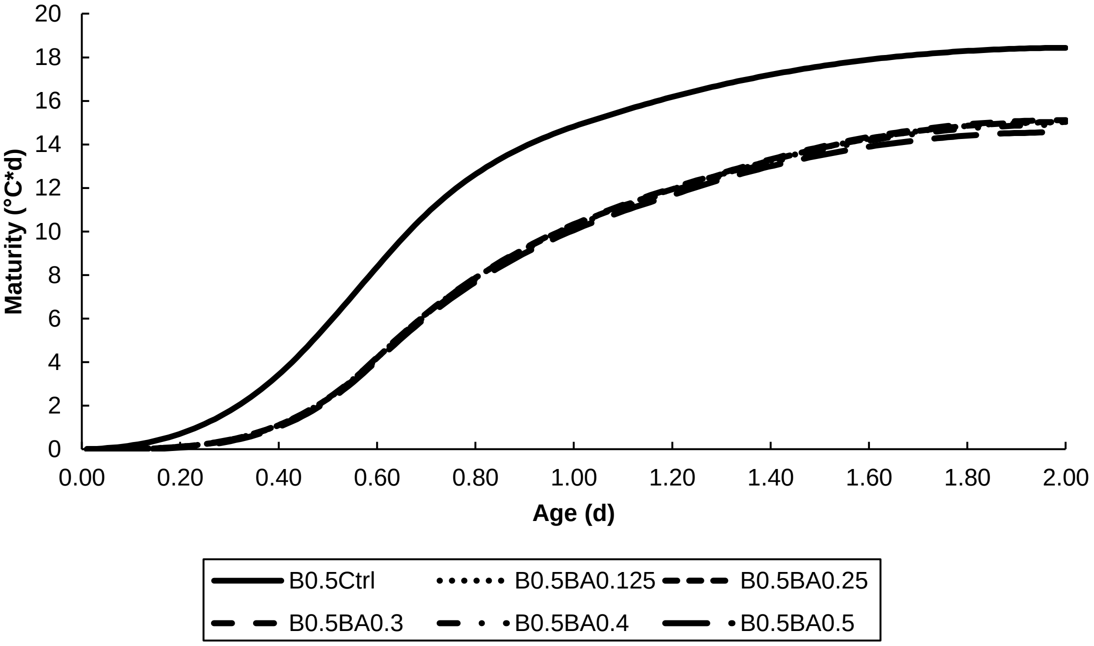

Figure 94 Maturity of BA mixtures (w/c = 0.5)

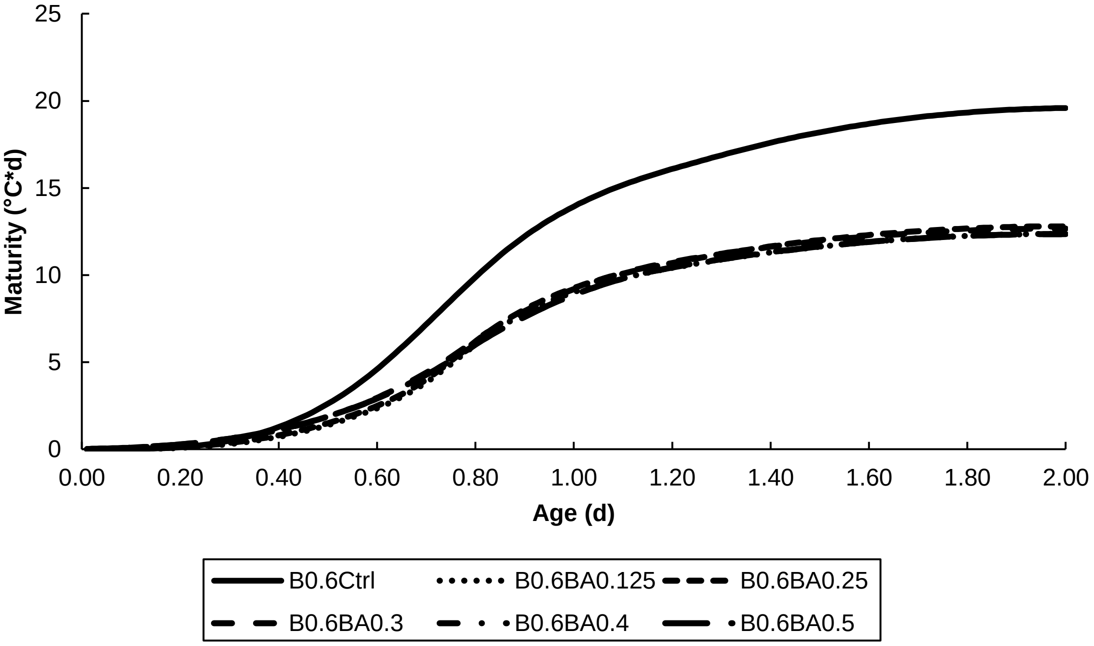

Figure 95 Maturity of BA mixtures (w/c = 0.6)

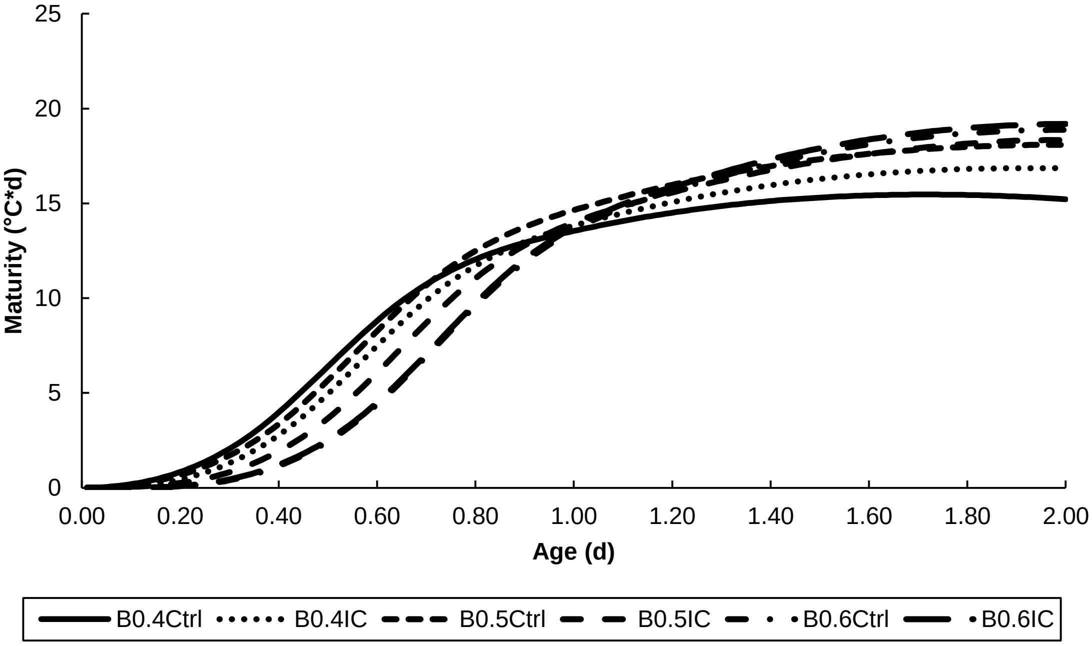

Figure 96 Maturity of IC mixtures

Analyzing the data above, several relationships where investigated regarding the maturity of the mixtures. Penetration resistance for set time have been known to be related with the maturity (Carino N. , 1984). The penetration resistance data obtained from the setting time testing was plotted vs maturity at the time of penetration and is presented from Figure 97 to Figure 109. The observed relationships for the retarders were mostly exponential as at the time of penetration their maturity increased exponentially, because, after all the retarder is consumed from the reaction, the hydration process that forms ettringite occurs, thus, reflecting a rapid increase in temperature inside the mixture. When the mixtures were not affected by retarders (Control and IC mixtures), a linear relationship was observed. The rate of temperature increase is more stable, because there is nothing affecting the early stages of hydration so there is not a significant change in the way heat is developed and the reaction occurs normally.

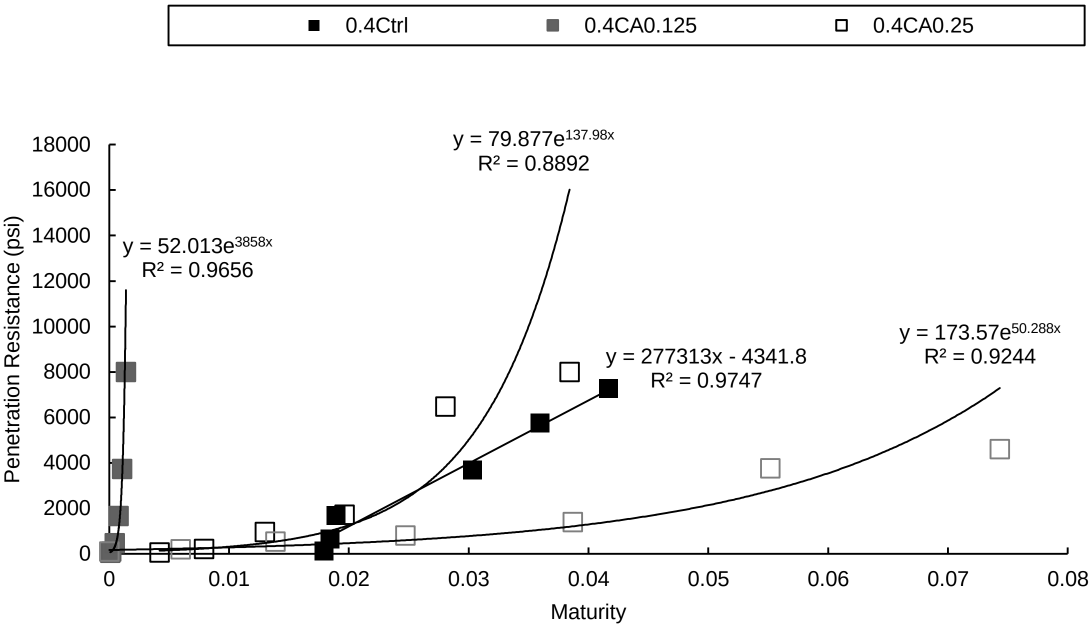

Figure 97 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.4) Part a

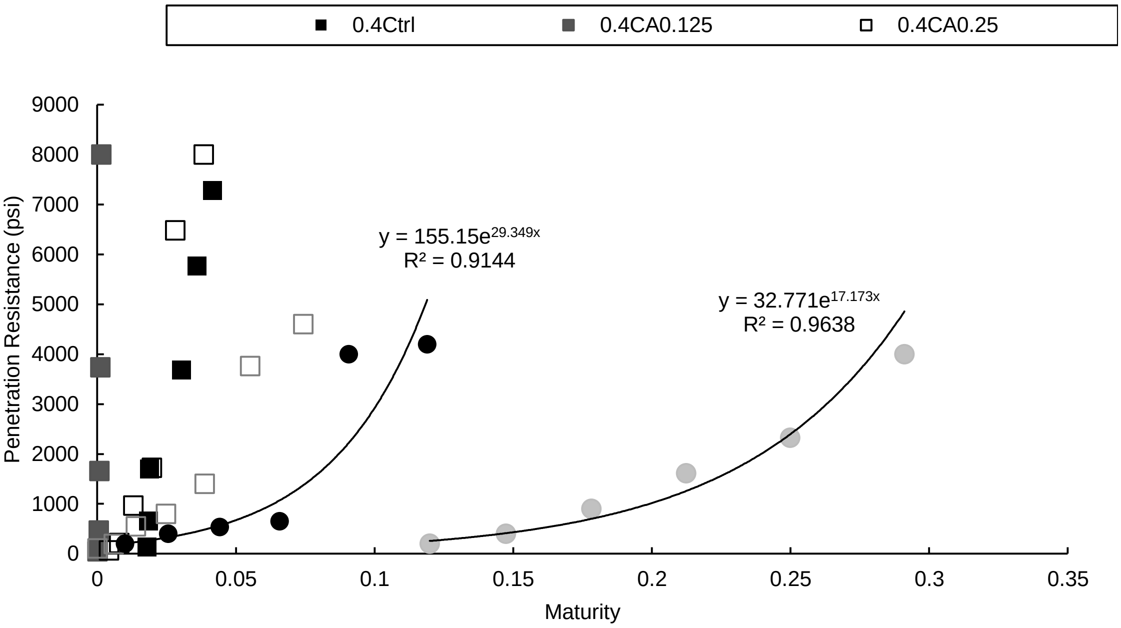

Figure 98 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.4) Part b

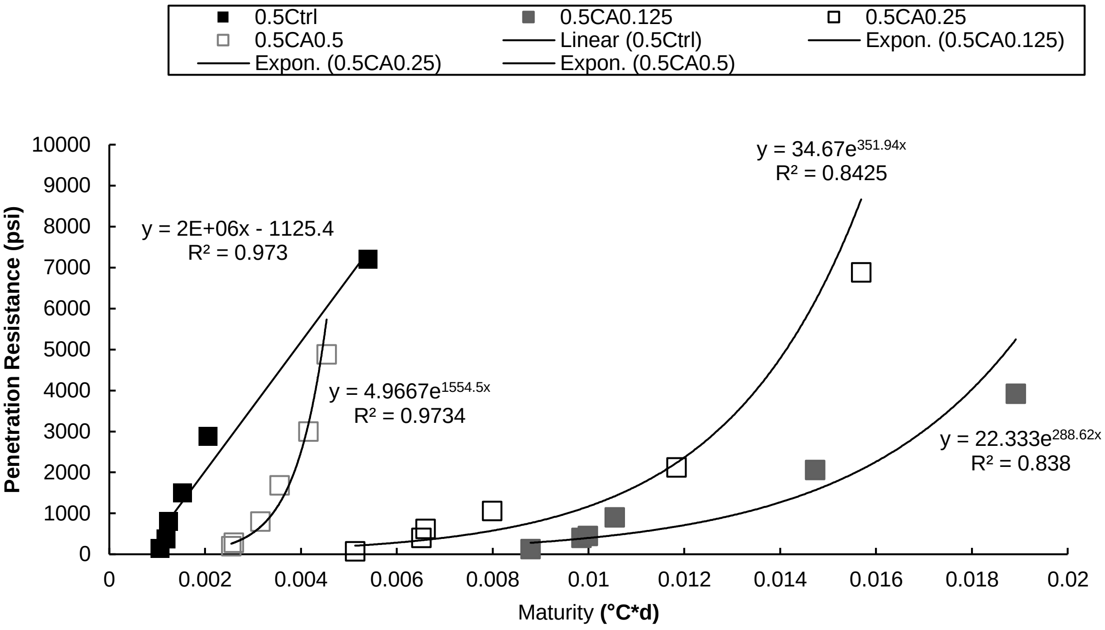

Figure 99 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.5) Part a

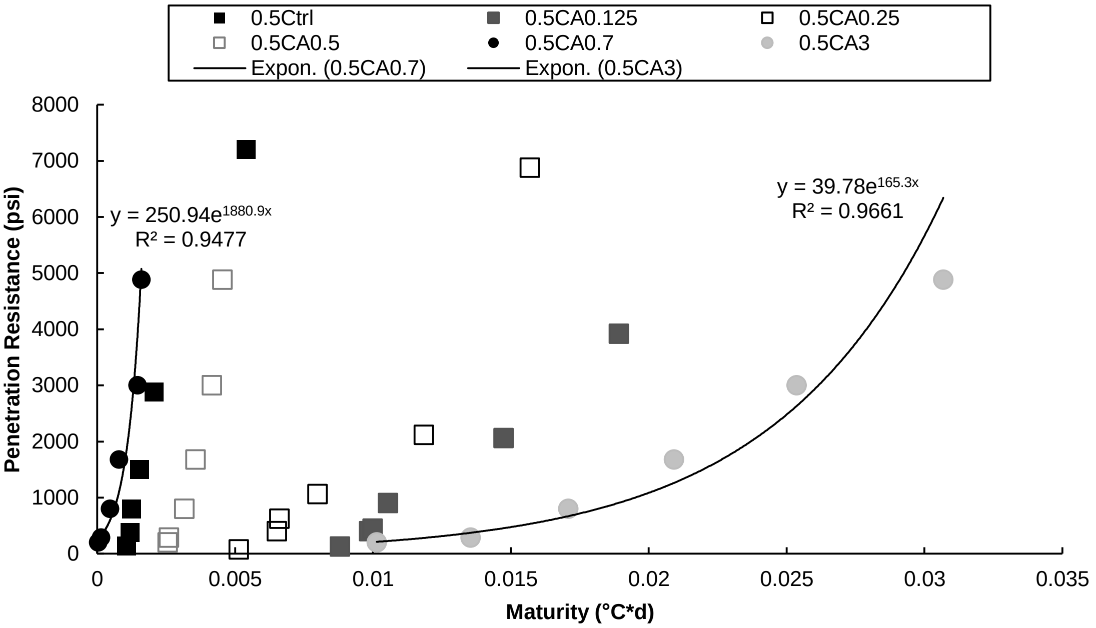

Figure 100 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.5) Part b

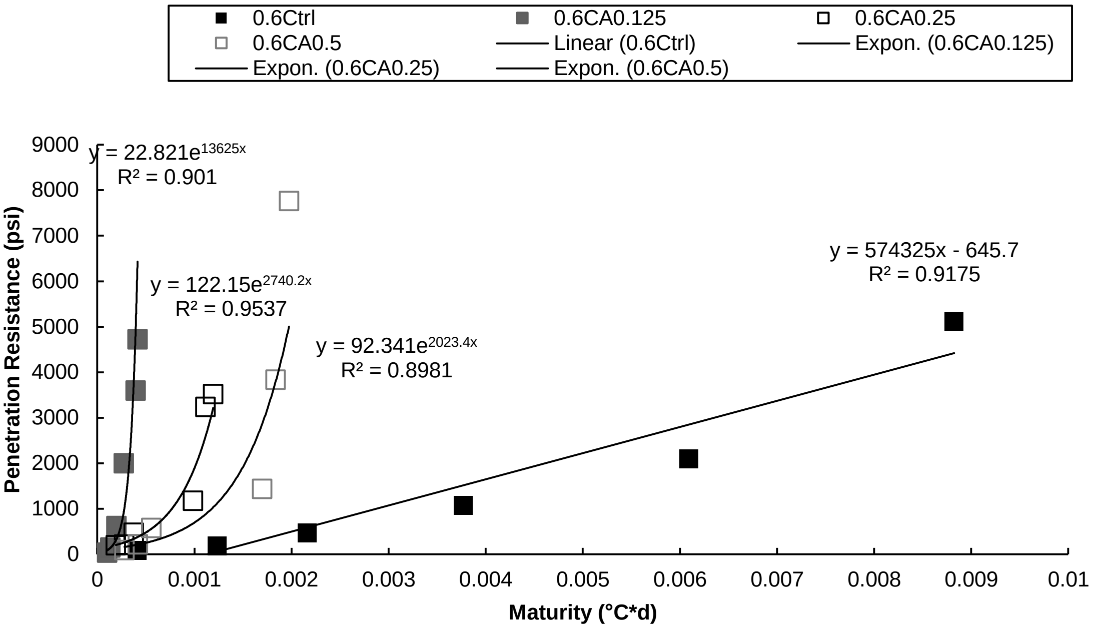

Figure 101 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.6) Part a

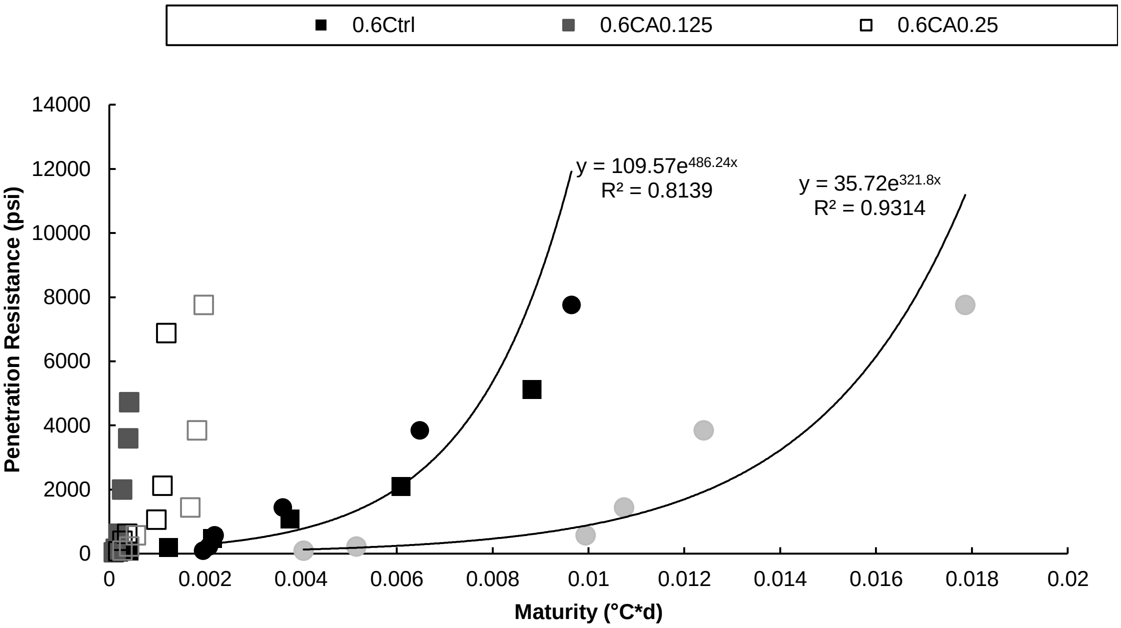

Figure 102 Relationship between Penetration resistance and maturity of CA mixtures (w/c = 0.6) Part b

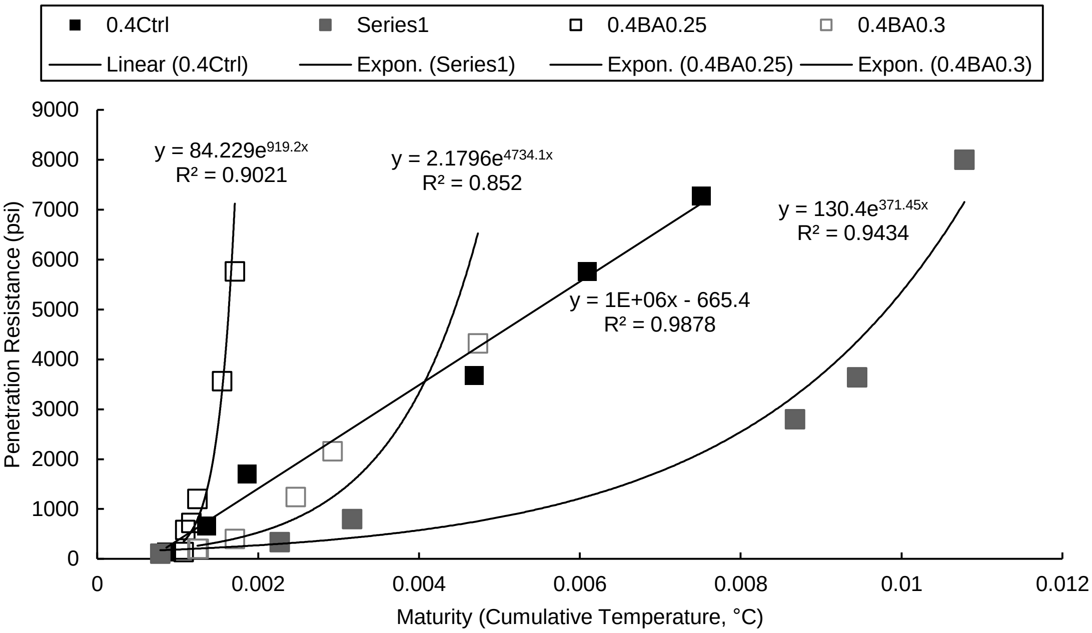

Figure 103 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.4) Part a

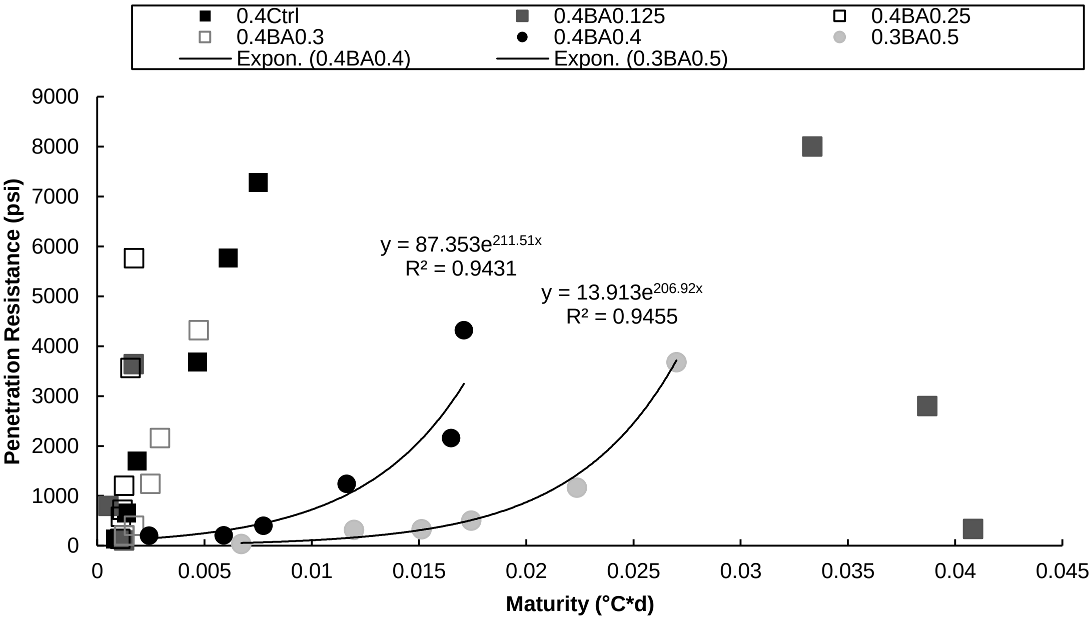

Figure 104 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.4) Part b

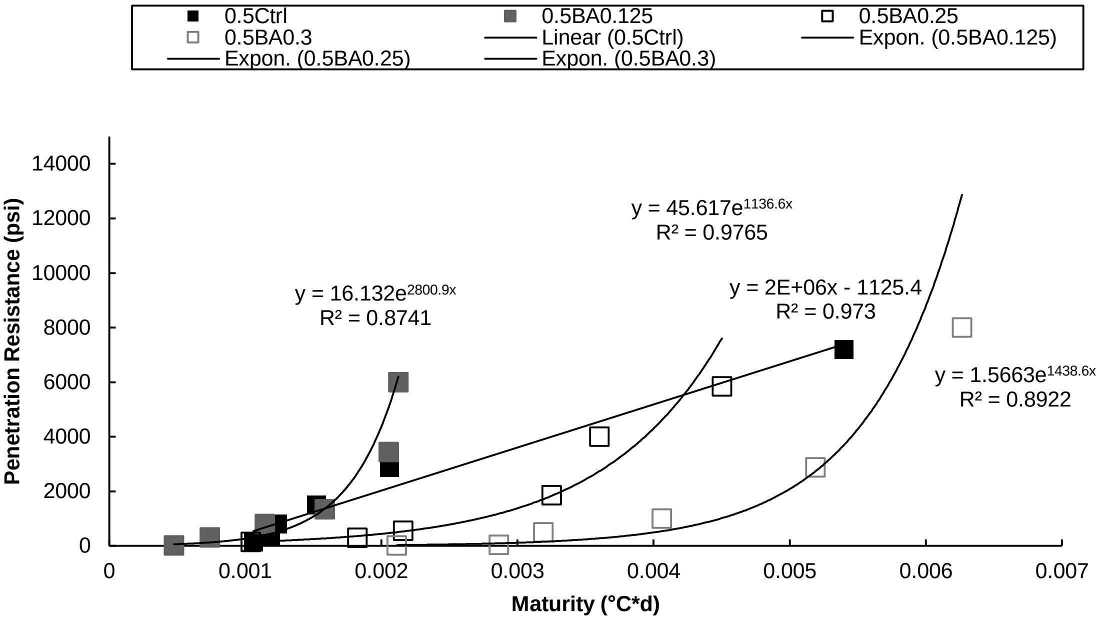

Figure 105 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.5) Part a

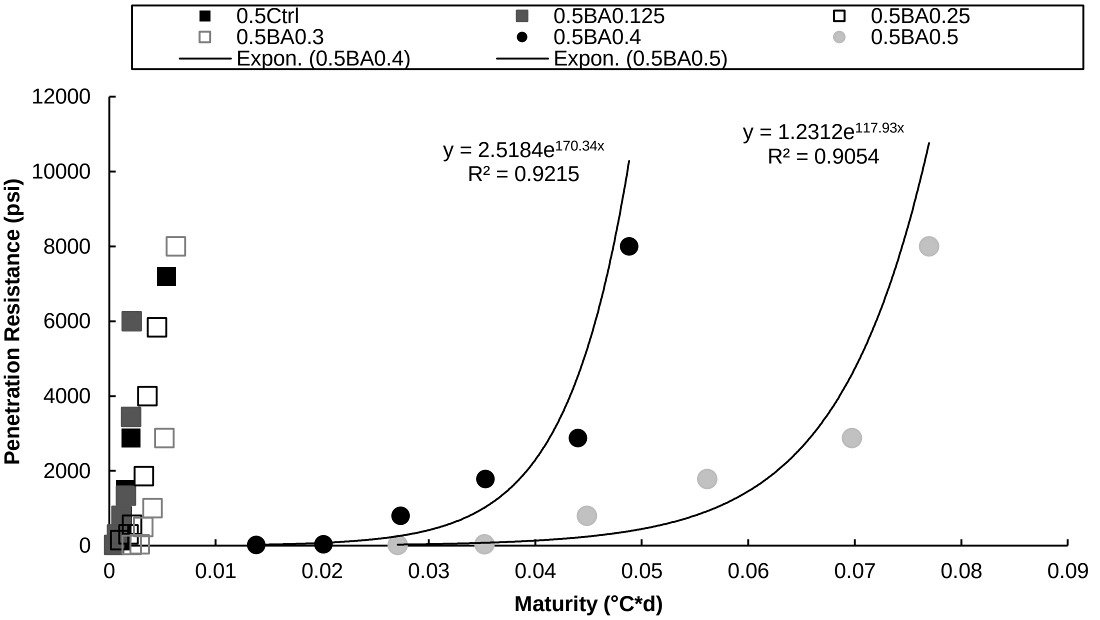

Figure 106 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.5) Part b

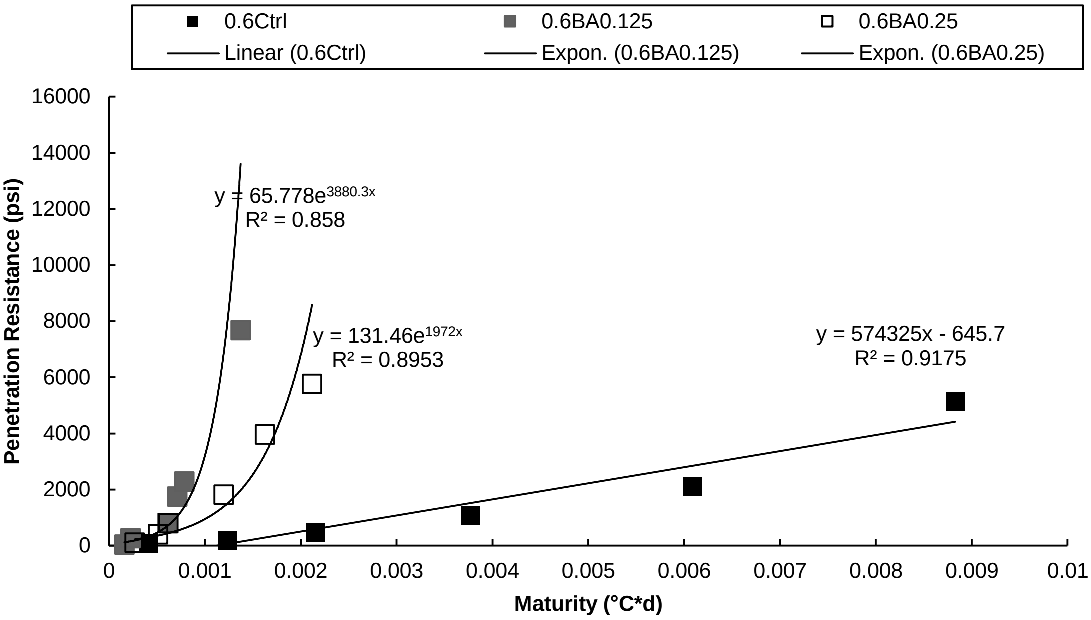

Figure 107 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.6) Part a

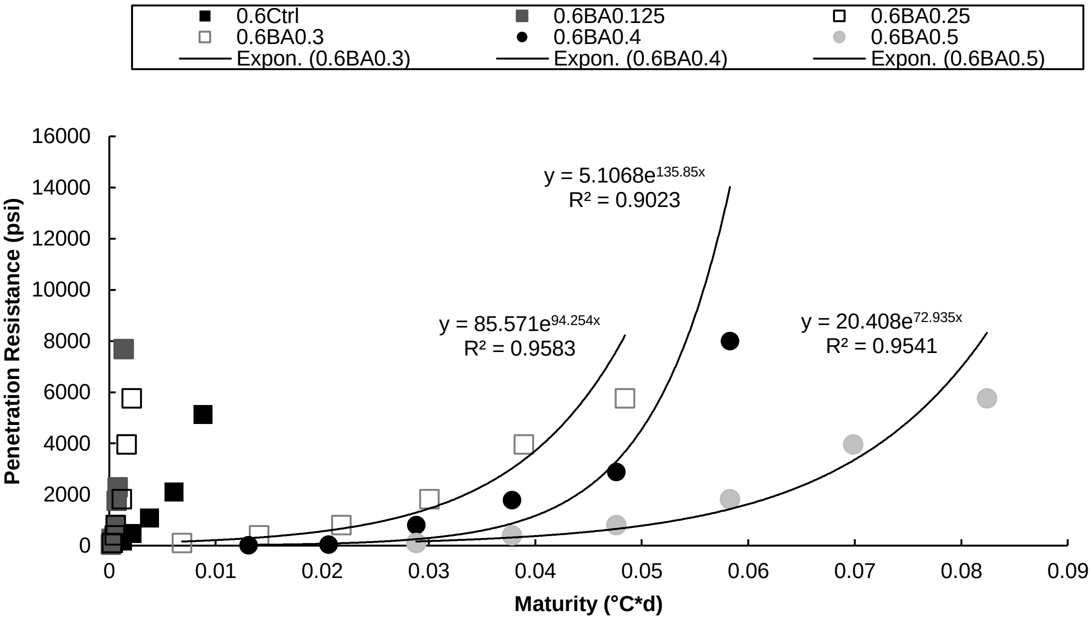

Figure 108 Relationship between Penetration resistance and maturity of BA mixtures (w/c = 0.6) Part b

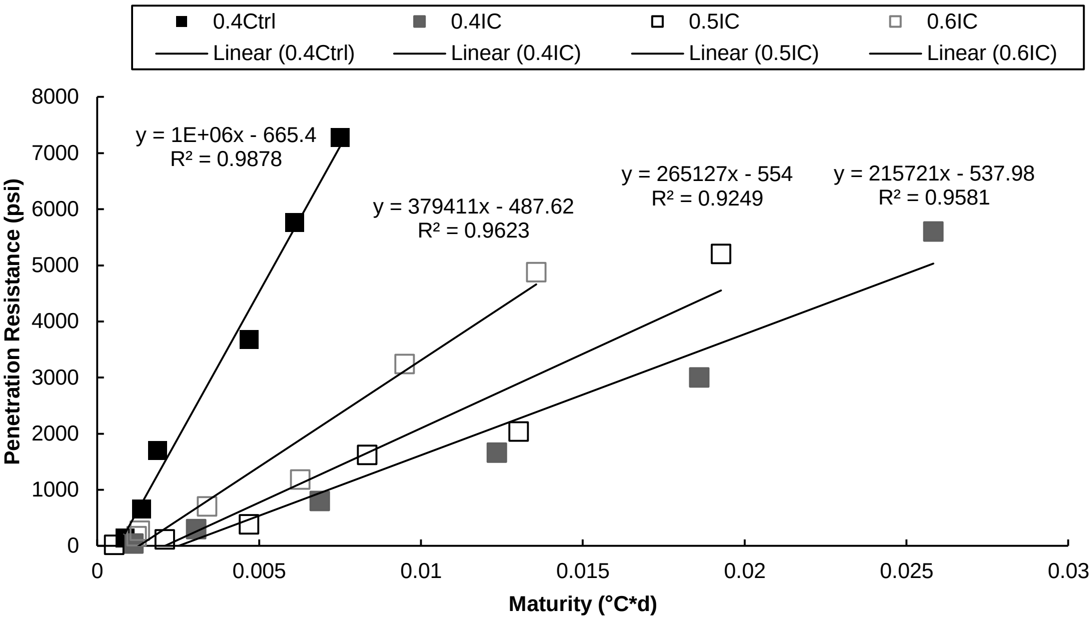

Figure 109 Relationship between Penetration resistance and maturity of IC mixtures

A possible relationship between maturity at 2 d and compressive strength (at 12 h and 28 d) was also investigated. Those results were not statistically significant and are not presented in this dissertation. Nevertheless, maturity has been proven to predict compressive strength at a specific age (Carino N. , 1984). Technically, compressive strength cannot be tested at the same time steps maturity was tested because of physical limitations. Figure 110 shows the compressive strength test of B0.4Ctrl, B0.4CA0.125 and B0.4BA0.125 fitted to a logarithmic regression. Comparing the trend of compressive strength (regression values), with the observed maturity, a logarithmic regression can be established with high R values, as shown in Figure 111. Consequently, the statistically significant observed relationship could be used to adequately predict concrete compressive strength by measuring maturity in-place. This could potentially change the way civil engineers measure compressive strength in the field.

To obtain an even more statistically significant relationship, more variables have been added to the maturity equation in previous research which were not considered for this dissertation (coefficient of proportionality, calorimetry, rate of maturation, limiting strength, activation energy, equivalent age and cumulative amount cement reaction (Tepke, Tikalsky, & Scheetz, 2004) (Carino & Tank, 1992) (Chanvillard & D'Aloia, 1997) (Chengju, 1989)). It has been proposed that concrete mixtures will achieve similar levels of early age compressive strength when their maturities are equal, irrespective of their temperature history (Carino N. , 1984). Consequently, measuring maturity could possibly be a reliable method to estimate compressive strengths of concrete mixtures. Maturity can be related to penetration resistance, which is used to determine set time. Moreover, set time is statistically related to compressive strength.

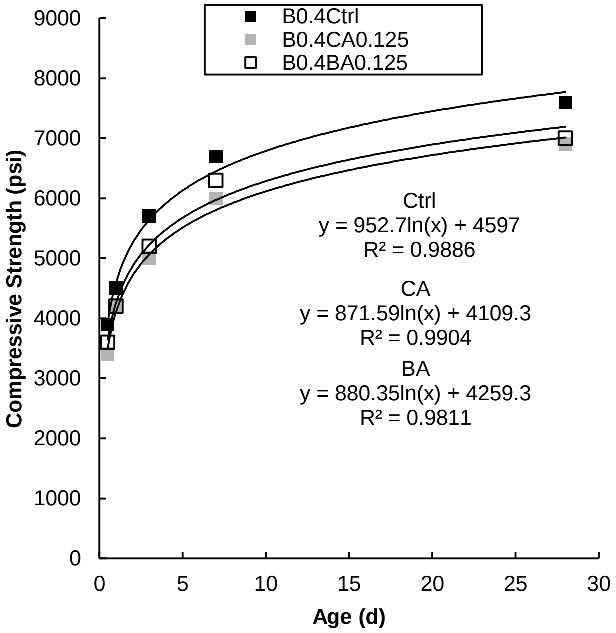

Figure 110 Compressive strength fitted to Age of testing

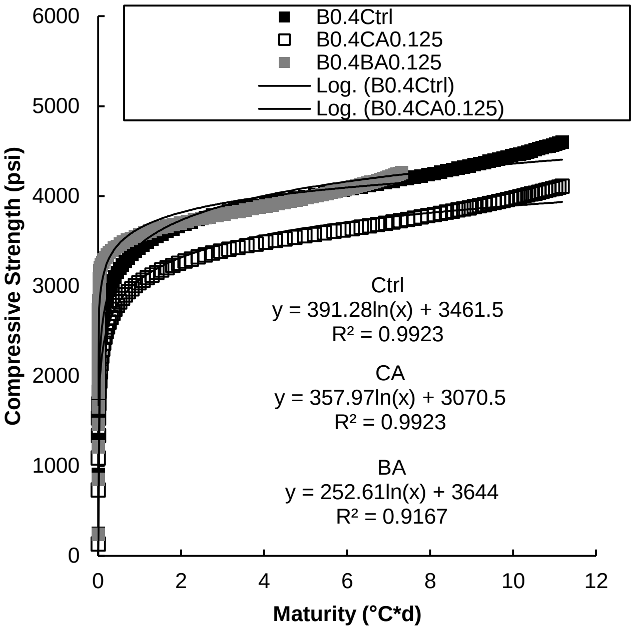

Figure 111 Compressive strength trend and maturity relationship

Figure 111 shows that there exists some error in the maturity data. The skew of the data represents the uncertainty that is present in the measured maturity. When concrete temperature gets closer to ambient temperature, the error in the measured data is more significant. A reference thermocouple is usually utilized to mitigate this error and was not implemented in this chapter. If there is some translational error and higher temperatures keep getting recorded it would appear as if maturity kept increasing, while nothing was actually occurring. For future research, a reference thermocouple should be utilized to mitigate this effect and obtain data with less uncertainty.

There are many benefits that the maturity method brings to Civil Engineering. With wireless technology it is possible to measure concrete temperature and estimate in-place compressive strengths without the need to cast cylinders at different ages (a concrete cylinder may cost around $150 to test). Therefore, a reduction in cost is to be expected when less cylinders are required per batch. The precision of this method depends on several factors, such as the maturity function for a specific mixture, thermal history and proportions. However, when this relationship is established, the maturity method could be very reliable to estimate in-place concrete strength providing another (and cheaper) way of determining it.

5.3 Conclusions

This chapter investigated the setting time, compressive strength and maturity of different CSA mortar mixtures with different admixtures. As in previous chapters, control CSA mixtures exhibited low setting times, high compressive strengths and improved rate of strength development. With the addition of admixtures, the setting times of this mixtures was retarded while compromising the rate of strength development and early compressive strength. Furthermore, the temperature peak of the mortars was lowered by the admixtures utilized, thus, liberating heat at a lower rate (slower reaction). Both CA and BA are known to not crystallize as other salts, but, to be complexed with Ca^{2+} and potentially lower its concentration in the pore solution which slows down the formation of AFt. After all the citrate and borate ions are complexed, the formation of ettringite is accelerated immediately. This was expected because of a reduced rate of strength development presented by the mixtures with admixtures.

The effect of water to cement ratio was also observed. An increase in water to cement ratio normally translates to a retarded setting time, a slower rate of strength development and a slower chemical reaction in the mixtures. However, when utilizing CA and BA, at w/c = 0.5, the setting time at lower concentrations was not retarded but accelerated. The same was not observed for w/c = 0.6. Most likely, this effect is due to the amount of water diluting part of the chemicals, thus reducing their effects. Because of time constraints, this effect should be considered for future research.

Thermal history proved to be an efficient method to determine compressive strength in-place of concrete mixtures. Maturity (which can be determined from thermal history) is a strong predictor of compressive strength (R values between 0.91 and 0.99) for CSA mixtures. This potentially could reduce construction costs by reducing the number of cylinders that need to be tested to obtain compressive strength at different ages. In large scale projects, this could be extremely beneficial. Also, maturity could help confirm compressive strength values obtained by compressive strength tests. In all, more research regarding maturity, CSA and admixture retarders is needed to obtain a more accurate regression and safety factors which would allow an even better prediction of compressive strength.

CHAPTER 6

CONCLUSIONS AND FURTHER RESEARCH

6.1 Introduction

The conclusions and suggested further research of this thesis are discussed in this chapter. A wide range of tests that focused on the effects of different admixtures and internal curing using PSLWA and CSA cement on shrinkage mitigation, rapid strength development, increasing workability were carried out. The main conclusions are presented as follows.

6.2 Conclusions

CSA repair media showed exceptional compressive strength (more than 4,000 psi in 4 h), split tensile strength (more than 200 psi in 4 h), modulus of elasticity (more than 3 x 10^6 psi in 4 h), and rate of strength development over OPC repair media, despite OPC mixtures including high dosages of accelerators and silica fume (20% and 30% of cement weight). Nevertheless, CSA volume stability (300 $\mu\varepsilon$ within first 8 h of autogenous shrinkage) was shown to be comparably worse than that of OPC with (200 $\mu\varepsilon$ within the first 8 h of autogenous shrinkage) or without the addition of silica fume (250 $\mu\varepsilon$ within the first 8 h of autogenous shrinkage). The addition of PSLWA decreased the total shrinkage (both autogenous and drying, around 30%) while also increasing the early-age expansion of both OPC and CSA mixtures. In addition, internally cured CSA mixtures exhibited an improvement to volume stability at the expense of mechanical strength properties. This was mainly due to the reduction of stiffness rather than the promotion of hydration. IC proved to be efficient in helping mitigate the volume stability problems observed in rapid repair media. Volume stability affects concrete repairs significantly. The ability of the repair concrete to be compatible with old concrete is crucial, thus, significant changes in volume may affect surrounding concrete potentially causing undesirable cracking and popping off. Mitigation of these afflictions would greatly benefit rapid repair media, as this is a common occurrence in current practice.

The low setting times normally exhibited by CSA cement mixtures were retarded with the addition of admixtures (CA, BA, SU, Coke) at different water to cement ratios (0.4, 0.5 and 0.6). By retarding the setting time of the mixtures (up to a factor of 15), a compromise in the rate of strength development was observed (up to 65% of strength loss with respect to the control). Rapid repair media is required to have enough working time so that it can be manipulated by contractors on site. CSA suffers from setting too fast, and it is often utilized as a secondary cementitious material to OPC. Utilizing CSA as the unique cementitious material in a mixture will provide a reduction in costs (bulk buying) and excellent mechanical properties at early-age. By using the admixtures, the working time is extended to workable levels and the strength is not compromised as much, delivering a more practical use for full CSA concrete mixtures.

Thermal history proved to be an efficient method to determine compressive strength in-place of concrete mixtures. Maturity (which can be determined from thermal history) is a strong predictor of compressive strength (R values between 0.91 and 0.99) for CSA mixtures. Maturity could potentially predict in-place strength for repair mixtures, thus reducing the need of casting concrete cylinder specimens. Wireless temperature and maturity sensors are available in the market, and some of them can predict strength for some types of concretes. This technology could improve the actual state of practice of rapid repair media by introducing a non-destructive test such as maturity that reduces the need for a high number of destructive tests (compressive strength, tensile strength, split tensile strength) which are currently employed by contractors and may reduce the costs of large-scale constructions. Consequently, utilizing a non-destructive test and reduce the time needed to finish a project because monitored maturity could indicate when the required strength has been reached, thus, signaling when project could be open to vehicles (in case of pavement) or when it could be safe to proceed to the next building stage.

The utilization of CA, BA, SU and Coke with CSA effectively reduced the effect of drying and autogenous shrinkage (as seen in Appendix C). When the concentration of admixtures was increased, the observed reduction was larger. Conversely, when the water to cement ratio was increased, the observed reduction was even larger.

In conclusion, CSA possesses the properties required to function as rapid repair media. It is superior in mechanical strength to OPC, and with the right admixtures, its volume stability is the same or better than accelerated OPC. With the right proportions and admixtures, CSA could possibly be the future of the rapid repair concrete industry in the next few years.

6.3 Recommendations for future research

The experimental procedures followed in this thesis were on small-scale specimens (cubes, cylinders, prisms). To better predict the effect of internal curing, admixtures and CSA cement mixtures in the field, further research on large-scale specimens must be conducted. These large-scale specimens should be subjected to weather effects, fatigue, bond properties, thermal deformation, plastic deformation and dynamic loads. These factors need to be considered in order to predict volume stability behavior more accurately.

The observed effect of the water to cement ratio of 0.5 to the setting time in Chapter 4, should be researched further. This effect should be observed through electron microscopy and a chemical analysis should be performed to determine what is happening with the reaction (pH levels, calorimetry). In addition, more water to cement ratios should be tested (less than 0.4 and greater than 0.6) to evaluate if there is a parabolic effect for setting times. Other admixtures mentioned in the literature should also be considered, and their effects should be observed with these water-to-cement ratios.

Other internal curing agents should be considered (such as SAP and other types of PSLWA) besides the PSLWA utilized in this research. Different types of pre-soaking methods for LWA should be studied to analyze the effectiveness of the different methods in volume stability and mechanical properties of concrete. Furthermore, the combination of both internal curing and the utilization of chemical admixtures should be tested. Possibly, at lower dosages of admixtures, a concrete mixture could have an improved volume stability without a lower early-age compressive strength.

To obtain more statistically significant relationships between maturity and compressive strength, more variables have been added to the maturity equation in the past which should be considered for future research depending on available equipment (coefficient of proportionality, calorimetry, rate of maturation, limiting strength, activation energy, equivalent age and cumulative amount cement reaction).

By measuring these variables, the maturity prediction will be more accurate and could potentially be utilized to predict the compressive strength for different types of concretes. Also, a reference thermocouple should be utilized to mitigate the skew obtained in some of the observed maturity of certain mixtures and obtain data with less uncertainty. Using this, more reliable data will be measured, thus, producing more accurate prediction models.

REFERENCES

ACI. (2013, January). *ACI Concrete Terminology.* Retrieved September 9, 2014, from www.concrete.org: http://www.concrete.org/portals/0/files/pdf/ACI_Concrete_Terminology.pdf

ACI. (2013). *ACI Concrete Terminology.* Farmington Hills, MI.

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

ACI Committee 308; ACI Committee 213. (2013). *Report on Internally Cured Concrete Using Prewetted Lightweight Aggregate.* Farmington Hills, MI: American Concrete Institute.

Ahmadi, B., & Shekarchi, M. (2010). Use of natural zeolite as a supplementary cementitious material. *Cement and Concrete Composite, 32*(2), 134-141.

Alexander, M., & Mindess, S. (2010). *Aggregates in concrete.* New York: Taylor and Francis.

Ardeshirilajimi, A., Wu, D., Chaunsali, P., & al., e. (2016). *Bridge Decks: Mitigation of Cracking and Increased Durability.* University of Illinois at URbana-Champaign. Urbana, IL: Illinois Center for Transportation.

ASCE. (1998). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

ASCE. (2001). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

ASCE. (2005). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

ASCE. (2009). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

ASCE. (2013). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

ASCE. (2017). *ASCE Report Card.* Reston, VA: American Society of Civil Engineers.

Atthakorn, T., Somchai, M., Chantana, P., & Yothin, U. (2014). Investigation of the Compressive Strength, time lags and decrement factors of AAC-lightweight concrete containing sugar sediment waste. *Energy and Buildings*, 516-525.

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

Banthia, N., Zanotti, C., & Sappakittipakorn, M. (2014). Sustainable fiber reinforced concrete for repair applications. *Construction and Building Materials, 62*, 405-412.

Barrett, T. (2015). *Improving service life of concrete structures through the use of internal curing: impact on practice.* West Lafayette, Indiana: Purdue University.

Bentz, D. P. (2007, July). Internal Curing of High-Performance Blended Cement Mortars. *Materials Journal, 104*(4), 408-414.

Bentz, D. P., & Snyder, K. (1999). Protected Paste Volume in Concrete- Extension to Internal Curing Using Saturated Lightweight Fine Aggregate. *Cement and Concrete REsearch, 29*, 1863-1867.

Bentz, D. P., & Weiss, J. (2010). *Internal Curing: A 2010 State-of-the-Art Review.* National Institute of Standards and Technology.

Bentz, D. P., Ferraris, C., De la Varga, I., Peltz, M., & Winpigler, J. (2010, Sep). Mixture Proportioning Options for Improving High Volume Fly Ash Concretes. *International Journal of PAvement Research and Technology, 3*(5), 234-240.

Bentz, D. P., Lura, P., & Roberts, J. W. (2005). Mixture Proportioning for Internal Curing. *Concrete International*, 35-40.

Bentz, D., & Jensen, O. (2004). Mitigation strategies for autogenous shrinkage cracking. *Cement and Concrete Composite* , 677-685.

Bentz, D., Geiker, M., & Jensen, O. (2002). On the mitigation of early age cracking. In B. P. Fagerlund (Ed.), *Proceedings of the 3rd International Seminar: Self-Desiccation and Its Importance in Concrete Technology,* (pp. 195-203). Lund, Sweden.

Bentz, D., Jones, S., Peltz, J., & Stutzman, P. (2015). Mitigation of autogenous shrinkage in repair mortars via internal curing. *Concrete in Australia, 41*(4), 35-39.

Bentz, D., Jones, S., Peltz, M., & Stutzman, P. (2015). *Influence of internal curing on properties and performance of cement-based repair materials.* Gaithersburg, MD: National Institute of Standards and Technology.

Bentz, D., M.R., G., & K.K., H. (2001). Shrinkage-reducing admixtures and early-age desiccation in cement pastes and mortars. *Cement and Concrete Research, 31*(7), 1075-1085.

Beretka, J., Sherman, N., Marroccoli, M., Pompo, A., & Valenti, G. (1997). Effect of composition on the hydration properties of rapid-hardening sulfoaluminate cements. In H. Justnes (Ed.), *Proceedings of the 10th International Congress* *on the Chemistry of Cement. II*, p. 2ii029. Gothenburg, Sweden: Amarki AB and Congrex.

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.

Bizzozero, J., Gosselin, C., & Scrivener, K. (2014). Expansion mechanisms in calcium aluminate and sulfoaluminate systems with calcium sulfate. *Cement and Concrete Research, 56*, pp. 190-202.

Bremner, T. &. (2009). Stephen J. Hayde: Father of the Lightweight Concrete Industry. *Concrete International*, p35-38.

Burris, L., & Kurtis, K. (2018). Influence of set retarding admixtures on calcium sulfoaluminate cement hydration and property development. *Cement and Concrete Research, 104*, 105-113.

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

Carino, N. (1984). The Maturity Method: Theory and Application. *Cement, Concrete and Aggregates, 6*(2), 61-73.

Carino, N., & Tank, R. (1992). Maturity functions for concretes made with various cements and admixtures. *ACI Materials Journal, 89*(2), 188-196.

Castro, J. (2011). *Moisture transport in cement based materials: Application to transport tests and internal curing.* West Lafayette, Indiana: Purdue University.

Castro, J., De la Varga, I., Golias, M., & Weiss, W. (2010). Extending Internal Curing Concepts to Mixtures Containing High Volumes of Fly Ash. *International Bridge Conference.* Pittsburgh, PA: Engineer's Society of Western Pennsylvania.

Castro, J., Keiser, L., Golias, M., & Weiss, J. (2011). Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures. *Cement & Concrete Composites*, 1001-1008.

Champenois, J. D. (2015). Influence of Sodium Borate on the early age of hydration of calcium sulfoaluminate cement. *Cement and Concrete Research*, 83-93.

Chanvillard, G., & D'Aloia, L. (1997). Concrete strength estimation at early ages: modification of the method of equivalent age. *ACI Materials Journal, 94*(6), 520-530.

Chaunsali, P., & Mondal, P. (2016). Physico-chemical interaction between mineral admixtures and OPC-calcium sulfoaluminate (CSA) cements and its influence on early-age expansion. *Cement and Concrete Research*, 10-20.

Chen, D., Zhou, W., Yi, W., & Won, M. (2014). Full-depth concrete pavement repair with steel reinforcements. *Construction and Building Materials, 51*, 344-351.

Chengju, G. (1989). Maturity of Concrete: Method for Predicting Early-Stage Strength. *ACI Materials Journal, 86*(4), 341-353.

Christodoulou, C., Goodier, C., Austin, S., Glass, G., & Webb, J. (2014). A new arrangement of galvanic anodes for the repair of reinforced concrete structures. *Construction and Building Materials, 50*, 300-307.

Clarke, J. (2002). *Structural lightweight.* CRC Press.

Cleary, J., & Delatte, N. (2008). Implementation of Internal Curing in Transportation Concrete. *Transportation Research Record*, 1-7.

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

Craeye, B., Geirnaert, M., & De Schutter, G. (2011). Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks. *Construction and Building Materials, 25*, 1-13.

Craeye, B., Geirnaert, M., & Schutter, G. (2011). Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks. *Construction and Building Materials*, 1-13.

Cusson, D., & Hoogeveen, T. (2008). Internal curing of hihg-performance concrete with pre-soaked fine lightweight aggregate for prevention of autogenous shrinkage cracking. *38*(6).

Cusson, D., Lounis, Z., & Daigle, L. (2010). Benefits of internal curing on service life and life-cycle cost of high-perfomrance concrete bridge decks - A case study. *Cement and Concrete Composites, 32*(5), 339-350.

Damtoft, J., Lukasik, J., Herfort, D., Sorrentino, D., & Gartner, E. (2008). Sustainable development and climate change initiatives. *Cement and Concrete Research, 38*(2), pp. 115-127.

De La Varga, I. (2013). *Increased fly ash volume and internal curing in concrete structures and pavements*. West Lafayette, IN: Purdue University, ProQuest Dissertations Publishing.

De la Varga, I., Castro, J., Bentz, D., & Weiss, J. (2012). *Application of internal curing for mixtures containing high volumes of fly ash.* Cement & Concrete Composites.

De la Varga, I., Spragg, R., Di Bella, C., Castro, J., Bentz, D., & Weiss, J. (2014). Fluid transport in high volume fly ash mixtures with and without internal curing. *Cement & Concrete Composites*, 102-110.

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

Dudziak, L., & Mechtcherine, V. (2008). Mitigation of volume changes of Ultra-High Performance Concrete (UHPC) by using Super Absorbent Polymers. *Second International Symposium on Ultra High Performance Concrete* (pp. 425-432). Dresden, Germany: Structural Materials and Engineering Series.

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.

Emmons, P., Vaysburd, A., & McDonald, J. (1994). Concrete repair in the future turn of the century - any problems. *Concrete International*, *16*(3), 42-49.

ESCSI. (2012). *ESCSI Guide Specifications for Internally Cured Concrete.* Chicago, IL: Expanded Shale, Clay and Slate Institute.

Espinoza-Hijazin, G., & Lopez, M. (2011). Extending internal curing to concrete mixtures with W/C higher than 0.42. *Construction and Building Materials, 25*(3), 1236-1242.

Galvão, J., Portella, K., Joukoski, A., & Mendes, R. (2011). Use of waste polymers inconcrete for repair of dam hydraulic surfaces. *Construction and Building Materials, 25*, 1049-1055.

Gediminas, K., Xiangming, Z., Castro-Gomes, J., Huang, S., & Saafi, M. (2015). Effects of lactic and citric acid on early-age engineering properties of Portland/calcium aluminate blended cements. *Construction and Building Materials*, 389-395.

Geiker, M. (1983). *Studies of Portland Cement Hydration: Measurement of Chemical Shrinkage and a Systematic Evaluation of Hydration Curves by Means of the Dispersion Model.* Lyngby, Denmark: Technical University of Denmark.

Geiker, M., Bentz, D., & Jensen, O. (2004). Mitigating autogenous shrinkage by internal curing. *ACI Special Publication 218*, 143-148.

Ghourchian, S., Wyrzykowski, M., Lura, P., Shekarchi, M., & Ahmadi, B. (2013). An investigation on the use of zeolite aggregates for internal curing of concrete. *Construction and Building Materials, 40*, 135-144.

Glasser, F., & Zhang, L. (2001). High-perfomance cement matrices based on calcium sulfoaluminate-belite compositions. *Cement and Concrete Research, 21*(12), 1881-1886.

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

Gonzalez-Corominas, A., & Etxeberria, M. (2014). Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. *Construction and Building Materials, 68*, 618-626.

Guan, Y., Gao, Y., Sun, R., Won, M., & Ge, Z. (2016). Experimental Study and Field Application of Calcium Sulfoaluminate Cement for Rapid Repair of Concrete Pavements. *Front. Struct. Civ. Eng.*

Gulikers, J., & van Mier, J. (1991). The effect of patch repairs on the corrosion of steel reinforcement in concrete. *CANMET/ACI*, 445-460.

Guthrie, W., & Yaede, J. (2013). Internal Curing of Concrete Bridge Decks in Utah: Preliminary Evaluation. *Journal of the Transportation Research Board*, 121-128.

Haddad, R., Al-Rousan, R., & Al-Sedyiri, B. (20113). Repair of shear-deficient and sulfate-damaged reinforced concrete beams using FRP composites. *Engineering Structures*, *56*, 228-238.

Hasholt, M., Jensen, O., Kovler, K., & Zhutovsky, S. (2012). Can superabsorbent polymers mitigate autogenous shrinkage of internally cured concrete without compromising the strength? *Construction and Building MAterials, 31*, 226-230.

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.

Henkensiefken, R. (2008). *Internal Curing in Cementitious Systems made using Saturated Lightweight Aggregate.* Purdue: Purdue University.

Henkensiefken, R. e. (2009). Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions. *Cement and Concrete Composites*, 427-437.

Henkensiefken, R., Nantung, T., & Weiss, J. (2009, July). Saturated Lightweight Aggregate for Internal Curing in Low w/c Mixtures: Monitoring Water Movement Using X-ray Absorption. *Strain, 47*(s1), 432-441.

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

Hoff, G. C. (2003). Internal Curing of Concrete Using Lightweight Aggregate. *Theodore Bremner Symposium on High Performance Lightweight Concrete* (pp. 185-203). Thessaloniki, Greece: Sixth CANMET/ACI International Conference on Durability.

Holm, T., Ooi, O., & Bremner, T. (2004). Moisture dynamics in lightweight aggregate and concrete. *Expanded Shale Clay and Slate Institute*, 12.

Holt, E. (2001). *Early age autogenous shrinkage of concrete* (Vol. 446). Espoo: Technical REsearch Centre of Finland, VTT Publications.

Hu, Y., & Ma, S. (2017). Influence of borax and citric acid on the hydration of calcium sulfoaluminate cement. *Chemical Papers- Slovak Academy of Sciences*, 1-10.

Huang, X., Ranade, R., Ni, W., & Li, V. (2013). On the use of recycled tire rubber to develop low E-modulus ECC for durale concrete repairs. *Construction and Building Materials, 46*, 134-1414.

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.

Jin, N., Seung, I., Choi, Y., & Yeon, J. (2017). Prediction of early-age compressive strength of epoxy resin concrete using the maturity method. *Construction and Building Materials, 152*(1), 990-998.

Jones, W. (2014). *Examining the freezing and thawing durability of concretes with improved performance through internal curing and other methods.* West Lafayette, IN: Purdue University.

Juenger, M., Winnefeld, F., Provis, J., & Ideker, J. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research, 41*, 1232-1243.

Justs, J., Wyrzykowski, M., Bajare, D., & Lura, P. (2015). Internal curing by superabsorbent polymers in ultra-high performance concrete. *Cement and Concrete Research*, 82-90.

Justs, J., Wyrzykowski, M., Winnefeld, F., Bajare, D., & Lura, P. (2014). Influence of superabsorbent polymers on hydration of cement pastes with low water-to-binder ratio. *Journal of Therm. Anal. Calorim., 115*, 425-432.

Kaufmann, K., Winnefeld, F., & Lothenbach, B. (2016). Stability of ettringite in calcium sulfoaluminate based cement pastes at elevated temperatures. *Advanced Cement Research*.

Kim, J.-K., Moon, Y.-H., & Eo, S.-H. (1998). Compressive strength development of concrete with different curing time and temperature. *Cement and Concrete Research, 28*(12), 1761-1773.

Kim, K., Subgranon, T., Tia, M., & Bergin, M. (2016). Internally Cured Concrete for use in Concrete Pavement Using Accelerated Pavement Testing and Finite-Element Analysis. *Journal of Materials in Civil Engineering, 28*(6).

Klieger, P. (1958). Early High Strength Concrete for Prestressing. *Proceedings, World Conference on Prestressed Concrete.* Chicago: Research and Development Laboratories of the Portland Cement Association.

Kohno, K., Okamoto, T., Isikawa, Y., Sibata, T., & Mori, H. (1999). Effects of artificial lightweight aggregate on autogenous shrinkage of concrete. *Cement and Concrete Research*, 611-614.

Kurdowski, W. (2014). *Cement and Concrete Chemistry.* Krakow, Poland: Springer.

Landgren, R. (1964). Determining the water absorption of coarse lightweight aggregate for concrete. *Portland Cement Association*(Bulletin 179).

Landgren, R. (1964). Water-vapor adsorption-desorption characteristics of selected lightweight concrete aggregates. *Portland Cement Association*.

Leach, J. (2017). *Internally cured concrete mixtures and specifications for highway infrastructure.* Charlotte, NC: University of North Carolina.

Li, J., Zhang, W., & Cao, Y. (2014). Laboratory evaluation of magnesium phosphate cement paste and mortar for rapid repair of cement concrete pavement. *Construction and Building Materials, 58*, 122-128.

Li, J., Zhang, W., & Cao, Y. (2014). Laboratory evaluation of magnesium phosphate cement paste and mortar for rapid repair of cement concrete pavement. *Construction and Building Materials, 58*, 122-128.

Lura, P. (2003). *Autogenous deformation and internal curing of concrete.* Technical University of Delft.

Lura, P., Couch, J., Jensen, O., & Weiss, J. (2009). Early-age acoustic emission measurements in hydrating cement paste: Evidence for cavitation during solidification dure to self-desiccation. *Cement and Concrete Research*, 861-867.

Lura, P., Wyrzykowski, M., Tang, C., & Lehmann, E. (2014). Internal curing with lightweight aggregate produced from biomass-derived waste. *Cement and Concrete Research*, 24-33.

Maguire, M., Collins, W., Halbe, K., & Roberts-Wollmann, C. (2016). Multi-Span Members with Unbonded Tendons: Ultimate Strength Behavior and Recommendations. *ACI Structural Journal, 113*(2), 8.

Maguire, M., Roberts-Wollmann, C., & Cousins, T. (2018). Live Load Testing and Long Term Monitoring of the Varina-Enon Bridge: Investigating Thermal Distress. *ASCE Journal of Bridge Engineering, 23*(3), 14.

Maguire, M., Thomas, R., Quezada, I., & Szary, P. (2015). *Developing a Low Shrinkage, High Creep Concrete for Infrastructure Repair.* Logan, UT: Rutgers.

Mangat, P. S., & Limbachiya, M. K. (1995). Repair material properties which influence long-term performance of concrete structures. *Construction and Building Materials, 9*(2), 81-90.

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

Marosszeky, M., & Wang, D. (1991). The study of the effect of various factors and subsequent bar corrosion. *Proeeedings Second International Conference On Durability of Concrete* (pp. 585-606). American Concrete Institute.

Martinola, G., Meda, A., Plizzari, G., & Rinaldi, Z. (2010). Strengthening and repair of RC beams with fiber reinforced concrete. *Cement and Concrete Composites, 32*(9), 731-739.

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

McPherson, G., & Muchnick, J. (2005). Effects of street tree shade on asphalt concrete pavement performance. *Journal of Arboriculture, 31*(6), 303-310.

Mechtcherine, V. (2013). Novel cement-based composites for the strengthening and repair of concrete structures. *Construction and Building Materials, 41*, 365-373.

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

Ming-zhe, A., Li-jun, Z., & Quan-xin, Y. (2008). Size effect on compressive strength of reactive powder concrete. *Journal of China University Mining and Technology*, 279-282.

Moffatt, E., & Thomas, M. (2017). Performance of rapid-repair concrete in an aggressive marine environment. *132*, 478-486.

Mohr, B., Premenko, L., & Nanko, H. a. (2005). Examination of wood-derived powders and fibers for internal curing of cement-based materials. In D. B. B. Persson (Ed.), *Proceedings of the 4th Interational Seminar: Self-Desiccation and Its Importance in Concrete Technology*, (pp. 229-244). Gaithersburg, MD.

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.

Morcous, G., Hatami, A., Maguire, M., Hanna, K., & Tadros, M. (2012). Mechanical and Bond Properties of 18-mm-(0.7-in.-) Diameter Prestressing Strands. *ASCE Journal of Materials in Civil Engineering, 24*(6), 735-744.

Moreno, D., Martines, P., & Lopez, M. (2014). Practical Approach for Assessing Lightweight Aggregate Potential for Concrete Performance. *ACI Materials Journal, 111*(2).

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

Nguyen, V., & al., e. (2011). The study of using rice husk ash to produce ultra high performance concrete. *Construction and Building Materials, 25*, 2030-2035.

Nobili, A., Lanzoni, L., & Tarantino, A. (2013). Experimental investigation and monitoring of a polypropylene-based fiber reinforced concrete road pavement. *Construction and Building Materials, 47*, 888-895.

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*.

Pang, X. (2015). The effect of water-to-cement ratio on the hydration kinetics of Portland cement at different temperatures. *Cementing Applied Science and Processes*, 11.

Paul, A., & Lopez, M. (2011). *Assessing Lightweight Aggregate Efficiency for Maximizing Internal Curing Performance.* ACI Materials Journal.

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

Perry, M., Fusiek, G., Niewczas, P., Rubert, T., & McAlorum, J. (2017). Wireless Concrete Strength Monitoring of Wind Turbine Foundations. *Sensors and Sensors Networks for Structural Health Monitoring, 17*(12), 2928.

Pettigrew, C., Barr, P., Maguire, M., & Halling, M. (2017). Behavior of 48-Year Old Double-Tee Bridge Girders made with Lightweight Concrete. *ASCE Journal of Bridge Engineering, 21*(2), 8.

Philleo, R. (1991). Concrete Science and Reality. (J. S. S.Mindness, Ed.) *Materials Science of Concrete*, 1-8.

Pigeon, M., & Saucier, F. (1991). Durability of repaired concrete structures. *ACI International Conference on Evaluation and REhabilitation of Concrete Structures and Innovation in Design*, (pp. 689-705). Hong Kong.

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

Poellmann, H., Auer, S., Kuzel, H., & Wenda, R. (1993). Solid-solution of ettringites 2. Incorporation of B(OH) and CrO4. *Cement and Concrete Research, 23*(2), 422-430.

Poole, A., & Sims, I. (2016). *Concrete Petrography: A Handbook of Investigative Techniques, Second Edition.* CRC Press.

Qian, J., You, C., Wang, Q., Wang, H., & Jia, X. (2014). A method for assessing bond performance of cement-based repair materials. *Construction and Building Materials*, *68*, pp. 307-313.

Quezada, I., Thomas, R., & Maguire, M. (2018). Internal curing to mitigate cracking in rapid set repair media. *ASTM Jounral of Advances in Civil Engineering Materials. Special Issue on Internal Curing*, *7*(4), 12p.

Radlinska, A., Rajabipour, F., Bucher, B., & al., e. (2008, December). Shrinkage Mitigation Strategies in Cementitious Systems: A closer look at differences in sealed and unsealed behavior. *Transportation Research Record: Journal of the Transportation*, *2070*(08), 59-67.

Ramseyer, C., & Bescher, E. (2014). Performance of Concrete Rehabilitation using Rapid Setting CalciumSulfoAluminate Cement at the Seattle-Tacoma Airport.

Rashawan, M., Diab, H., & El-Fattah, Y. (2016). Improving of lightweight self-curing concrete properties. *Journal of Engineering Sciences*, *44*(3), 259-271.

Sakulich, A., & Bentz, D. (2013). Mitigation of autogenous shrinkage in alkali activated slag mortars by internal curing. *Materials and Structures*, *46*, 1355-1367.

Samson, G., Phelipot-Mardelé, A., & Lanos, C. (2015). Thermal and mechanical properties of gypsum-cement foam concrete: effects of surfactant. *European Journal of Environmental and Civil Engineering*, 1-20.

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.

Schlitter, J., Bentz, D., & Weiss, J. (2013). Quantifying stress development and remaining stress capacity in restrained, internally cured mortars. *ACI Materials Journal*, 3-11.

Sciumè, G., Benboudjema, F., De Sa, C., Pesavento, F., Berthaud, Y., & Schrefler, B. (2013). A multiphysics model for concrete at early age applied to repairs problems. *Engineering Structures, 57,* 374-387.

Sharif, A., Rahman, M., Al-Gahtani, A., & Hameeduddin, M. (2006). Behaviour of patch repair of axially loaded reinforced concrete beams. *Cement and Concrete Composites, 28,* 734-741.

Song, X., Wei, J., & He, T. (2009). A method to repair concrete leakage through cracks by synthesizing supper-absorbent resin in situ. *Construction and Building Materials, 23,* 386-391.

Streeter, D., Wolve, W., & Vaughn, R. (2013). *NYSDOT Report 290-7 Field Performance of Internally Cured Concrete Bridge Decks in New York State.* NYSDOT.

Szary, P., & Roda, A. (2013). *Bridge Resource Program.* Piscataway, NJ: Center for Advanced Infrastructure and Transportation.

Taffese, W., & Sistonen, E. (2013). Service life prediction of repaired structures using concrete recasting method. *11th International Conference on Modern Building Materials, Structures and Techniques. 57,* pp. 1138-1144. Procedia Engineering.

Talbolt, C., Pigeon, M., Beaupré, D., & Morgan, D. (1994). Influence of surface preparation on long term bonding of shotcrete. *ACI Materials Journal, 91*(6), 560-566.

Tayeh, B., Abu Bakar, B., Johari, M., Voo, L., & Y. (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.

Taylor, P., Hosteng, T., Wang, X., & Phares, B. (2016). *Evaluation and Testing of a Lightweight Fine Aggregate Concrete Bridge Deck in Buchanan County, Iowa.* Buchanan, Iowa: Institute for Transportation.

Tazawa, E., & Miyazawa, S. (1995). Influence of Cement and Admixtures on Autogenous Shrinkage of Cement Paste. *Cement and Concrete Research, 25*(2), 281-287.

Tazawa, E., Miyazawa, S., & Kasai, T. (1995). Chemical Shrinkage and Autogenous Shrinkage of Hydrating Cement Paste. *Cement and Concrete Research, 25*(2), 288-292.

Tepke, D., Tikalsky, P., & Scheetz, B. (2004). Concrete maturity field studies for highway applications. *Transportation Research Record: Journal of the Transportation Research Board, 1893*(1), 26-36.

Thanongsak, N., Yoshika, S., Supab, C., & Arnon, C. (2015). Microstructure, characterizations, functionality and compressive strength of cement-based materials using zinc oxide nanoparticles as an additive. *Journal of Alloys and Compounds*, 1-10.

Thoft-Christensen, P. (2012). Infrastructures and Life-Cycle Cost-Benefit Analysis. *Structure & Infrastructure Engineering, 8*(5), 507-516.

Thomas, R., Maguire, M., Sorensen, A., & Quezada, I. (2018). Calcium Sulfoaluminate Cement. *Concrete International, 40*(4), 65-69.

Tittleboom, K., De Belie, N., De Muynck, W., & Verstraete, W. (2010). Use of bacteria to repair cracks in concrete. *Cement and Concrete Research*, 157-166.

Trauchessec, R., Mechling, J., Lecomte, A., Roux, A., & Le Rolland, B. (2015). Hydration of ordinary Portland cement and calcium sulfoaluminate cement blends. *Cement & Concrete Composites, 56*, 106-114.

Trtik, P. e. (2010). Neutro tomography investigation of water release from superabsorbent polymers in cement paste. *International Conference on Material Science and 64th RILEM Annual Week.* Aachen, Germany.

van Breugel, K. a. (2000). Potential of Mixtures with Blended Aggregates for Reducing Autogenous Deformation in Low Water/Cement Ratio Concrete. *Proceedings of the 2nd International Symposium on Structural Lightweight Aggregate Concrete* (pp. 463-472). Kristiansand, Norway: S. Helland, I. Holand and S.Smeplass.

Vaysburd, A., & Emmons, P. (2000). How to make today's repairs durable for tomorrow - corrosion protection in concrete repair. *Construction and Building MAterials, 14*, 189-197.

Velazco, G., Almanza, J., Cortés, D., Escobedo, J., & Escalante-Garcia, J. (2014). Effect of citric acid and t he hemihydrate amount on the properties of a calcium sulphoaluminate cement. *Materiales de Construccion, 64*(316), 8.

Villareal, V., & Crocker, D. (2007). Better Pavements through Internal Hydration. *Concrete International*, 32-36.

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).

Wang, K., Helene, P., & Monteiro, P. (2006). Potential use of zinc in the repair of corroded reinforced concrete. *Cement and Concrete Composites*, 707-715.

Weber, S., & Reinhardt, H. (1997). A New Generation of High Performance Concrete: Concrete with Autogenous Curing. *Advanced Cement-Based Materials,* 56-98.

Wei, Y., Xiang, Y., & Zhang, Q. (2014). Internal Curing Efficiency of Prewetted LWFAs on Concrete Humidity and Autogenous Shrinkage Development. *Journal of Materials in Civil Engineering*, 947-954.

Weiss, J. (2016). *Internal Curing for Concrete Pavements.* Washington, DC: FHWA.

Weiss, J., Ley, M., Sutter, L., Harrington, D., Gross, J., & Tritsch, S. (2016). *Guide to the Prevention and Restoration of Early Joint Deterioration in Concrete Pavements.* Ames, IA: Iowa Highway Research Board.

Whiting, D., Nagi, M., & Okamoto, P. A. (1994). Early strength gain of rapid highway repair concrete. *Concrete International ACI, 16*(8), 28-35.

Winnefeld, F., & Lothenbach, B. (2010). Hydration of calcium sulfoaluminate cements - Experimental findings and thermodynamic modelling. *Cement and Concrete Research, 40*, 1239-1247.

Won, J., Kim, J., Lee, S., Lee, S., & Park, S. (2011). Mix proportion of high-strength, roller-compacted, latex-modified rapid-set concrete for rapid road repair. *25*, 1796-1800.

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

Wyrzykowski, M., Lura, P., Pesavento, F., & Gawin, D. (2012). Modeling of Water Migration during Internal Curing with Superabsorbent Polymers. *ASCE Journal of Materials in Civil Engineering, 24,* 1006-1016.

Xion, G., Wu, X., Li, F., & Yan, Z. (2011). Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars. *Construction and Building Materials, 25*(5), 2263-2268.

Yaede, J. (2013). *Internal Curing of Concrete Bridge Decks in Utah: Mountain View Corridor Project.* Provo, UT: All Theses and Dissertation.

Yang, Z., Brown, H., Huddleston, J., & Seger, W. (2016). Restrained Shrinkage Cracking and Dry Shrinkage of Rapid0Set PRepackaged Cementitious Materials. *Journal of Materials in Civil Engineering, 28*(6).

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

Yikici, T., & Chen, R. (2015). Use of maturity method to estimate compressive strength of mass concrete. *Construction and Building Materials, 95*(1), 802-812.

Yildirim, S., Meyer, C., & Herfellner, S. (2015). Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. *Construction and Building Materials, 91*, 288-296.

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

Zajac, M., Skocek, J., Bullerjahn, F., & Ben Haha, M. (2016). Effect of retarders on the early hydration of calcium-sulpho-aluminate (CSA) type cements. *Cement and Concrete Research, 84*(1), 62-75.

Zhutovsky, S., & Kovler, K. (2013). Hydration kinetics of high-performance cementitious systems under different curing conditions. *Materials and Structures, 46*, 1599-1611.

Zhutovsky, Z., Kovler, K., & Bentur, A. (2002, March). Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage. *Materials and Structures, 35*, 97-101.

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

Zuniga, J. (2013). *Development of Rapid, Cement-based Repair Materials for Transportation Structures.* Austin, Texas: University of Texas.

APPENDICES

APPENDIX A

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.

APPENDIX B
RELATIONSHIP PROCEDURE FOR PHASE II

Statistical Analysis Software (SAS) Results

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

Simple Statistics						
Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
cmty3	8	446.25000	382.16255	3570	0	850.00000
ctscm	8	256.25000	355.00252	2050	0	750.00000
sfquant	8	85.00000	120.20815	680.00000	0	255.00000
water	8	234.75000	28.49436	1878	195.00000	255.00000
nwcoarse	8	875.00000	724.56884	7000	0	1400
nwfine	8	450.00000	621.05900	3600	0	1200
lwcoarse	8	356.25000	491.67171	2850	0	950.00000

Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
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

Simple Statistics						
Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
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 Relationship 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

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

	cmty3	ctscm	sfquant	water	nwcoarse	nwfine	lwcoarse	lwfine	w2cmratio
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

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

	cmty3	ctscm	sfquant	water	nwcoarse	nwfine	lwcoarse	lwfine	w2cmratio
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
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 Relationship 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

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

	acc	hrwr	slump	air	unitw	compr4	compr6	compr24	compr7d
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
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

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

	acc	hrwr	slump	air	unitw	compr4	compr6	compr24	compr7d
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 Relationship 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

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

	emod	split	iset	fset	drysh	ring	creepc	freeze
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
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

VITA

Ivan Quezada, PhD

EDUCATION

- **Ph.D Degree, Structural Engineering** May 2018

Utah State University, Logan, UT **3.85 GPA**
Awarded a 4-year full Scholarship for Doctoral Studies from the Dom. Rep. Government

- **M.S Degree, Structural Engineering** May 2014

Utah State University, Logan, UT **3.94 GPA**
Awarded a 2-year full Scholarship for Graduate Studies from the Dom. Rep. Government
Passed FE exam in the state of Utah Oct 2013

- **B.S Degree, Civil Engineering** May 2011

Santo Domingo's Institute of Technology, Santo Domingo, Dom. Rep. **3.49 GPA**

WORK EXPERIENCE

- **Structural Engineer Ph.D Researcher**

Utah State University, Logan, UT, Aug 2014 – July 2018

- Responsible of conducting various ASTM tests (C39,C496,C1698,C1581, and more) on diverse concrete specimens
- Proportioning 150+ concrete mixtures in order to optimize set time, shrinkage and early age properties
- Writing State of the Art research papers, Experiment Design and Comprehensive Testing Reports
- Developing experimental procedures and proportions in order to optimize concrete mixtures
- Utilizing statistical analysis software (SAS) to analyze data from ASTM tests and experiments
- Analyzing structural elements utilizing software in order to determine forces and deformations

- **Structural Project Developer and Supervisor**

Rafael Rosario Structural Engineering, Santo Domingo, Dom. Rep. Feb 2011 to Aug 2012

- ***1,262,570.14 square feet designed*, 150 projects completed**
- Worked alone and on teams in order to draft and calculate structural design projects
- Investigated actual conditions of structures on the field
- Supervised formwork and placement of steel reinforcing before casting
- Model structures utilizing diverse structural analysis and design software suites
- Followed the IBC, the AISC Steel Construction Manual, the ACI 318-11 Building Code and others
- Designed Susan Marie Residences, a 2-story foam wall structure, Apr. 2011
- Designed Grumed Hospital, a 7-story hospital with 2 stories underground, Sept 2011
- Designed the LDS Church at Guayacanes, Dom. Rep., June 2012
- Designed Vistana 2 Tower, a 13-story twin building in San Cristobal, Dom. Rep. July 2012
- Designed FBA's Industrial Warehouse, 1 – story steel structure, Dom. Rep. May 2012

ENGINEERING SKILLS

- Structural Analysis
- AutoCAD2014/Civil3D
- ETABS
- STAAD
- SAP2000
- RISA 2D/3D
- MATLAB
- SAS
- MathCad,
- GT Strudl
- Midas

LEADERSHIP EXPERIENCE

- Dominican Student Association at Utah State University, **President** 2013-2014, 2016-2017
- Society of Hispanic Professional Engineers at Utah State University, **Graduate Ambassador,** 2013-2017
- Resident Assistant Position, ResLife Staff Student Housing at Utah State University 2015-2017

AWARDS RECEIVED

- International Organization of the Year, Dominican Student Association, 2014 (Utah State University)
- International Student of the Year, Nominated, 2014 (Utah State University)
- Mountain View Towers, Employee of the Year, 2016-2017 (Utah State University)