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Jose Ricardo Zuniga

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**The Thesis Committee for Jose Ricardo Zuniga
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**Development of Rapid, Cement-based Repair Materials for
Transportation Structures**

**APPROVED BY
SUPERVISING COMMITTEE:**

Supervisor:

Kevin Folliard

Thanos Drimalas

**Development of Rapid, Cement-based Repair Materials for
Transportation Structures**

by

Jose Ricardo Zuniga, B.S.C.E

Thesis

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Dedication

To my parents, family and friends. Thanks for your support.

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Abstract

Development of Rapid, Cement-based Repair Materials for Transportation Structures

Jose Ricardo Zuniga, M.S.E.

The University of Texas at Austin, 2013

Supervisor: Kevin Folliard

The deterioration of today's infrastructure particularly roadways and bridge decks has continued to increase over the years due to the larger axle loads, higher traffic volumes of densely populated cities. These highly congested areas have required the need to repair and rehabilitate the affected pavements in a timely manner with minimal traffic interruptions. Different rapid hardening binders were tested in this project to evaluate and characterize their performance when subjected to concrete distresses such as alkali-silica reaction, delayed ettringite formation, corrosion, freezing and thawing, salt scaling, sulfate attack, material incompatibility and volume changes. Among the cements tested were calcium aluminate cement, calcium sulfoaluminate cement, accelerated portland cement, alkali-activated fly ash, and three other proprietary blends available to the public. This thesis will summarize the preliminary findings of a comprehensive laboratory study focusing on rapid repair materials – the final results of this study will be included in future publication (theses and final project report).

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Chapter 1: Introduction

1.1 BACKGROUND

The deterioration of today's infrastructure particularly roadways and bridge decks has continued to increase over the years due to the larger axle loads, higher traffic volumes of densely populated cities. These highly congested areas have required the need to repair and rehabilitate the affected pavements in a timely manner with minimal traffic interruptions. Lane closures lasting more than a day are no longer acceptable to the general public so the Texas Department of Transportation (TxDOT) has been working to develop guidelines for "fast-track" concrete repair.

Normal portland cement concrete mixtures are too slow in achieving the typical 3000 psi compressive strength at 3 hours, or 400 psi flexural strength at 4 hours, that is currently recommended for a repair material prior to lanes being opened to traffic and thus over the past several decades the need for rapid hardening concrete mixtures has become extremely popular. The main goals for a successful rapid repair project are to minimize traffic interference, travel delays, and costs while at the same time providing a durable repair.

The main types of cementitious materials for rapid setting concrete mixtures include, but are not limited to, calcium aluminate cement concrete, calcium sulfoaluminate cement concrete, accelerated portland cement concrete, alkali-activated fly ash concrete, and other proprietary blends available to the public. One of the reasons why these materials have become popular for repair on pavements is their ability to achieve high early strengths for speed of construction and repair, but their fast rate of reaction sometimes takes a toll, especially when it comes to durability.

Durability issues especially those related to alkali-silica reaction (ASR), delayed ettringite formation (DEF), freezing and thawing, sulfate attack, and corrosion from chloride intrusion have caused most infrastructure deterioration, so the main goal of this study is to implement a thorough and comprehensive laboratory testing program that will evaluate and address these issues which will then provide a final database that can be used to select materials that can provide the necessary properties for a successful, economical and durable repair.

1.2 SCOPE AND OBJECTIVES

This research project conducted at the University of Texas is funded by the Texas Department of Transportation (TxDOT). The main objective of this research is to provide recommendations on the most effective, economical, and durable replacement methods for partial and full depth repairs of roadways and bridge decks. The testing regime for this project is comprised of two main phases.

This thesis will focus on Phase I of this research project which includes a preliminary screening program to obtain a reasonable testing matrix that satisfies fresh concrete properties such as: suitable working time (pot life), flow, workability, and a compressive strength of 3000 psi at 3 hours. Typical early strength binders common in repair practice such as calcium aluminate cement (CAC), calcium sulfoaluminate cement (CSA), Type III portland cement, and variations of these binders as well, were evaluated for proper mixture proportions and strength requirements. CSA and CAC are also evaluated as latex-modified concrete using a styrene-butadiene latex polymer. This initial screening test includes a set of commercially available prepackaged proprietary mixtures, which through a jointed effort by TxDOT and their needs, were determined to be of interest.

Phase II is ongoing and is a comprehensive laboratory program that tests the hardened and durability properties of a subset of the acceptable mixtures determined from Phase I that were deemed viable as actual field mixtures. The following properties are currently being tested according to the following ASTM standards:

- ASTM C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
- ASTM C 672 Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
- ASTM C 1012 Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
- ASTM C 1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction
- ASTM C 157 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
- ASTM C 1556 Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion
- Modified version of ASTM C 1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

This research thesis focuses primarily on Phase I of the project with Phase II currently ongoing. Based on the rigorous laboratory testing program on different binder mixtures, the research team will develop practical and usable field mixture designs that can achieve not only the short term goals of minimum compressive strength and modulus of rupture, but also the long term goals of durability and service life.

1.3 NOTATIONS

Cement chemists have used a shorthand notation for some of the phases in concrete. These notations have been used throughout this thesis and are as follows:

- C CaO
- S SiO₂
- H H₂O
- A Al₂O₃
- F Fe₂O₃
- \$ SO₃

1.4 CONTENT

The remaining part of the thesis is divided into the following chapters which include:

- Chapter 2 presents a literature on rapid repair materials. The most common types of materials used to this day are examined further and the benefits of each material are described in more detail.
- Chapter 3 describes a laboratory evaluation of the materials chosen to examine for this project. Mixture proportioning, mixing, casting and curing is also given in this section along with a description and breakdown of Phase I and Phase II of this project.
- Chapter 4 presents the findings from Phase I including fresh, hardened, and durability properties. A description of the mixture proportions chosen for the extensive laboratory testing program is also given in this section.
- Chapter 5 presents the conclusion on the results of Phase I and includes a brief discussion of the ongoing and future work remaining on the project. The properties and methods for Phase II are described in more detail in this section.

Chapter 2: Literature Review

2.1 INTRODUCTION

The focus of this literature review is to bring to light some of the needs and requirements for repair materials along with a background and benefits that today's popular binders bring to a high early strength rapid repair job. This chapter also includes any special provisions or specifications for these binders that serve as a starting guide for the durability research needs for this project.

2.2 NEEDS AND REQUIREMENTS

The increase in deterioration to today's infrastructure's pavements has led to an increase in the number of binders and types of mixture designs available for rapid repair and rehabilitation. Typical ordinary portland cement (OPC) mixtures are acceptable for new pavement construction because contractors do not rely on high early strengths soon after placement. On the other hand, roads and bridge decks that have been open to traffic especially in densely populated areas, cannot be simply shut down to allow for repairs because this causes large traffic delays and involves high costs to keep the lanes closed to ensure the safety of construction workers for the duration of the repair. For this reason the implementation of rapid early strength materials for fast-track concrete repair has become quite popular with transportation officials. These rapid-setting materials can be very expensive in comparison to OPC concrete, but the high early strengths, durability and speed of construction compensate for the higher upfront material cost.

Typical short term requirements for these fast-track jobs are 3000 psi compressive strength at 3 hours or 400 psi flexural strength at 4 hours, a reasonable working time and flow of the concrete mixture. Certain binders have become popular for these high early strength jobs such as calcium aluminate cement, calcium sulfoaluminate cement,

accelerated Type III portland cement, alkali-activated fly ash binders, and also prepackaged proprietary blends. These binders typically have no problems meeting the short term goals of strength but their durability properties have not been extensively tested. Durability issues that have been of large concern throughout the years include alkali-silica reaction, delayed ettringite formation, sulfate attack, freezing and thawing, and corrosion. The selected mixes from Phase I of this project will be subjected to a comprehensive laboratory program that will test the durability of the materials to these forms of attack to determine whether these binders will meet the long term durability requirements for fast-track concrete placement.

2.3 TYPES OF MATERIALS

A variety of binders that exhibit high rates of reaction and early-age strength have been developed within the past century and have been harnessed for rapid repair construction to minimize traffic delays and improve performance. The most popular binders to date were selected to conduct an extensive laboratory testing regime to test the fresh, hardened and durability properties. A detailed literature review for each one of these binders is described below.

2.3.1 Calcium Aluminate Cement Concrete

2.3.1.1 Introduction

Calcium aluminate cement (CAC) started to appear in the late 19th and early 20th centuries in Europe. Different in composition from OPC, this blend was engineered to be resistant to high sulfate environments and seawater. Work done by L. J. Vicat in the 1840's to change the chemical makeup of cements, especially the ratio of silica+alumina to that of calcium+magnesium was one of the precursors to the development of CAC (Gosselin, 2009). A few years later, this work was continued by Jules Bied who

experimented with these ratios and came up with a cement low in silica and high in alumina, and finally patented the blend as Ciment Fondu Lafarge in 1908. Nowadays the use of bauxite, a relatively pure and expensive raw material, is the primary source of alumina for the manufacture of CAC (Gosselin, 2009). CAC is typically around four to five times more expensive when compared to OPC. For this reason, CAC is not a major competitor against OPC, thus its use is limited to special areas such as refractory, dry mix mortars, self-leveling compounds and rapid repair. A brief description of the chemical composition and hydration process of CACs is explained in the following sections.

2.3.1.2 Chemical Composition

Several grades of CAC exist and vary in alumina and iron contents and their composition is shown in Table 1. Two different types of bauxite are used to manufacture CAC. Red bauxite typically contains around 20% of iron oxides and typically forms a brown to dark grey cement, while white bauxite contains little to no iron oxides and forms a light grey to white cement. For the purposes of this research Ciment Fondu was chosen as our source for CAC as it is most readily available and the most common blend used for these rapid repair applications. For this specific blend of CAC typical ranges for alumina content are around 40-60%.

Table 1: Composition ranges for calcium aluminate cements from Scrivener (2003)

Grade	Colour	Al ₂ O ₃	CaO	SiO ₂	Fe ₂ O ₃ + FeO	TiO ₂	MgO	Na ₂ O	K ₂ O	Countries of manufacture
'Standard' low alumina	Grey or buff to black	36-42	36-42	3-8	12-20	<2	~1	~0.1	~0.15	France, Spain, Croatia, USA, India, Eastern Europe
Low alumina, low iron	Light buff or grey to white	48-60	36-42	3-8	1-3	<2	~0.1	~0.1	~0.05	France, USA, India, Korea, Brazil
Medium alumina	White	65-75	25-35	<0.5	<0.5	<0.05	~0.1	<0.3	~0.05	France, UK, USA, Japan, China, India, Korea, Brazil
High alumina	White	≥80	<20	<0.2	<0.2	<0.05	<0.1	<0.2	~0.05	USA, France, Japan, Brazil, Korea

The main compound in any CAC is monocalcium aluminate (CA) and typically comprises 40-60% of the cement. The second most available compound in CAC is $C_{12}A_7$, also called mayenite; this phase is important and contributes greatly to the setting of the cement. Too much of this phase can cause flash setting in the concrete, so its percentage is typically regulated in the manufacturing process. Other phases in CAC include C_2S (belite), C_2AS (gehlenite), ferrite solid solution, and other phases containing iron and silicon. The percentages of these secondary phases can reach up to 50% total of the cement but their reactivity is far less and much slower than monocalcium aluminate and $C_{12}A_7$, so their early age contributions are not as readily analyzed (Scrivener, 2003).

2.3.1.3 Hydration and Conversion

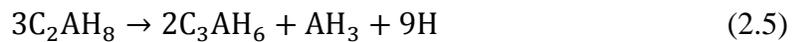
As mentioned above, the main hydration reactant is monocalcium aluminate, CA, and follows some of the same hydration rules as OPC. The first step is the dissolution of the CA into Ca^{2+} and $Al(OH)^{4-}$ ions, and then precipitation into its hydrates. The main products in CAC are formed according to reactions (2.1) to (2.3).



The main difference between these calcium aluminate hydrates and the calcium silicates formed though OPC hydration is the fact that some of these hydrates are metastable and thermodynamically wish to exist as the stable phases of AH_3 or C_3AH_6 . The metastable phases, CAH_{10} and C_2AH_8 , form temporarily and are sensitive to the water availability in the solution and temperature. For example the more readily available water is in the solution (typically a w/c greater than 0.7 for concrete mixtures) the more the chemistry favors the formation of the metastable phases. With lower w/c, there is not

enough water to fully hydrate the metastable phases so some formation of the stable phases can be seen.

Temperature also dictates which hydrates will be favored in the hydration process. The formation of CAH_{10} is favored up to a temperature of 75-100°F, at temperatures above 150°F the nucleation of C_3AH_6 is seen, and at temperatures in between, the formation of C_2AH_8 and AH_3 are most commonly seen. The process by which these metastable phases transform to the thermodynamically stable phases is called conversion and the transformation of these phases follows equations (2.4) and (2.5).



This process can be slow and take decades to complete if high w/c and the ambient temperature is below 95°F. On the other hand if low w/c are used and the mixture sees temperatures above 150°F in the first hours of hydration conversion can take place within the first few days. If the metastable and stable phases were similar in morphology there would be no problem with conversion, but the different amounts of combined water and densities of these phases cause problems in the concrete matrix. The amount of combined water is much less in stable phases (AH_3 or C_3AH_6) than in metastable phases (CAH_{10} or C_2AH_8) so their densities increase as conversion takes place (Campas & Scrivener, 1998). Typical densities and combined water values are shown in Table 2.

Table 2: Density and combined water for calcium aluminate hydrates from Campas & Scrivener (1998)

Phase	Density (kg/m ³)	Combined water (%)
CAH ₁₀	1720	53
C ₂ AH ₈	1750	40
C ₃ AH ₆	2520	28
AH ₃	2400	35

This densification of the stable phases brings about a reduction in the solid volume in the matrix as well as an increase in the porosity which in turn causes a decrease in strength. Up to a 50% reduction in strength has been seen in certain cases (Barborak, 2010). This reduction in strength caused several CAC structures to collapse in the UK after World War II when CAC was used as a construction material in Europe (Campas & Scrivener, 1998). Conversion was not given 100 percent of the blame as forensic analysis of the structures showed structural design problems. Since then, the conversion process has been studied further but CAC still remains banned in certain structural applications. Although conversion is inevitable, researchers have found ways to determine the converted reduced strength of CAC mixtures by casting cylinders in an insulated box and allowing the temperature to reach 140°F (Barborak, 2010). This degree of heat drives the formation of the stable hydrates and effectively creates the final composition that the mixture will see in its lifetime, including the highest levels of porosity and thermodynamically stable phases. It is important to note that once the concrete has attained these stable phases, the compressive strength of the material remains stable and might see a slight increase in time with hydration of unhydrated cement grains. Special provision such as TxDOT's SS-4491 allows this process to be used to attain the converted compressive strength and use that value as the final design strength of the mixture (Barborak, 2010). CAC concrete may be different in chemistry

and behavior but once the mechanisms are understood the use and implementation of CAC concrete can be very simple and straightforward.

2.3.1.4 Benefits of Using CAC Concrete

Some of the benefits that CAC concrete has over OPC concrete include the following:

- high resistance to temperature and chemical attack
- high sulfate resistance
- high resistance to alkali-silica reaction
- lower CO₂ emissions during production
- higher early strengths upon setting

The original purpose for creating CACs was to provide sulfate resistant cement. External sulfate attack usually consists of sulfates from the environment, either from soils or groundwater, reacting with the AFm phases in traditional OPC concrete. The external sulfates convert the AFm phases, particularly monosulfate, to the more stable ettringite causing expansion and consequently the deterioration of the concrete. In CAC concrete the main products, both stable and metastable, are calcium aluminate hydrates such as CAH₁₀, C₂AH₈, AH₃ and C₃AH₆. With minimal to no amount of monosulfate phases in CAC concrete to react with the external sulfates and form ettringite there is little to no sulfate attack. Another difference from OPC concrete is the lower pH of CAC concrete, typically around 11.97 to 12.4, as compared to 13.4 for OPC concrete. This low pH is still able to passivate the steel just like OPC concrete but corrosion may still occur by either the lowering of the pH by carbonation or by the ingress of chlorides (Macias, 1996). Minimal research has been conducted to determine any chloride ingress relationships for CAC concrete but field behavior and durability can be seen in existing

CAC members. CAC concrete members in marine environments have shown a dense surface layer up to 50mm thick containing chlorides, monosulfate, and Friedel's salt. Even though chlorides have been found to that depth in those concrete elements, no signs of corrosion in the reinforcing steel were observed (Scrivener, 2003).

2.3.2 Calcium Sulfoaluminate Cements

2.3.2.1 Introduction

Calcium sulfoaluminate cements (CSA) were developed in China in the 1970's and classified as China's "Third Cement Series" (Pera & Ambroise, 2004). The raw materials used to form CSA are limestone, gypsum, and bauxite which result in a sulfate based clinker as opposed to the silicates of OPC. CSA clinker's main chemical composition includes the following phases: belite (C_2S), tetracalcium trialuminate sulfate (C_4A_3S) also known as yeelimite, and gypsum. The rapid growth of ettringite is the mechanism by which CSA cements attain strength. There are two different mechanisms by which ettringite forms in CSA depending on the availability of CH (Liao & Wei, 2011). These mechanisms will be discussed in the next section. Some of the properties achieved by the use of calcium sulfoaluminate cements include:

- high early strength
- expansive and self-stressing mixtures
- shrinkage compensating mixtures

The limited availability of raw materials, especially bauxite (source of alumina) increases the cost of the cement and inhibits the widespread use as an alternative to portland cement.

2.3.2.2 Chemical Composition

CSA cement is produced when burning limestone, bauxite and gypsum in a rotary kiln at 1250°C, 200 degrees lower than portland cement. CSA contains some of the same chemical compounds contained in OPC such as C_2S , C_3S , C_4AF and also C_4A_3S known as ye'elemite or Klein's compound (Winnefeld F. , 2010). A comparison of the different percentages of each compound for OPC and CSA are shown in Table 3. Minor phases in CSA include C_4AF , $C_{12}A_7$, C_3A and C_6AF_2 .

Table 3: Comparison of portland cement and CSA from Bescher & Ramseyer (2008)

Portland Cement Composition					
ASTM TYPE	C_3S	C_2S	C_3A	C_4AF	C_3S
I	59	15	12	8	2.9
II	46	29	6-8	12	2.8
III	60	12	12-15	8	3.9
IV	30	46	5-7	13	2.9
V	43	36	4-5	12	2.7
CSA Cement Composition					
	C_3S	C_2S	C_3A	C_4AF	C_3S
	30	45	0	2	15

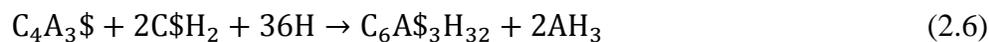
The lack of iron phases in the chemistry of the cement give it a light grey color, Figure 1 shows a sample of the CSA cement used for this research. The hydration products formed from these compounds along with mechanistic behavior of the reactions are described in the following section.



Figure 1: Sample CSA showing light grey color

2.3.2.3 Hydration

The most important reaction in CSA is the formation of ettringite ($C_6A_3H_{32}$). Ettringite forms from the reaction of ye'elemite with gypsum according to equations (2.6) and (2.7) depending on the amount of calcium hydroxide in solution.



When calcium hydroxide is not present as in reaction (2.6), the ettringite growth is non-expansive but does result in high early strengths, typically around 4000 psi compressive strengths by 3 or 4 hours for a well-designed mixture. In the presence of calcium hydroxide, reaction (2.7), the formation of ettringite is expansive and is used for self-stressing concrete elements and shrinkage resistant cement. The ettringite crystal microstructure influences the setting time, strength development and shrinkage of the concrete (Pera & Ambroise, 2004). The difference in behavior depending on the overall composition of the cement has been exploited by cement producers to target their specific needs, either shrinkage compensating concrete, expansive and self-stressing concrete, or high early strength concrete.

2.3.2.4 Benefits of Using CSA Concrete

Several benefits of using CSA cement are observed even before mixing with water. The production of CSA cement occurs at 2280°F, 360 degrees lower than portland cement, effectively reducing the amount of energy during production. The amount of limestone calcined in order to produce CSA cement is also considerably lower than that needed to produce the calcium silicates of portland cement (Juenger, 2011). Sulfate based clinkers are also more porous than OPC clinker and thus require less energy to grind (Winnefeld & Pelletier-Chaignat, 2011). So overall the energy needed for the total production of CSA for calcining, and grinding is considerably less than that needed for portland cements and CO₂ emissions can be reduced by 80% (Juenger, 2011). Although the savings in energy are recognized the production of CSA is still more expensive due to the cost of bauxite as a raw material.

These CSA cements also exhibit high sulfate resistance. The unique chemistry of this binder leads to the formation of stable ettringite as the main hydration product along with minor amounts of AFm phases, C-S-H gel and gibbsite. For this reason any additional sulfates in the environment do not cause a deleterious effect on the concrete. These sulfate cements also show high impermeability and chemical resistance, low drying shrinkage due to their expansive nature, and low alkalinity. Typical pH values for CSA concrete is around 10.5-11, much lower than portland cement concrete which is above 13. This lower alkalinity prevents the dissolution of silicate particles and thus reduces the chance of ASR occurring in the concrete (Scrivener, 2003). The other benefits have already been discussed in the previous sections, and those included the

rapid strength gain, the expansive behavior and shrinkage compensating properties of the concrete.

2.3.3 Latex-Modified Concrete

2.3.3.1 Introduction

Bridge decks contain large amounts of reinforcing steel that should be protected from corrosion. In cold weather bridge decks tend to suffer from freezing due to cold winds through the top and bottom of the structure so DOTs use deicing salts to prevent snow or ice buildup. Microcracking of bridge decks allow the migration of these chlorides into the reinforcement layers and cause corrosion of the steel. For this reason low permeability concrete and proper curing has been used for years to prevent early age cracking and slow down or prevent chlorides from penetrating into the structural steel (BASF, 2011).

Latex-modified concrete has been used for decades to create a durable and low permeability bridge deck concrete overlay. Research for modified concrete began in 1952 by DOW Chemicals and five years later in 1957 conducted their first field trials on U.S. 23 in Cheboygan, MI (DOW, 1995). The latex modifier used for these mixtures was a styrene butadiene rubber (SBR) latex polymer consisting of approximately 48% solids and 52% water, and these proportions are still being used to date. Latex-modified concrete has typically been done with CSA cement, portland cement or a mixture of the two. For this research project latex will be added to CSA and CAC concrete mixtures only.

2.3.3.2 Specifications and Criteria

Research conducted in the late 1950s and 1960s by Dow Chemical Company aimed to achieve a combination of styrene-butadiene polymer with concrete mixtures to

decrease the permeability to chlorides and increase flexural properties of the concrete. Addition of latex polymer ranged from 5 to 20 % by weight of cement. All the research done by Dow Chemical Company as well as private laboratories led to the formation of guidelines for the construction of latex-modified concrete. The American Concrete Institute developed a set of rules and guidelines for proper placement and design for latex-modified concrete in ACI 548.4 Specification for Latex-Modified Concrete Overlays which sets a minimum of 15% latex addition by solids (ACI 548.4 , 2011). Contractors and mixture designers need to take into account that the styrene-butadiene polymer comes in an approximate 50/50 suspension so the amount of water added to the mixture should be adjusted accordingly. Some specifications and requirements for the proper implementation of a very-early-strength latex-modified concrete overlay include (ACI 548.4 , 2011):

- One-third calcium sulfoaluminate and two-thirds dicalcium silicate or any other hydraulic cement meeting strength requirements
- Thickness of overlay should be 1.25” to 4”
- 15% latex addition minimum
- Maximum w/c of 0.40
- Fine aggregate range by weight of total aggregate should be within 55-70 percent
- Moist curing by damp burlap and plastic sheeting should be applied as soon as possible until the opening of traffic.

The development of more sophisticated technological equipment, screeds, and volumetric mixers has led to more specified construction and efficiently placed overlays for latex-modified concrete. The added benefits of using latex modified concrete are described in the following section.

2.3.3.3 Benefits of Latex-Modified Concrete

The original properties sought through latex-modified concrete research were reduced permeability, increased flexural and increased tensile strength of the concrete. Compressive strengths were reduced at early ages but by 28 days the strengths were equivalent to non-latex concrete mixtures. During concrete hydration micro-cracks start to form within the concrete matrix and compromise durability even before it is opened to traffic (Won, 2011). When using latex-modified concrete the latex fills in these micro-cracks and reduce the permeability of the concrete by creating links that overlap over these cracks as shown in Figure 2. Research data for latex-modified concrete has proven these added benefits and typical results are shown in Figure 3 below. The addition of latex requires lower w/c which generally produce lower porosity and higher strengths, and have also shown a decrease in the modulus of elasticity of the concrete which makes for better performance when subjected to traffic loading.

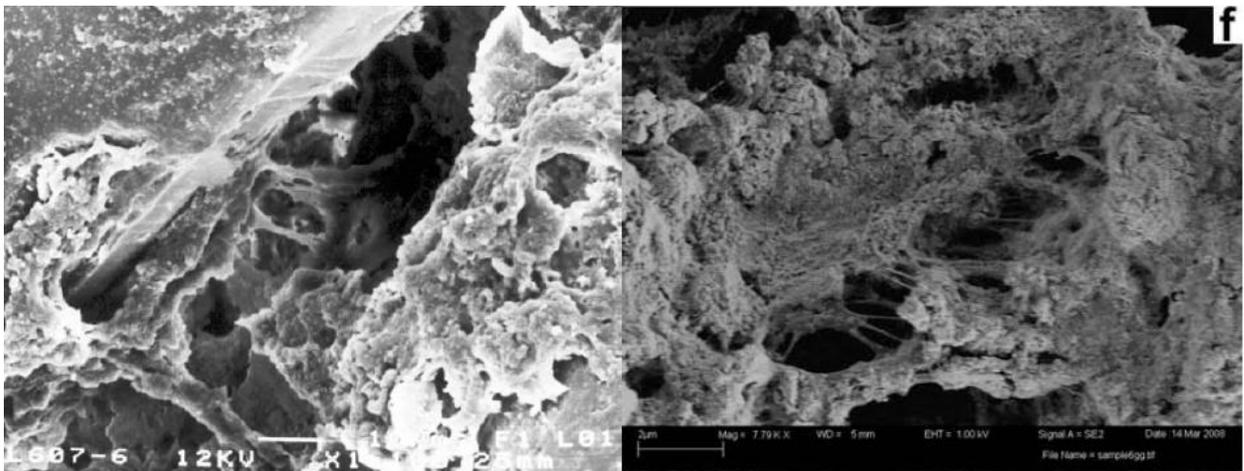


Figure 2: SEM images of SBR-modified mortars from Vincke & Wanseele (2002) left and from Yang & Shi (2009) right.

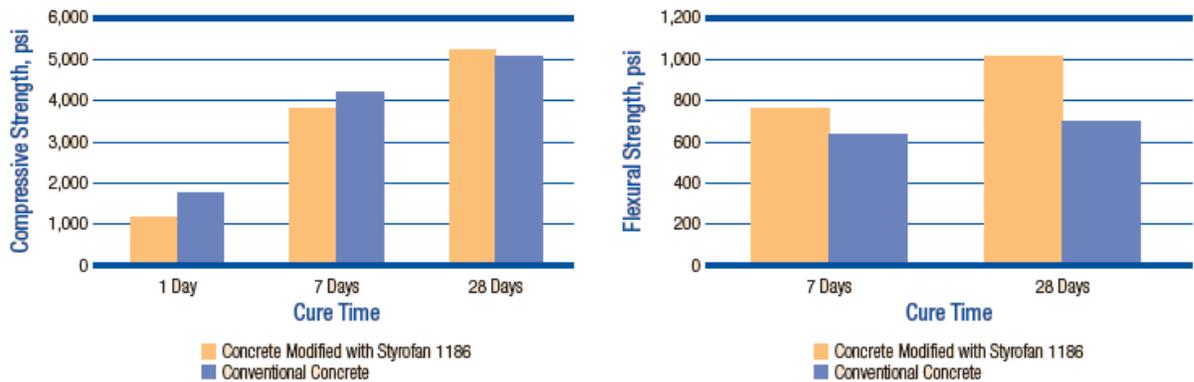


Figure 3: Average compressive and flexural strengths for latex-modified concrete from BASF (2011)

Latex also improves bonding to substrate when used as an overlay by providing a stronger adhesion by the polymer links described above. Latex serves as a mild air entraining admixture as well and typically results in 4 ± 1 percent entrained air that along with the stronger polymer bonds provides durability against salt scaling, and freezing and thawing cycles. For this reason mixtures containing latex will be subjected to freezing and thawing cycles without any additional air-entraining agents.

2.3.4 Alkali-Activated Fly Ash

2.3.4.1 Introduction

With sustainability as one of the hottest words these days, the need for an innovative and waste incorporating concrete mixture has been the topic of much interest in the research community. The use of fly ash, slag and silica fume has been used for decades to reduce the amounts of cement used and to benefit from the pozzolanic or hydraulic reactions from these supplementary cementitious materials (SCMs) (PCA, 2010). Research done in the 1930s and 1940s looked at the cementitious properties of clinkerless cements. These cement blends consisted of either slag or fly ash activated by

alkaline solutions. The most common activators used are potassium hydroxide, sodium hydroxide or “waterglass” a sodium silicate solution. These cements aim to be a competitor and alternative to portland cements that positively impacts the environment.

2.3.4.2 Chemical Composition

The chemical composition of most of the alkali-activated cements varies widely with the type of SCM and the origin of each material. The most common materials used for these cements include slag, class F fly ash (low calcium ash), and class C fly ash (high calcium ash). Class F ash is pozzolanic in nature, slag is hydraulic and class C ash is generally somewhere in between the two. Typical chemical analysis for these materials is shown in Table 4. ASTM C618 specifies the criteria for fly ash and natural pozzolans and requires the sum of SiO₂, Al₂O₃ and Fe₂O₃ to be a minimum of 70 percent for class F ash and 50 percent for class C ash (ASTM C 618, 2011).

Table 4: Chemical analysis and typical fineness for selected SCMs from PCA (2010)

Composition, %	Class F fly ash	Class C fly ash	Ground slag
SiO ₂	52	35	35
Al ₂ O ₃	23	18	12
Fe ₂ O ₃	11	6	1
CaO	5	21	40
SO ₃	0.8	4.1	9.0
Na ₂ O	1.0	5.8	0.3
K ₂ O	2.0	0.7	0.4
Total Na eq. alk	2.2	6.3	0.6
LOI	2.8	0.5	1.0
Blaine fineness, m ² /kg	420	420	400

The alkali activators used for these materials include sodium silicate solutions (Na₂SiO₃), sodium hydroxide (NaOH), or potassium hydroxide (KOH). These solutions

are usually 8-12M and very caustic in nature and thus require delicate use to prevent any harm to the users or the environment (Komljenovic, 2010). The chemical composition of the materials used should be determined to better select the type of solution and molarity that leads to the best quality product.

2.3.4.3 Hydration

As seen in Table 4 the main components of the waste materials used for alkali-activated concrete are Al_2O_3 , SiO_2 , and CaO . The amount of reactive CaO (not all the calcium from the waste materials will react) of the mixture affects which type of hydration products will precipitate in solution. The high quantities of calcium in class C ash and slag tend to create C-(A)-S-H gel much similar to the C-S-H in OPC concrete and can be analyzed using similar techniques (Juenger, 2011). The hydration between low calcium ash and the alkali-activator forms an amorphous alumino-silicate gel, N-A-S-H, and full analysis of the hydration is yet to be performed.

High molar solutions of either NaOH or KOH are typically used to dissolve the aluminosilicates into solution (Fernandez-Jimenez, 2005). As mentioned above the nature of the materials used will determine the primary gel formed during precipitation including the Ca/Si ratio and alumina content within that gel, but a mixture of both types of gels is not uncommon especially with high calcium ash. After precipitation of the gel the moisture content and any heat will drive the products to form a more thermodynamically stable, dense and crystalline form. A simplified hydration schematic is shown in Figure 4 below.

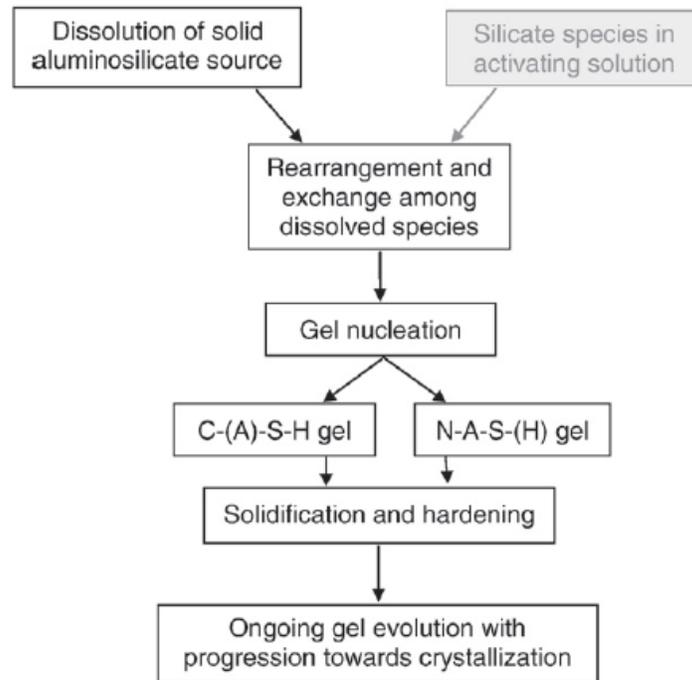


Figure 4: Alkali activation process schematic from Juenger (2011)

Although heat curing will increase the strength and maturity of the concrete, it is not necessary and high early strengths can be achieved through the proper dose and chemistry of the activator. Careful analysis of the raw material composition should be done in order to dial in the activator quantities to achieve high strengths at room temperature. With proper chemical analyses of the cementitious materials of these waste products, both strength and durability comparable to that of good quality portland cement concrete can be achieved (Shi & Fernandez-Jimenez, 2011).

2.3.4.4 Benefits of Using Alkali-Activated Fly Ash

The main benefit of using alkali-activated cement is primarily the positive environmental impact through the use of waste materials, which reduce the need for portland cement and CO₂ emissions. Similar strengths to portland cement can be achieved through the use of high molar alkaline solutions and heat curing. Depending on

the chemical makeup of the fly ash and the alkali-activator the following properties for alkali-activated concrete can be obtained:

- reduced setting time
- accelerated strength gain
- higher flexural strength than OPC concrete in some cases
- high heat resistance due to the lack of free $\text{Ca}(\text{OH})_2$
- high acid and sulfate resistance
- in moist conditions lower water and chloride permeability

All of these benefits make alkali-activated concrete an optimistic and probable replacement for OPC at some point in the future but some durability issues have been noted.

- It has been shown that carbonation in alkali-activated concrete can occur much faster than in portland cement concrete which allows for corrosion of the steel.
- The use of reactive aggregate also makes alkali-activated fly ash concrete more susceptible to ASR.
- Admixtures such as superplasticizers, water reducers, and air-entrainment are usually ineffective as they tend to disintegrate in the highly alkaline environment (Shi & Roy, Alkali-Activated Cements and Concretes, 2005)

These durability issues along with unclear hydration kinetics, curing regime, caustic activating solutions and the variation in composition of the waste material of alkali-activated concrete make it difficult to use as a replacement for OPC concrete. Nevertheless, the positive impacts that alkali-activated systems can have on the environment should encourage further research to establish a set of guidelines for its use as an alternative to portland cement.

2.3.5 Accelerated Portland Cement Mixtures

2.3.5.1 Introduction

Accelerated portland cement concrete has been used for years to obtain high-strength concrete within a few hours after placement to repair deteriorated pavements. These high early-strength concrete mixtures are not rapid-setting but are nonetheless more expensive than new pavement concrete because of the addition of chemical admixtures, higher cement content per cubic yard and the equipment used for placement (Macadam & Folwer, 1984). With the incorporation of curing blankets and the use of heated material these concrete mixtures result in 3000 psi compressive strength and 350 psi flexural strength in as little as 6 hours. These concrete mixtures are sometimes referred to as “fast-track” or “Class K concrete” and typically require a minimum of seven sacks of cement per cubic yard, air entrainment, large doses of non-chloride accelerator, and low water to cement ratios with the aid of polycarboxylate superplasticizers (Temple & Ballou, 1984).

2.3.5.2 Chemical Composition

For accelerated portland cement concrete, ASTM Type III cement is used to achieve the high early-strengths needed for a “fast-track mix.” Type III is a portland cement containing the same composition as any portland cement including C_3S , C_2S , C_3A , C_4AF and gypsum. Typical composition percentages for Type III cements are shown in Table 5 below.

Table 5: Typical Type III cement composition

Portland Cement Composition					
	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	C\$
ASTM TYPE III	60	12	12-15	8	3.9

Type III portland cement contains about 12-15 percent C₃A which has one of the highest reaction rates of any phase in portland cement. This hydration is slowed down by the addition of gypsum during the grinding process, otherwise C₃A can cause flash setting of the concrete. The cement is also ground much finer than any of the other ASTM Type cements (generally around 5480 cm²/g Blaine fineness) to promote a higher reactivity and heat generation that will then produce higher early strengths in concrete (ASTM C 150, 2012). The higher heats of hydration and early strength gain make it a preferred material for prestressed concrete (Chen, 2009).

Alite, or C₃S, comprises roughly 60 percent of the total hydration reactants of Type III cement and is the main early strength component in OPC. This phase hydrates quickly and provides the initial and final sets of the concrete (Chen, 2009). During hydration this phase creates more calcium hydroxide than C₂S which does not add to the strength of the concrete but with a fast construction mentality this fact is usually overlooked.

C₂S is present in the portland cement at around 12% and has a slower reaction rate than C₃S. This phase contributes mainly in the long term strength gain. It requires less energy to create in the production process but the need for early strength favors the production of alite.

C₄AF is a minor phase in OPC that comes from the flux agent that is added in the production process to reduce the temperature needed to melt the raw materials (Chen, 2009).

2.3.5.3 Hydration

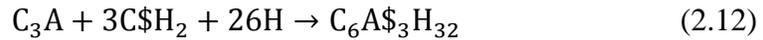
The hydration of portland cement has been known for decades and will not be described in full depth in this literature review. C_2S and C_3S hydrate according to the equations (2.8) and (2.9) below to form calcium silicate hydrates referred to here as C-S-H.



C-S-H is the main load bearing component in concrete and is what gives portland cement concrete its strength. CH is also a main product in OPC concrete but does not add to the strength of the concrete and is readily attacked by acids and sulfates. The use of SCMs has been used for years to reduce the amount of CH in the matrix by having it react with the available silica in these SCMs thereby reducing the permeability of the concrete through additional C-S-H. C_3A reacts with water to form calcium aluminate hydrates such as C_2AH_8 and hydrogarnet (C_3AH_6) as shown in the equations (2.10) and (2.11) (Folliard, 2010).



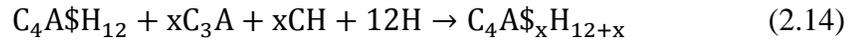
In the presence of gypsum ($C\$H_2$) as in OPC, C_3A forms AFm and AFt phases as shown in reactions (2.12) through (2.14). First reacting with gypsum to form ettringite ($C_6A\$_3H_{32}$), then when gypsum is consumed additional C_3A reacts with ettringite to form monosulfate ($C_4A\$H_{12}$). This phase is readily attacked by sulfates in the environment causing such problems as delayed ettringite formation, external sulfate attack, and even thaumasite. For this reason Type III is not used in high sulfate environments and the ACI code limits the C_3A content for cements used in those types of environments (ACI 318, 2011).



C_3A in the presence of gypsum



C_3A reaction when gypsum is consumed



C_3A when ettringite is consumed

C_4AF phases in OPC follow similar reactions to C_3A , first forming AFt phases with gypsum, then AFm phases when gypsum is consumed. This is a minor phase in concrete and hydrates quickly but not as fast as C_3A hydration.

2.3.5.4 Benefits of Using Accelerated Portland Cement Concrete

The main benefit of using an accelerated portland cement concrete mixture is the familiarity the contractors and DOT departments have with this particular cement. This is not a rapid-setting formulation so flash setting is not a problem. These mixtures usually require high doses of accelerators and superplasticizers, the use of heated material and insulated curing blankets.

The first accelerators used with portland cement were chloride based but issues with corrosion led to the banning of such products in structural elements. For this reason non-chloride accelerators such as calcium nitrate or calcium nitrite have been developed. For these high early strength concrete mixtures the highest dosage of accelerators is usually used to obtain the strengths needed. Most of these accelerators are in liquid suspensions and thus caution should be used when calculating the total water in the mixture by subtracting the amount of accelerator from the mixing water. If powder based

accelerators are used their proper dosage weight is added to the total mixing water and stirred.

The maturity of portland cement concrete is well established so it is known that curing at higher temperatures generally leads to faster strength gain. In the field higher temperatures are reached by the use of heated materials and by trapping the heat of hydration within the concrete matrix through the use of insulated blankets (Kurtz, Balaguru, Consolazio, & Maher, 1997). Records have shown that by using Type III portland cement strengths of 3000 psi have been attained within six to nine hours of placement. The higher cement contents and low water to cement ratios (typically at or above 700 lbs per cubic yard and 0.35 respectively) result in a less permeable material but make it more susceptible to drying shrinkage, ASR, and sulfate attack because of the higher C₃A content, and alkalis in the bulk concrete. Testing for these forms of attack will be done for these mixes as well to determine how the durability of the concrete may be affected by these specific proportions. These mixtures are by no means inexpensive either, the use of accelerators and insulated blankets add an additional \$1.00 per 1.67 m² of pavement and costs easily and quickly add up (Ghafoori & Tays, 2007).

2.3.6 Proprietary Blends

2.3.6.1 Introduction

Throughout the years companies have developed their own proprietary rapid hardening mixtures for highway repair. The main use for these proprietary blends is for rapid repair of small sections of pavement and are usually sold as individual bagged units typically around 0.5ft³. Specifications, site preparations, and mixing procedures are located on these products. For this research project each individual proprietary blend was mixed according to the company's recommendations.

2.3.6.2 Chemical Composition

Several chemical compositions for rapid setting cements exist for the general public including magnesium phosphate, gypsum modified portland cements, alkali-activated blends, accelerated portland and silica fume cements and even polymer based “cements”. Most of these proprietary blends obtain the necessary strength requirements with no complications but some are notorious for not providing the durability properties that pavements require and need constant maintenance.

2.3.6.3 Hydration

Most of these proprietary cements are sold as “ready-to-use” and only require mixing with a prescribed amount of water. Polymer based rapid repair blends are usually sold all together and only require mixing resins and hardeners along with aggregates. Most of the hydration of these cements occurs within the first hours and not much occurs after hardening of the concrete.

2.3.6.4 Benefits of Proprietary Blends

The use of these rapid-setting cements allows the fast patching of small areas and requires minimal lane closure times for complete repair. The necessary strength gain of these mixtures is reliable and repeatable for individual bags. The workability, flow, quick hydration and ease of use of these prepackaged materials make them user friendly and many provide durable and long lasting repairs.

Chapter 3: Materials

3.1 INTRODUCTION

A wide range of cement binders, admixtures and aggregates were selected for this laboratory testing. Additional cements were added throughout the course of the project as the needs arose. The following sections describe the materials used in the study.

3.2 CEMENTS AND SUPPLEMENTARY CEMENTITIOUS MATERIALS

3.2.1 Calcium Aluminate Cements

Two calcium aluminate cements were used in this study and denoted CAC-1 and CAC-2 for the purposes of this thesis.

CAC-1 is a pure calcium aluminate cement containing roughly 60% monocalcium aluminate as the main reactant and has one of the highest Fe_2O_3 contents of the CACs available. The high iron content of this cement provides its dark grey color and is by far the most common calcium aluminate cements. Fast setting times and high early strengths can be achieved through the use of lithium based accelerators. CAC-2 is a blended product that contains CAC and fly ash dosed with proprietary additives to produce high early strengths, increased durability and manage setting times for specific projects. No additional admixtures are required for this “all-in-one blend”. The chemical composition of these two materials is contained in Table 6.

3.2.2 Calcium Sulfoaluminate Cements

Three different sources of calcium sulfoaluminate cements (CSA) were chosen for this study and denoted CSA-1, CSA-2, and CSA-3. CSA-1 is a readily available cement in the United States and is often used for TxDOT projects, while CSA-2 and CSA-3 contain proprietary admixtures and have been developed for specific areas requiring low

permeability, long term durability and high frost resistance. The oxide analysis of these three products is contained in Table 6.

3.2.3 Portland Cement

A single Type III portland cement (as per ASTM C 150) was chosen for this study from a local central Texas source. Type III cements exhibit higher early strengths and heat of hydration compared to other types of portland cement. This cement is not considered fast-setting but with the use of admixtures, higher cement contents and curing procedures can significantly reduce setting times. A minimum cement content of 700 pounds per cubic yard was used for preliminary testing and adjusted thereafter to achieve better results. The oxide analysis is contained in Table 6.

3.2.4 Fly Ash

Two different fly ashes were used in the project, one is classified as a Class C fly ash (as per ASTM C 618) and the other a Class F fly ash, these ashes are from Cason, Texas and Rockdale, Texas, respectively. The Class C ash used contains high amounts of CaO and is highly reactive, often used for flash fill applications. Table 6 provides the chemical composition of the fly ash.

3.2.5 Condensed Silica Fume

Used primarily in Phase I to achieve high early strengths in portland cement mixtures, silica fume is nearly 90 percent amorphous SiO₂ and used as an SCM to reduce the amount of CH through the formation of C-S-H gel. A maximum 8 percent silica fume by replacement of cement was used for this study.

Table 6: XRF oxide analysis for prepackaged materials

Oxides % wt	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	SrO	Mn ₂ O ₃	P ₂ O ₅	TiO ₂
CAC-1	4.62	39.71	13.94	37.54	0.64	0.23	0.03	0.14	0.02	0.4	0.11	1.75
CAC-2	13.384	32.507	12.593	43.721	2.127	1.027	0.558	0.219	0.178	0.163	0.403	1.734
CSA-1	14.22	15.58	0.98	49.84	1.46	14.73	0.16	0.47	0.16	0.07	0.11	0.57
CSA-2	14.4	15.01	0.92	49.54	1.34	14.18	0.327	0.55	N/A	N/A	N/A	N/A
CSA-3	14.71	14.8	0.84	48.79	1.26	15.85	0.295	0.54	N/A	N/A	N/A	N/A
Class F fly ash	52.07	23.07	3.96	11.65	2.06	0.48	0.403	0.74	N/A	N/A	N/A	N/A
Class C fly ash	30.78	17.44	5.89	29	6.47	3.83	2.19	0.34	0.47	0.05	0.86	1.37
Silica Fume	90	0.4	0.4	1.6	N/A	0.4	0.5	2.2	N/A	N/A	N/A	N/A
Type III	20.67	4.21	3.6	64.28	0.61	3.63	0.053	0.68	N/A	N/A	N/A	N/A

3.2.6 Prepackaged Products

3.2.6.1 P-AAFA

This binder system is an alkali-activated fly ash blend which comes pre-packaged and consists solely of fly ash, both class C and class F, and a specific dose of alkali activator. This product comes in a ready-to-use bag including 3/8" maximum size aggregate and fine graded sand which is then mixed with a prescribed amount of water. This is a fast-setting mixture with initial set times at 73°F around 15 minutes and workability is greatly reduced after only 5 minutes of initial contact with water. Setting time can be delayed by a few minutes with proprietary packets that are added to the water before mixing. XRF analysis for this material as well as the other prepackaged materials is located in Table 7.

3.2.6.2 P-2

This proprietary blend is used for horizontal concrete repair for high early-strength. This is a non-gypsum blend containing silica fume with set times at 73°F between 20-30 minutes for final set. The suppliers of the product state shrinkage compensation and resistance to freezing and thawing are achieved. This ready to use pre-packaged blend only requires a prescribed amount of water for use.

3.2.6.3 P-3

This proprietary blend is not rapid-setting but was included in the testing matrix. This polymer modified repair material also contains silica fume. It reaches approximately 2000 psi compressive strengths at 1 day, and provides freezing and thawing resistance according to the manufacturer's specifications. This ready to use pre-packaged blend only requires a prescribed amount of water for use.

3.2.6.4 P-4

This proprietary blend is sold as a rapid repair material, reaches high early strengths and can be open to traffic in as little as 1 hour. This product is a portland cement and silica fume blend mixed with proprietary admixtures to reach high early strengths. This ready to use pre-packaged blend only requires a prescribed amount of water for use.

Table 7: XRF oxide analysis for prepackaged materials

Oxides %wt	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O
P-AAFA	22.391	17.61	4.35	31.44	9.75	6.49	0.685	0.276
P-2	16.43	11.83	3.56	53.28	1.29	8.46	0.264	0.36
P-3	24.87	4.33	2.78	58.73	1.34	2.24	0.261	0.37
P-4	23.53	10.19	2.26	46.22	0.7	13.29	0.142	0.46

3.3 ADMIXTURES AND ADDITIVES

3.3.1 Water Reducer

A polycarboxylate high-range water reducer was used to increase the plasticity of these repair mixtures with low water to cement ratios. The water reducer is compatible with all the bulk cements used in the study, no admixtures were used for the pre-packaged proprietary blends. This water reducer meets ASTM C 494 Types A and F.

3.3.2 Accelerator

Two liquid accelerators were used in this study. A non-chloride based accelerator was selected for the portland cement accelerated mixtures. This accelerator meets criteria for ASTM C 494 Types C and E. The maximum dose allowed was used for portland cement mixtures so the total water content was adjusted for these high doses.

A LiSO₄ based accelerator was used for the calcium aluminate cement in this study. Doses from 0.5-2.5% by cement weight were used to accelerate the mixture and attain the necessary 3 hour compressive strengths.

3.3.3 Retarder

Citric acid was used as a retarder for calcium aluminate and calcium sulfoaluminate cements in doses that did not exceed 0.2% by mass of cement. At higher temperatures, these fast-setting cements can set up in a matter of minutes so citric acid is used to delay the setting time by 20 minutes or more. This admixture was added as a powder to the mixing water.

3.3.4 Additives

A styrene-butadiene latex polymer was used for calcium aluminate and calcium sulfoaluminate cements to increase bond strength and reduce permeability. Latex-modified concrete has been used for decades for bridge deck overlays to provide a durable repair. The latex-modifier is a suspension of 47.2% solids and 52.8% water by mass. The water in the modifier must be taken into account and reduced from the mixing water to attain the water to cement ratio desired.

3.3.5 Air-Entrainment

Air-entraining admixtures were used for a subset of the mixtures that were tested for freezing and thawing as well as salt scaling durability properties. It has been shown that air entrainers incorporated into concrete mixtures at the correct air content and proper air void spacing is the most effective way to provide the required resistance against these durability issues. The selected air entraining admixture is an aqueous solution of organic materials that provides the necessary air content and spacing factor for scaling and freeze-thaw cycle resistance.

A second method known to increase freeze-thaw durability is to produce concrete with a sufficiently low water to cement ratio; low water to cement ratios reduce the capillary porosity and size of pores which in turn reduces the amount of freezable water

that causes distress (Pigeon & Pleau, 1995). Some mixtures tested in Phase I and II contain very low w/c and may exhibit resistance through both mechanisms.

3.4 AGGREGATES

3.4.1 Coarse Aggregates

Two coarse aggregates were used for this study. Table 8 provides the mineralogy and physical properties of the coarse aggregates. A 3/8” dolomitic limestone rock (CA1) was used to replicate thin overlay and partial depth repair mixtures. For a subset of mixtures testing alkali-silica reaction, a non-reactive limestone aggregate (CA2) from San Antonio, TX was used.

3.4.2 Fine Aggregates

Two fine aggregates were used for this study. Table 8 provides the mineralogy and physical properties of the fine aggregates. A siliceous natural river sand (FA1) from the Colorado River in Central Texas was used for the regular mixtures in the study. The second fine aggregate (FA2) tested was for ASR testing. This aggregate is a highly reactive sand from El Paso, TX.

Table 8: Aggregate properties

Aggregates	Absorption	Specific Gravity	Minerology
CA1	0.6	2.8	Siliceous sand
CA2	3	2.57	Dolomitic Limestone
FA1	0.6	2.62	Limestone
FA2	0.69	2.6	Quartz/Chert/Feldspar

3.5 ANALYTICAL PROCEDURES

The main laboratory testing for this project was separated into two phases. Phase I involved a screening test to determine the mixture proportions needed to attain a certain compressive strength, typically 3000 psi, at 3 hours or 400 psi flexural strength at 4 hours. Phase II of the study involved a more thorough characterization of the materials selected from Phase 1. These test methods are described in this section.

The “all-in-one” bagged products that require only water to use are pre-blended with coarse and fine aggregate, cement and any admixtures. In order to run analysis on the binders, these materials were subjected to a sieve analysis to determine particle size distribution and approximate binder content. A sample of the binder fraction was used for the chemical analysis.

Most of the binders contain portions of crystalline and amorphous material and thus both x-ray diffraction (XRD) and x-ray fluorescence (XRF) techniques were implemented to further characterize these materials. X-ray diffraction (XRD) techniques were used to qualitatively analyze the crystalline phases of the binders. A Siemens D500 diffractometer with a DacoMP controller was used for the XRD analysis of this project and is shown in Figure 5. X-ray beams are rotated from 5° to 70° 2θ with a 0.02° step size and 4 second dwell time for each sample. The incident beam comes from a copper source, and passes through the stationary sample and diffract back to the x-ray detector. Crystalline phases of the sample diffract at specific angles and are detected and recorded to determine the quantity of each phase. The use of an internal standard is commonly used for quantitative Rietveld analysis, zinc oxide was used for this study. The amorphous content of the materials does not diffract beams and show up as background “noise” as shown in Figure 6 so other techniques are available to further analyze the materials.



Figure 5: Siemens D500 diffractometer used for XRD

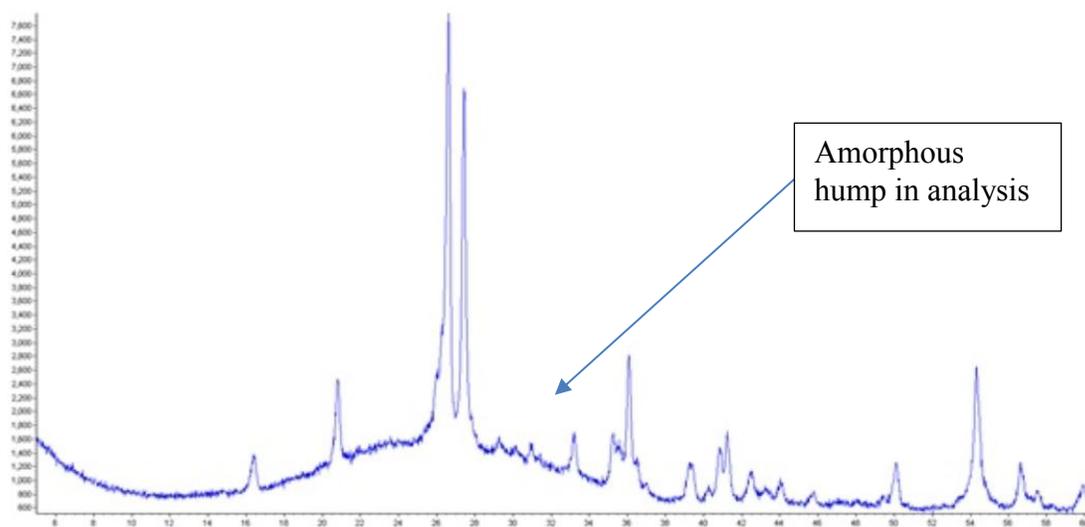


Figure 6: Example of amorphous hump in XRD sample

X-ray fluorescence was used to quantify the oxide composition of the materials chosen for the study. The samples were run using a Bruker S4 Explorer, shown in Figure 7, at the TxDOT laboratories at Cedar Park, Texas. X-rays are used to excite the innermost electrons of the atoms in a sample creating vacancies in those electron shells. As these vacancies are filled by electrons in outer shells, light is emitted and detected by the equipment. Since each element emits distinct light waves, the detection and quantification of oxide compositions in the sample can be determined. An example of an XRF spectrum is shown in Figure 8.



Figure 7: Bruker S4 Explorer used for XRF analysis

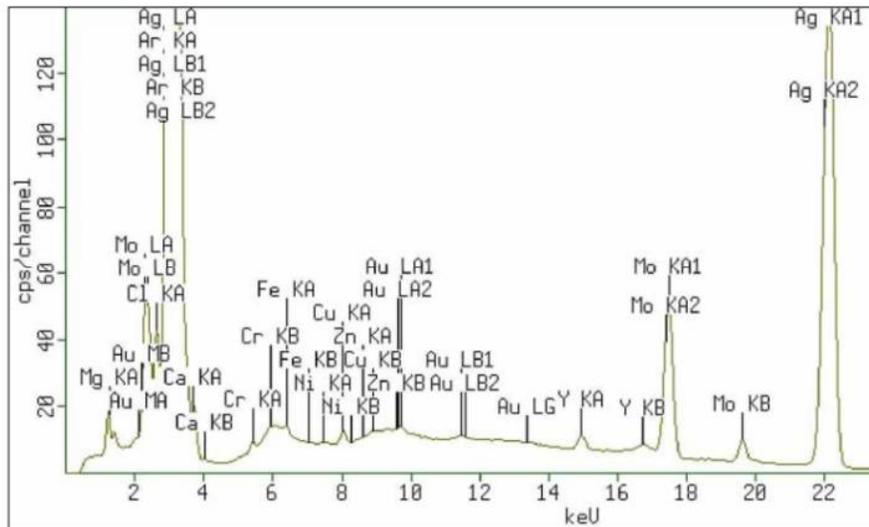


Figure 8: Sample of an XRF spectrum analysis

Isothermal calorimetry was used to characterize the heat of hydration of certain binder systems at constant temperature. These temperature controlled chambers help characterize the behavior of the systems by eliminating the temperature variable. Typical laboratory calorimeters are not capable of accurately testing these high early strength materials due to the high heats of hydration generated within the sample. For this reason the Grace AdiaCal TC calorimeter, a special calorimeter calibrated at The University of Texas at Austin to evaluate high heats of hydration was used to test these samples. Samples are placed in individual cells and sensors within the chamber monitor the heat generation within the sample and compare it to a reference sensor that then diverts the energy away from the sample to achieve isothermal conditions (Bentivegna, 2012).

Phase II of the project is currently ongoing and results for XRD, XRF and a full analysis on calorimetry will not be discussed in this Thesis. This thesis will provide results from Phase I of the project which is in Chapter 4.

Chapter 4: Phase I Initial Screening Program

4.1 INTRODUCTION

A total of six cements and four proprietary mixtures were selected in the initial screening program and subjected to chemical analysis. The proprietary mixtures is available in a “ready-to-use” bag and only require the addition of water while the other six products need to have the addition of aggregate, admixtures, and water. For these bulk cements, variations in cement content, water to cement ratio, admixture doses and latex additives were determined to achieve a nominal target compressive strength of 3000 psi at 3 hours as the main criteria for acceptance into Phase II. Some of the parameters measured alongside compression strength included workability, flow, and approximate setting time.

4.2 MATERIAL CHARACTERIZATION

4.2.1 X-ray Fluorescence

All the cements selected for this initial screening program were characterized using x-ray fluorescence (XRF) as described in Chapter 3 and reproduced below in Tables 9 and 10. XRD will occur during Phase II of the project which is currently ongoing.

4.2.2 Particle Size Distribution

For those pre-packaged all-in-one materials a sieve analysis was done to characterize the particle size distribution and to obtain the binder proportion in order to be analyzed by XRF. The sieve analysis for the proprietary blends is shown in Figures 9 through 12. The percentage of cementitious material for each mixture was determined to be around the same amount: 36.2% for P-AAFA, 31.5% for P-2, 32.0% for P-3, and 33.7% for P-4.

Table 9: Oxide analysis for bulk material

Oxides % wt	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	SrO	Mn ₂ O ₃	P ₂ O ₅	TiO ₂
CAC-1	4.62	39.71	13.94	37.54	0.64	0.23	0.03	0.14	0.02	0.4	0.11	1.75
CAC-2	13.384	32.507	12.593	43.721	2.127	1.027	0.558	0.219	0.178	0.163	0.403	1.734
CSA-1	14.22	15.58	0.98	49.84	1.46	14.73	0.16	0.47	0.16	0.07	0.11	0.57
CSA-2	14.4	15.01	0.92	49.54	1.34	14.18	0.327	0.55	N/A	N/A	N/A	N/A
CSA-3	14.71	14.8	0.84	48.79	1.26	15.85	0.295	0.54	N/A	N/A	N/A	N/A
Class F fly ash	52.07	23.07	3.96	11.65	2.06	0.48	0.403	0.74	N/A	N/A	N/A	N/A
Class C fly ash	30.78	17.44	5.89	29	6.47	3.83	2.19	0.34	0.47	0.05	0.86	1.37
Silica Fume	90	0.4	0.4	1.6	N/A	0.4	0.5	2.2	N/A	N/A	N/A	N/A
Type III	20.67	4.21	3.6	64.28	0.61	3.63	0.053	0.68	N/A	N/A	N/A	N/A

Table 10: Oxide analysis for pre-packaged material

Oxides %wt	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O
P-AAFA	22.391	17.61	4.35	31.44	9.75	6.49	0.685	0.276
P-2	16.43	11.83	3.56	53.28	1.29	8.46	0.264	0.36
P-3	24.87	4.33	2.78	58.73	1.34	2.24	0.261	0.37
P-4	23.53	10.19	2.26	46.22	0.7	13.29	0.142	0.46

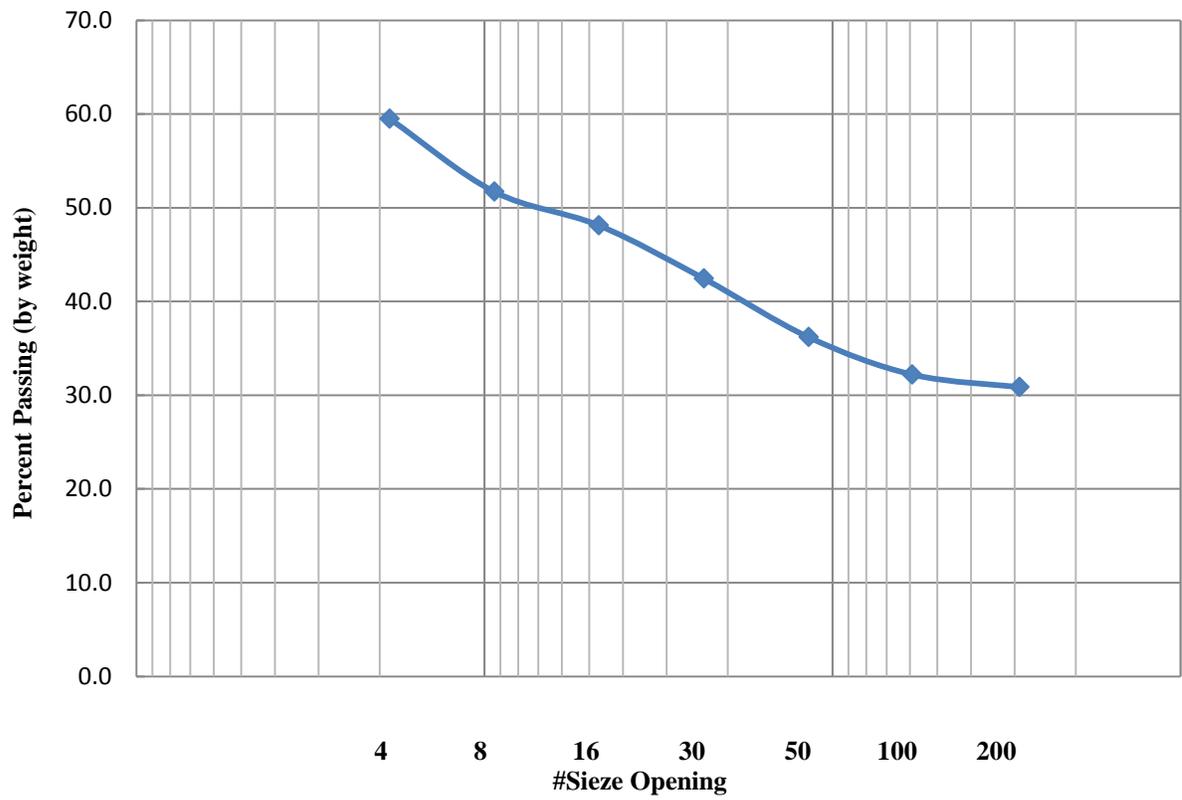


Figure 9: Sieve analysis for proprietary blend P-AAFA

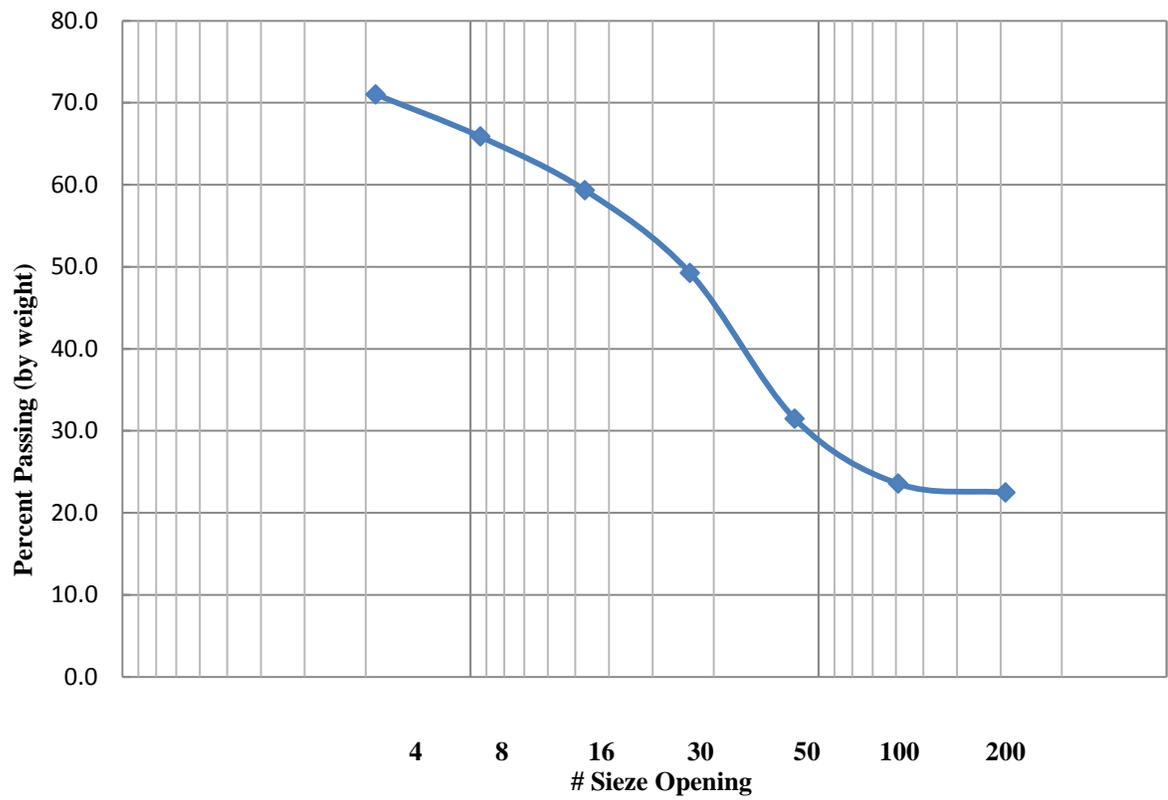


Figure 10: Sieve analysis for proprietary blend P-2

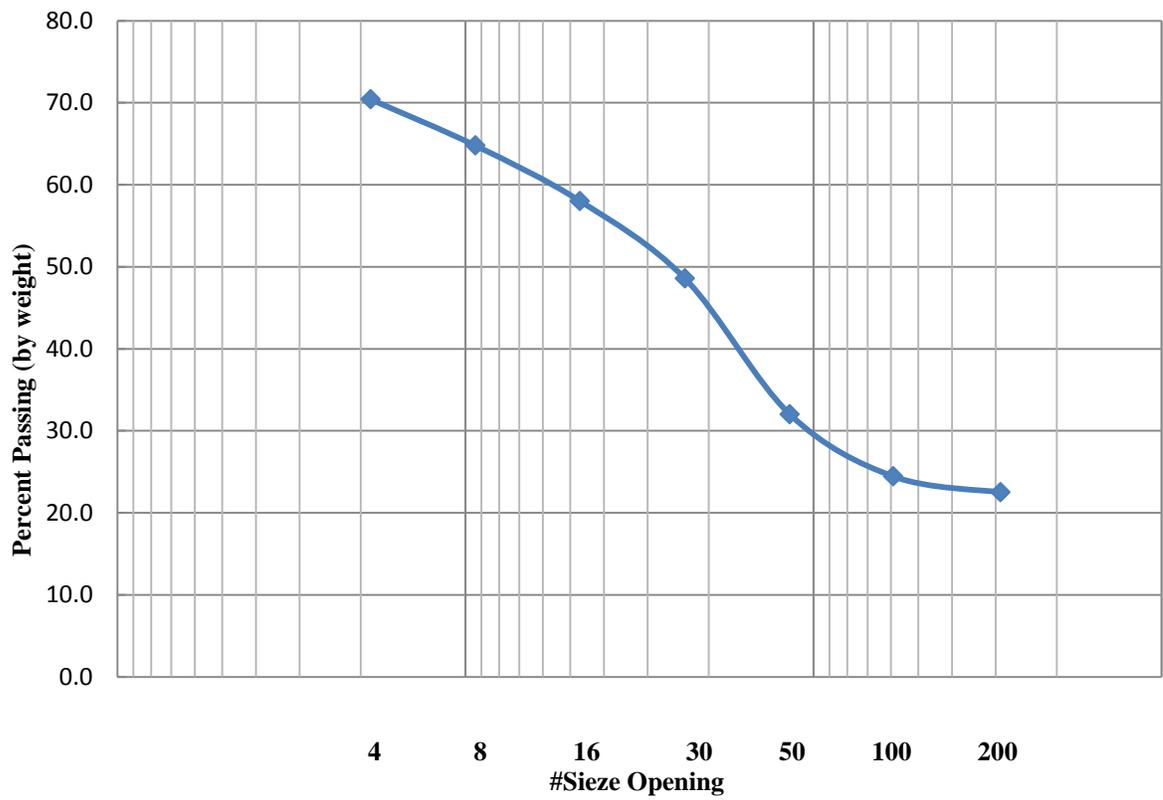


Figure 11: Sieve analysis for proprietary blend P-3

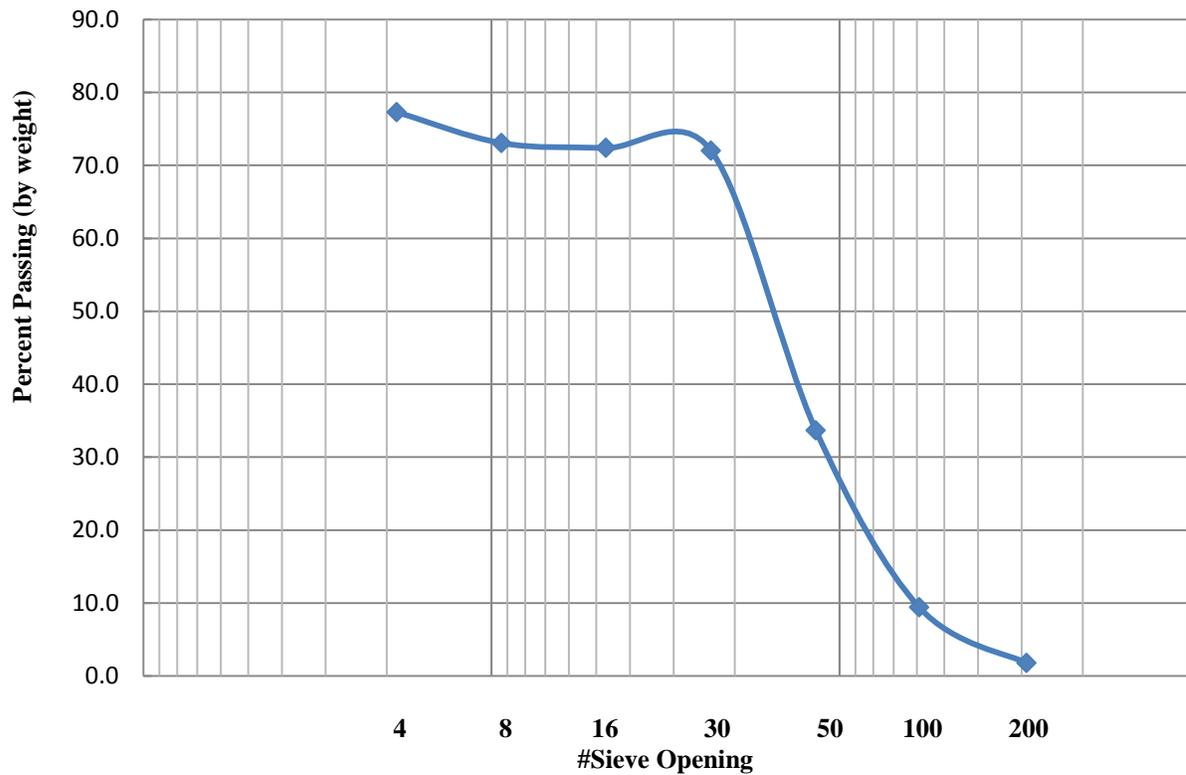


Figure 12: Sieve analysis for proprietary blend P-4

4.3 ACCEPTABLE CRITERIA FOR REPAIR MATERIALS

Although the specific use for repair materials varies widely, the goal for this study is to create a set of guidelines for the proper placement and selection of durable materials for horizontal applications such as bridge decks and for partial to full depth repairs. Based on prior research, from the experience of TxDOT officials and project managers, a set of criteria for concrete mixtures was selected and includes:

- target strengths, most commonly set to 3000 psi compressive at 3 hours or 400 psi flexural at 4 hours
- minimum required workability time for satisfactory placement
- robustness of the mixture to simulate field experiences
- 28 day design strength
- durability requirements

The initial screening program focused on the fresh properties including admixture compatibility, flow, water demand, bleeding and compression strength curves. For the subset of mixtures that met these initial criteria a more extensive testing regime was developed to test for durability concerns. This ensured that resources were not wasted on mixture designs that are not practical for field application. Figure 13 shows the typical properties for any concrete mixture and will be the basis for the research conducted in this study.

<i>Fresh Properties</i>	<i>Hardened Properties</i>	<i>Durability Properties</i>
<ul style="list-style-type: none"> • Water demand • Slump and slump retention • Air-entraining agent demand • Admixture/binder compatibility • Setting time • Bleeding 	<ul style="list-style-type: none"> • Compressive strength • Tensile strength • Flexural strength • Elastic modulus • Heat of hydration (isothermal and semi-adiabatic calorimetry) • Maturity (for selected binders) • Drying shrinkage • Thermal expansion/contraction • Restrained and unrestrained volume change (using cracking frame approach, as per TxDOT 4563 and 6332) • Bond strength (with substrate) 	<ul style="list-style-type: none"> • Alkali-silica reaction • Delayed ettringite formation • External sulfate attack • Freeze-thaw • Salt scaling • Transport properties (resistivity, diffusion, etc.) • Corrosion of reinforcing steel

Figure 13: Fresh, hardened and durability properties

4.4 MIXING PROCEDURES

All mixtures in the initial screening program were mixed in a 1.77 cubic feet mixer from Northern Industrial as shown in Figure 14. Most of the mixtures followed similar guidelines and any differences are noted below.



Figure 14: Northern Industrial mixer used for Phase I

4.4.1 Prepackaged Proprietary Blends

For the all-in-one blends that only require the addition of water the following mixing procedures were used:

- For P-AAFA the mixer was pre-wet and drained of excess water. A total of $2 \pm 1/8$ quarts of water was needed for each bag. Once the mixer had started, add half of the required water and the bagged unit and continue mixing for 1 minute. After this 1 minute, the remaining water was added and mixed for an additional 5-6 minutes and then the mixture was ready for placement into the specified area.
- For P-2 a total 4.6 pints of water per bag were required, all of which was added to the bagged mix while spinning. A total of 3-5 minutes was required for mixing.

- For P-3 all of the water was added to the mixer, 5.5 pints per bag. While the mixer was spinning the contents of the bag were added and mixed for a maximum of 3 minutes. An additional 0.5 pint was optional if needed.
- For P-4 3.25 quarts of water were required per bag, all of which was added to the mixer prior to the addition of the materials. A total of 3-5 minutes was needed to attain the desired consistency and then cast.

4.4.2 Bulk Cement Mixtures

Materials for each mixture were gathered and the moisture content of the aggregates was determined at least 24 hours prior to mixing. The cement, aggregates, water (separated into two approximately equal amounts) and admixtures were weighed prior to mixing. If a latex-modifier was required, it was also added to the total water and mixed thoroughly. With the exception of the accelerated portland cement mixtures, all chemical admixtures were added to one of the water containers and set aside.

The mixer was pre-wetted and drained before the addition of any material. The required fine and coarse aggregate were then added to the mixer along with the mixing water not containing any admixtures and spun for 1 minute. After this initial mixing period, the cement was added to the mixer and continued to spin for 30 seconds, at which point the rest of the water containing admixtures was slowly added over a period of 30 seconds. The mixture was then allowed to mix for an additional 1-2 minutes depending on its consistency.

Portland cement mixtures differed slightly in the addition of admixtures due to the high doses required. The total amount of accelerator was added to the mixing water and mixed thoroughly. The aggregate was added to the mixer along with half of the

admixture-water solution and mixed for 1 minute. The cement was then added to the mixer and allowed to mix for 30 seconds. After this, the rest of the water was added to the mixer over a period of 30 seconds and then allowed to mix for an additional minute. At this point the superplasticizer was added to the mixture and allowed to spin for 2 minutes, and after that mixing time the air-entrainer was added straight to the cement and allowed to spin for a minimum of 1 minute. This mixture is not fast-setting so the longer mixing time does reduce the available working time of the mix. The casting and curing procedures are discussed in the next section.

4.5 CASTING AND CURING PROCEDURES

The two types of samples cast in Phase I are shown in Figure 15. In order to not waste material for this initial testing, small 0.65 ft³ size mixtures were cast. This size was enough to cast a set of eighteen 2” cubes and eighteen 3” x 6” cylinders to be tested at 2 hour, 3 hour, 4 hour, 5 hour, 6 hour, 12 hour, and 24 hours as well as 3 days, 7 days and 28 days after mixing. Two cubes and two cylinders were tested at each time interval for compressive strength.

Cubes were cast in two layers and tamped using a nonabsorptive, nonabrasive, nonbrittle tamper per ASTM C 109 requirements in four rounds as specified in ASTM C 109 and described in Figure 16 (ASTM C 109, 2012).



Figure 15: Cube and cylinder samples for Phase I mixtures

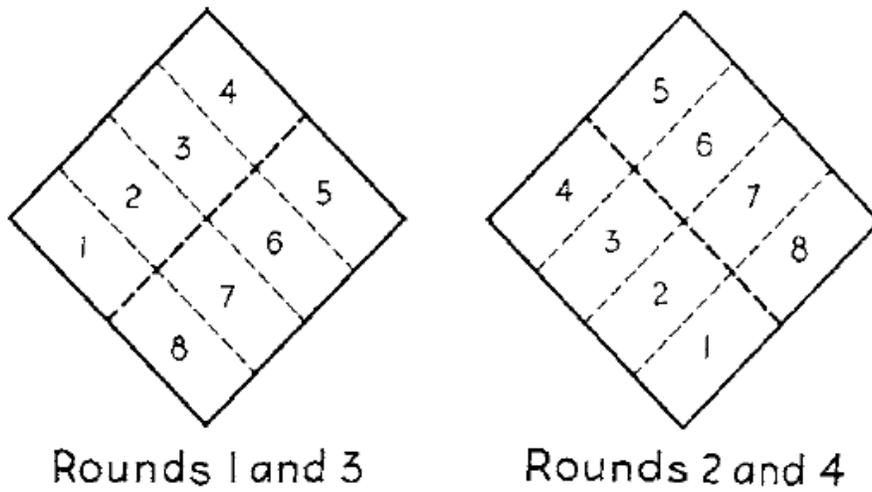


Figure 16: Order of tamping in molding of test specimens from ASTM C 109 (2012)

Cylinders were cast in a similar fashion in two layers, rodded 25 times each and struck on the sides to release any entrapped air. After both layers of concrete were rodded, both the cubes and the cylinders were struck off any excess material with a wood trowel. Typically final finishing is done after any bleed water has evaporated, but in the case of these rapid hardening mixtures, final finishing was conducted as soon as possible after finishing with the wood trowel to prevent premature setting with an unfinished surface.

Cubes and cylinders were cast simultaneously for the bulk cement mixtures to compare compressive strengths between the two specimens. The two specimens provided a good correlation which allowed for less material waste, especially with the pre-bagged mixtures. This allowed 2 inch cubes to be used as the sole compressive sample. A sample strength gain curve for one of the initial CSA-1 mixtures is shown in Figure 17 for cubes and cylinders.

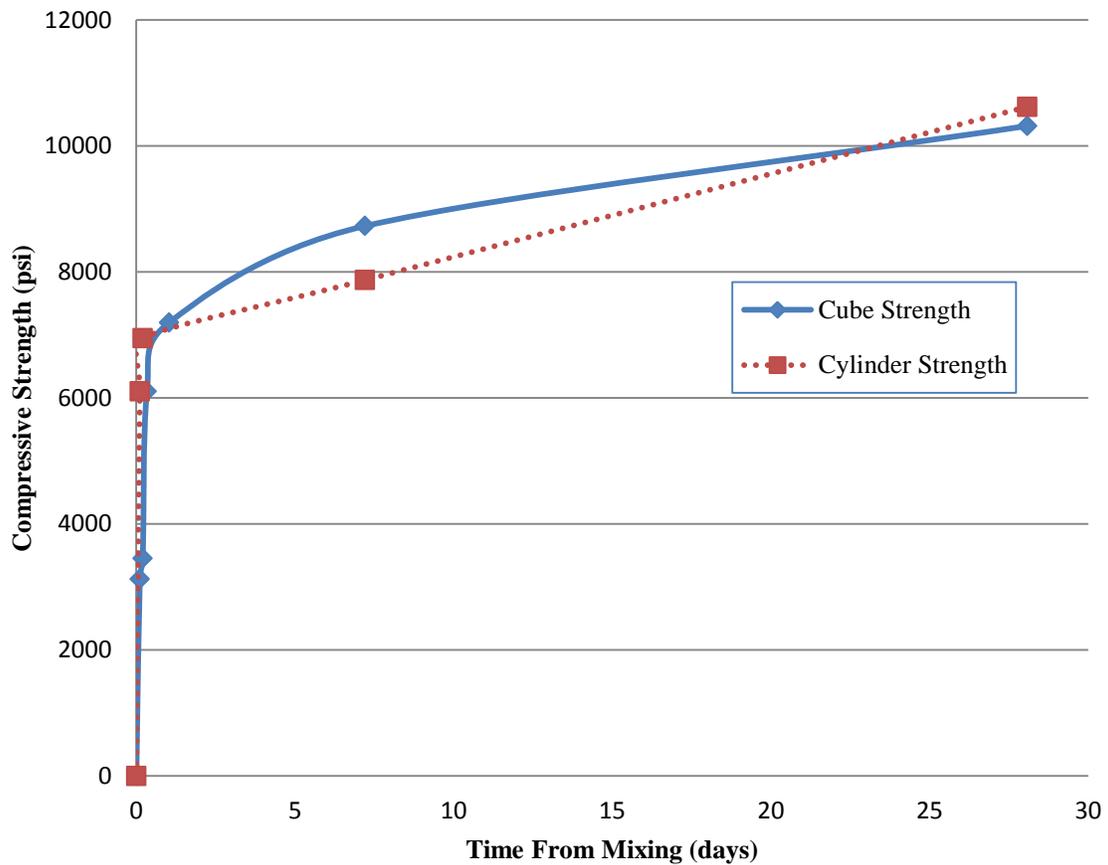


Figure 17: Graph showing correlation between cube and cylinder samples

Curing for all samples was done with wet burlap. The burlap was left in a bucket full of water for approximately 24 hours prior to mixing to allow the burlap to soak completely. The high heat generation tends to evaporate the water on the surface of the sample so constant rewetting was done for the first 3 to 4 hours until the sample reached 3000 psi compressive strength. Samples were left in a temperature controlled room until 1 day after mixing and then stripped from the formwork and placed in a 73° F and 100% relative humidity chamber until the end of the testing period. Figure 18 shows a typical curing setup.



Figure 18: Curing set up for Phase I using damp burlap

4.6 MIX MATRIX AND PROPORTIONS

A series of mixtures involving the six binder systems in combination with admixtures and additives was developed for testing. The series included the following set:

1. Type III portland cement blended with silica fume, high dosages of non-chloride accelerator and superplasticizers with very low water to cement ratios.
2. A straight calcium sulfoaluminate concrete mixture, referred to as CSA-1, with and without citric acid as a retarding admixture.
3. A calcium sulfoaluminate latex-modified concrete mixture. This mixture contained 15% latex modifier and referred to as CSA-LX.
4. Two proprietary calcium sulfoaluminate concrete mixtures, these cements were extended using fine and coarse aggregate and citric acid as needed. The mixes are labeled CSA-2 and CSA-3.
5. A straight calcium aluminate cement mixture, referred to as CAC-1, modified with different LiSO_4 accelerator doses and citric acid retarder if needed.
6. A proprietary calcium aluminate cement blend with fly ash, CAC-F, this blend did not require any additional admixtures, used as-is.

7. A calcium aluminate latex-modified concrete mixture, CAC-LX. Latex content was varied from 10-20% for preliminary screening test.
8. Four ready-to-use proprietary blends. These mixtures were mixed as-is with the recommended amount of water from the supplier.

Series 1-7 required modifications in cement content with a minimum of 658 pounds (7-sack) of cement per cubic yard. Water to cement ratios, admixture doses and latex addition were also varied according to the type of concrete mixture. Table 11 shows the range of additive doses tested with each series. The four pre-packaged mixtures were unaltered and only water was added. A total of 85 small scale mixtures were cast but only 26 mixtures passed the initial strength requirements for early age strength. Table 11 lists those 26 mixtures along with the 3 hour, and 28-day compressive strength.

Table 11: Mixtures passing Phase I along with admixture doses

Mixes Passing Screening Test	Cement Type/ Content	3 Hour Strength (psi)	28 Day Strength (psi)	w/c	ACC	HRWR % or by cwt	Citric Acid % by cwt	Latex % by cwt
	CSA-1	5070	10779	0.42	N/A	N/A	N/A	N/A
	CSA-1	3176	10318	0.40	N/A	N/A	N/A	N/A
	CSA-1	3171	11250*	0.40	N/A	N/A	0.25	N/A
	CSA-1	5556	11250*	0.40	N/A	0.25%	N/A	N/A
	CSA-1	5975	11250*	0.38	N/A	0.7	N/A	N/A
	CSA-LX	3854	7632	0.38	N/A	N/A	N/A	10
	CSA-LX	3913	8373	0.35	N/A	N/A	N/A	15
	CSA-LX	4219	7726	0.35	N/A	N/A	N/A	10
	CAC	3700	11250*	0.40	0.75	N/A	N/A	N/A
	CAC	4572	11250*	0.40	1	N/A	N/A	N/A
	CAC	3910	11250*	0.40	1.25	N/A	N/A	N/A
	CAC-1	4410	11250*	0.38	1	N/A	N/A	N/A
	CAC-1	3199	11250*	0.38	1	0.25%	N/A	N/A
	CAC-1	3278	11250*	0.38	1.25	0.50%	N/A	N/A
	CAC-1	4182	11250*	0.38	1.25	0.35%	N/A	N/A
	CAC-1	4290	11250*	0.38	2	N/A	0.1	N/A
	CAC-1	2993	9664	0.38	2	0.25%	0.1	N/A
	PC Type III	Not rapid- setting	11200	0.35	10oz / 100lbs cement	13oz / 100lbs cement	N/A	N/A
	CAC-2	3118	7840	0.4	N/A	N/A	N/A	N/A
CSA-2	3859	6170	0.42	N/A	1oz /100lbs cement	0.2	N/A	
CSA-3	2880	8385	0.4	N/A	N/A	0.2	N/A	
CAC-LX (4 hr strength not 3hr)**	2970**	6280	0.35	2	N/A	N/A	10	
P- 4	3560	7180	N/A	N/A	N/A	N/A	N/A	
P-2	4555	10553	N/A	N/A	N/A	N/A	N/A	
P-1	3287	10536	N/A	N/A	N/A	N/A	N/A	
P -3	Not rapid- setting	10960	N/A	N/A	N/A	N/A	N/A	

11250* Maximum peak load of cube compression machine

** 4 hour strength not 3 hour

With the help and input from TxDOT and faculty advisors a subset of these 26 mixtures were selected for a more exhaustive series of testing that focus on the hardened and durability properties described in section 4.3, and reproduced in Figure 19 below. The selected mixtures listed in Table 12 have passed into Phase II, currently ongoing testing, and no complete data has been generated at the time of this thesis. Complete mixture proportions along with strength gain curves for these mixes are included in Appendix A.

<i>Fresh Properties</i>	<i>Hardened Properties</i>	<i>Durability Properties</i>
<ul style="list-style-type: none"> • Water demand • Slump and slump retention • Air-entraining agent demand • Admixture/binder compatibility • Setting time • Bleeding 	<ul style="list-style-type: none"> • Compressive strength • Tensile strength • Flexural strength • Elastic modulus • Heat of hydration (isothermal and semi-adiabatic calorimetry) • Maturity (for selected binders) • Drying shrinkage • Thermal expansion/contraction • Restrained and unrestrained volume change (using cracking frame approach, as per TxDOT 4563 and 6332) • Bond strength (with substrate) 	<ul style="list-style-type: none"> • Alkali-silica reaction • Delayed ettringite formation • External sulfate attack • Freeze-thaw • Salt scaling • Transport properties (resistivity, diffusion, etc.) • Corrosion of reinforcing steel

Figure 19: Fresh, hardened and durability properties for a successful mixture

Table 12: Proportions for selected mixtures passing to Phase II

<i>Mixes Going on to Phase II</i>	Cement Type/ Content(lbs)	3 Hour Strength (psi)	28 Day Strength (psi)	w/c	ACC	HRWR % or by cwt	Citric Acid % by cwt	Latex % by cwt
	P-AAFA	3287	10536	N/A	N/A	N/A	N/A	N/A
	P-2	4555	10553	N/A	N/A	N/A	N/A	N/A
	P -3	Not rapid- setting	10960	N/A	N/A	N/A	N/A	N/A
	P- 4	3560	7180	N/A	N/A	N/A	N/A	N/A
	CSA-1 (700)	5070	10779	0.45	N/A	1.0oz / 100lbs cement	0.2	N/A
	CSA-LX (700)	3500	5800	0.38	N/A	N/A	0.2	15
	CSA-2 (658)	3860	6170	0.42	N/A	1.0oz / 100lbs cement	0.2	N/A
	CSA-3 (658)	2880	8385	0.40	N/A	N/A	0.2	N/A
	CAC-1 (700)	4182	6520	0.38	1.25	0.35%	N/A	N/A
	CAC-2 (752)	3118	7840	0.35	N/A	N/A	N/A	N/A
	CAC-LX (705)	2970**	6280	0.35	2	N/A	N/A	10
	Type III PC (658)	Not rapid- setting	11200	0.35	10oz / 100lbs cement	13oz / 100lbs cement	N/A	N/A

** 4 hour strength not 3 hour

Chapter 5: Conclusions and Future Work

This chapter summarizes the conclusions from Phase I of the project. The current and ongoing testing plan for Phase II and the future plans for the remainder of the study are provided below.

5.1 CONCLUSIONS AND ONGOING RESEARCH

From the 26 rapid repair mixture designs that met the criteria in Phase I, 12 were selected for a more comprehensive study to test performance and durability. These mixtures included a variety of promising mixture designs from the initial screening program, all the pre-packaged proprietary blends, as well as some mixture designs that did not pass the strength requirements of Phase I but were of interest to TxDOT. The selected mixes varied in cement content, water to cement ratio and admixture doses, and are viable field mixture for repair construction. These mixtures showed plenty of working time, a reasonable setting time, and fast strength gain. Several key issues described below will be evaluated through an extensive laboratory program that is currently ongoing.

In order to evaluate the effects of the wide range of temperatures in Texas, mixing of the samples will be done at 73°F, as well as 50°F and 100°F. The following hardened properties will also be of concern:

- Splitting tensile strength following ASTM C 496
- Flexural strength following ASTM C 78, simple beam with third-point loading
- Modulus of elasticity following ASTM C 469
- Rigid and free shrinkage frame with real time-temperature history
- Drying shrinkage testing following ASTM C 157
- Coefficient of thermal expansion on 28 day specimens using a submersible Linear Variable Differential Transformer, or LVDT

Key durability issues that have plagued concrete structures for years will also be tested during Phase II and include the following:

- For bulk cements alkali-silica reaction will be tested using highly reactive fine aggregate and for pre-packaged blends concrete samples will be tested as-is according to ASTM C 1293
- External sulfate attack will be evaluated following ASTM C 1012
- Corrosion concerns will be addressed through the use of the following:
 - Chloride diffusion tests using ASTM C 1556
 - Chloride resistivity using a modified version of ASTM C1202
- With the exception of latex-modified concrete and proprietary blends, air-entraining agent will be added to all binder systems and quantified to achieve a target air content of 6 ± 1 percent and tested for:
 - 300 cycles of freeze-thaw testing following ASTM C 666
 - 50 cycles of salt scaling following ASTM C 672
 - Air-void analysis using RapidAir
- Response to repetitive loading of repaired sections will be evaluated by flexural fatigue tests

Using the results from Phase II a subset of the mixtures that show promising results will be selected for field trial evaluations for current TxDOT projects.

5.2 FIELD TRIALS

Field trials will be conducted at J.J. Pickle Research Campus on simulated bridge decks as shown in Figure 20. Rectangular sections with dimensions of 2ft X 10ft X 4in

will be cut out from the cast in place concrete that were poured on precast concrete panels.



Figure 20: Bridge deck cutouts for rapid repair site

Each cutout will be “repaired” using three or four promising mixtures from Phase II. Interfacial bonding, thermal compatibility, permeability and early age strength are all important for a durable long lasting repair, thus the following properties will be monitored and evaluated:

- early age compressive strength
- 28 day tensile, flexural and bond strength
- elastic modulus
- coefficient of thermal expansion for thermal compatibility
- drying shrinkage
- heat generation using imbedded thermocouples

Field data along with the laboratory testing will make it possible to draw correlations between the hardened properties and the long term concrete durability of the

repair materials. The results of this investigation will provide guidelines and implementation techniques on a series of usable field mixtures of rapid-hardening concrete for rapid repairs of bridge decks and pavements that require partial or full depth repairs.

Appendix A: Phase I Compressive Strengths

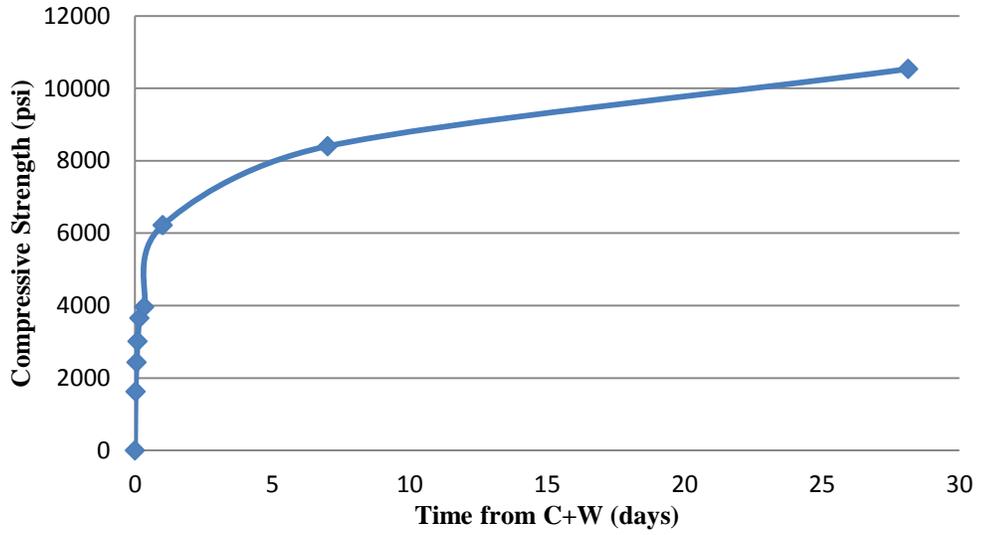


Figure 21: P-AAFA compressive strength curve

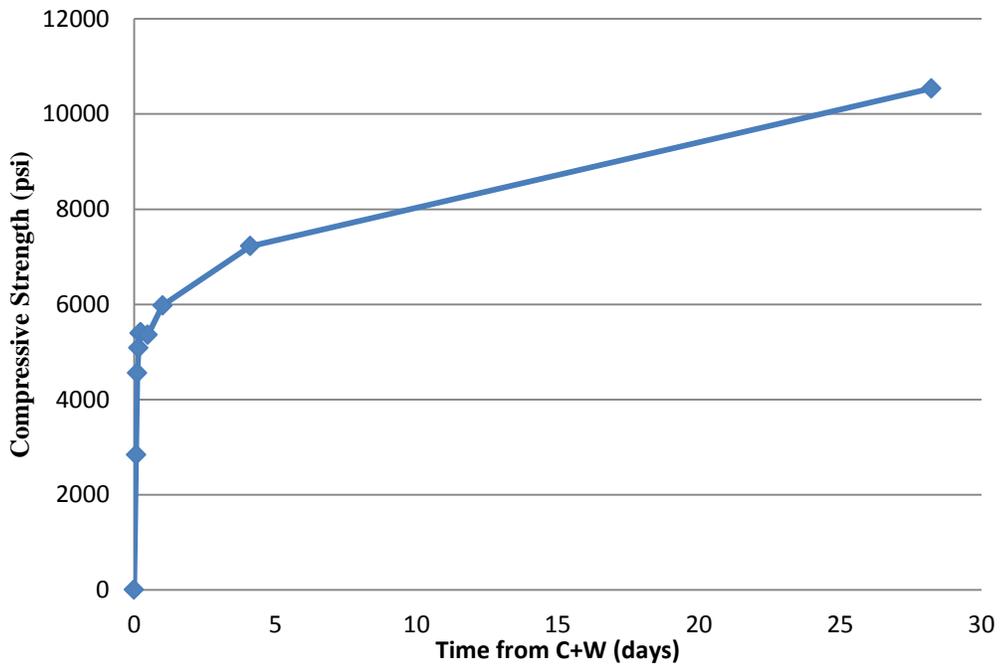


Figure 22: P-2 compressive strength curve

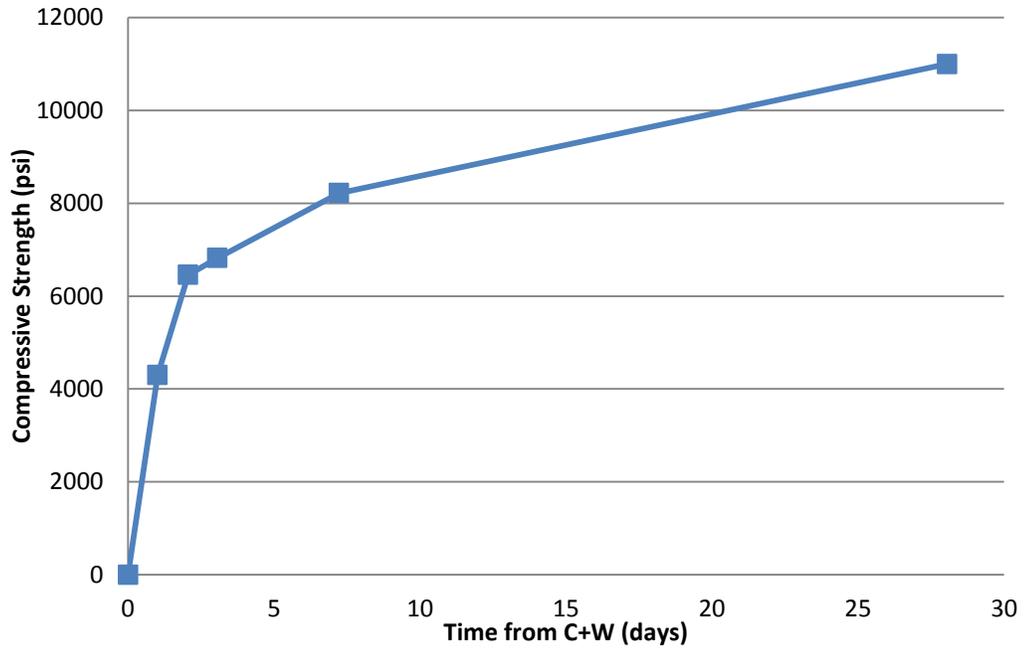


Figure 23: P-3 compressive strength curve

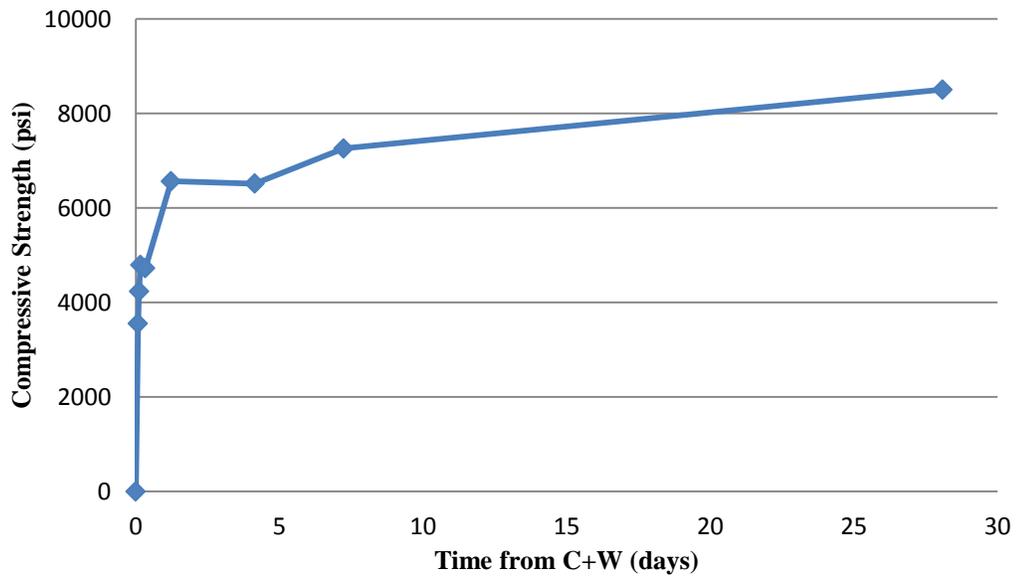


Figure 24: P-4 compressive strength curve

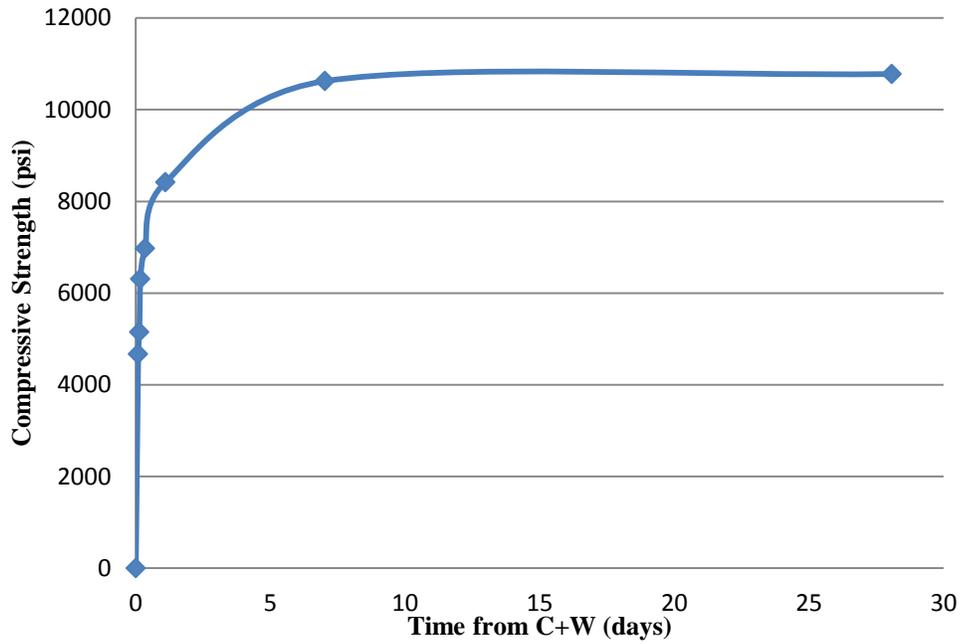


Figure 25: CSA-1 compressive strength curve

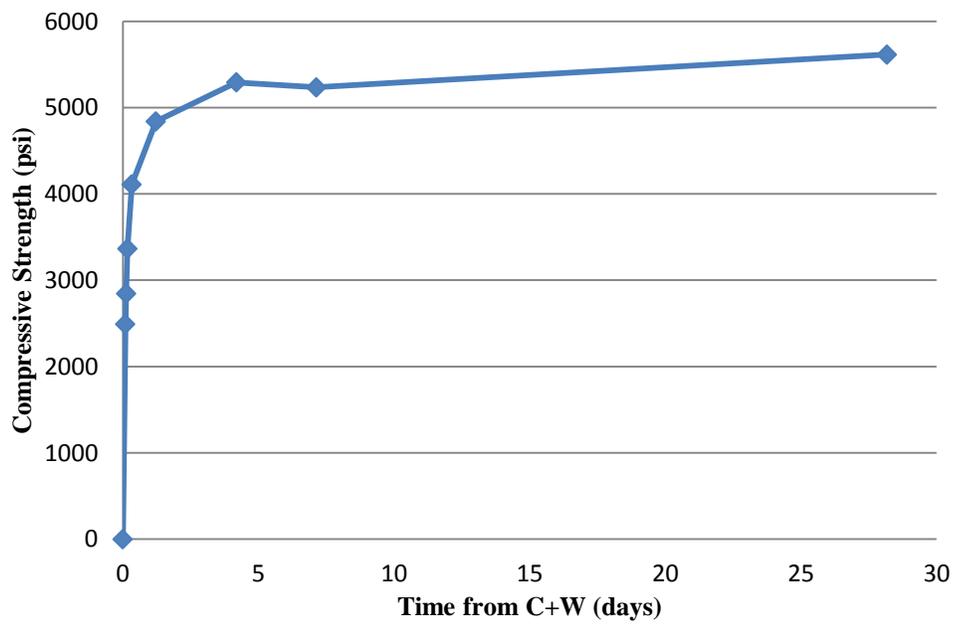


Figure 26: CSA-Latex compressive strength curve

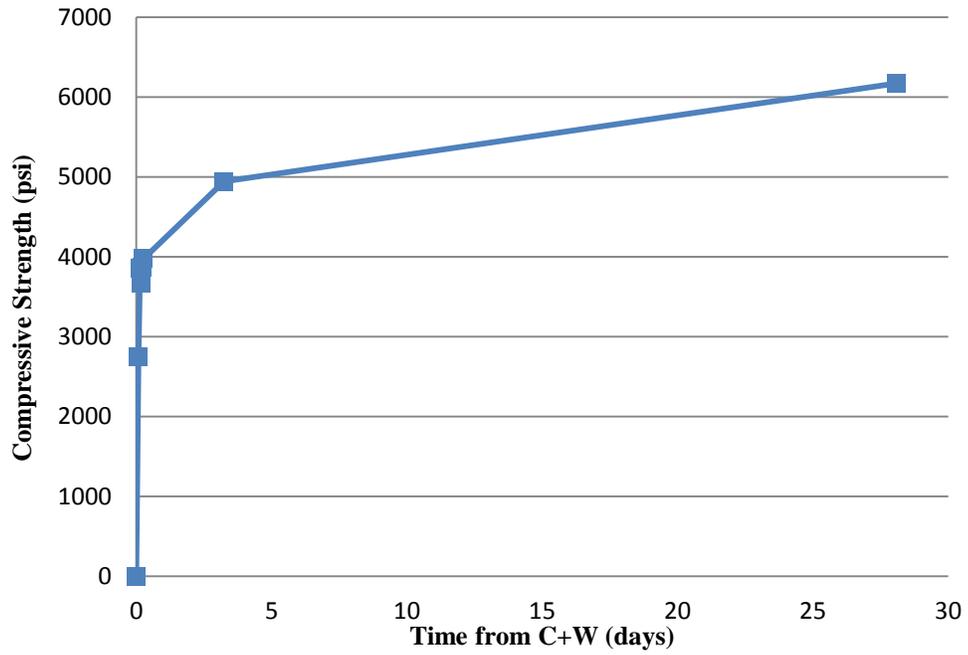


Figure 27: CSA-2 compressive strength curve

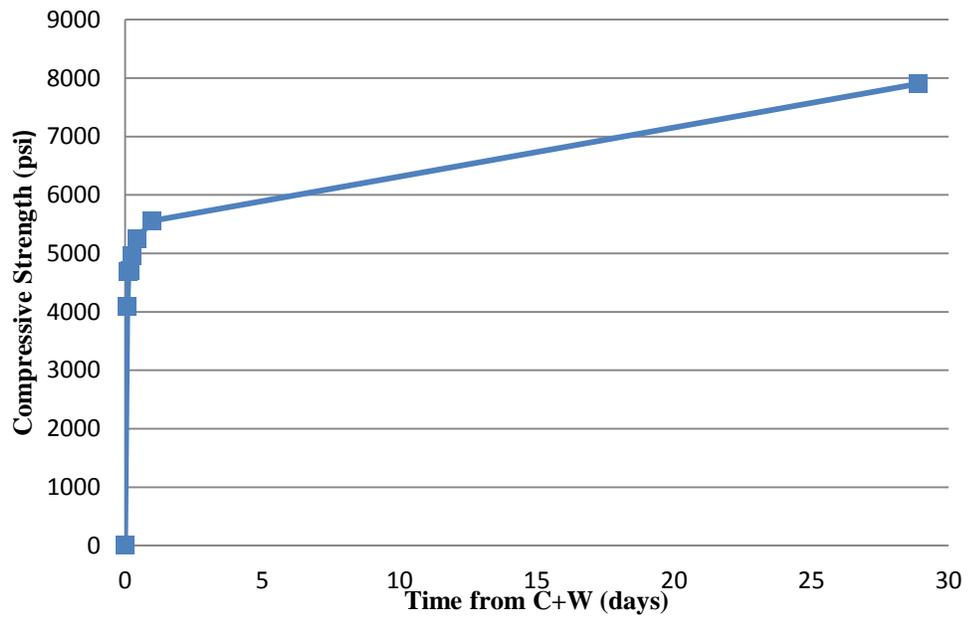


Figure 28: CSA-3 compressive strength curve

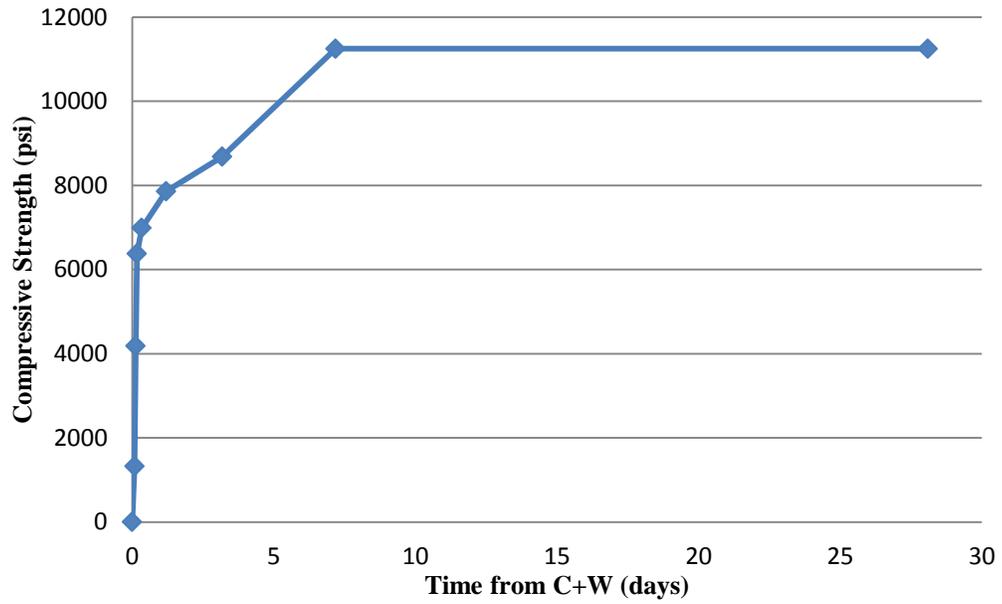


Figure 29: CAC-1 compressive strength curve

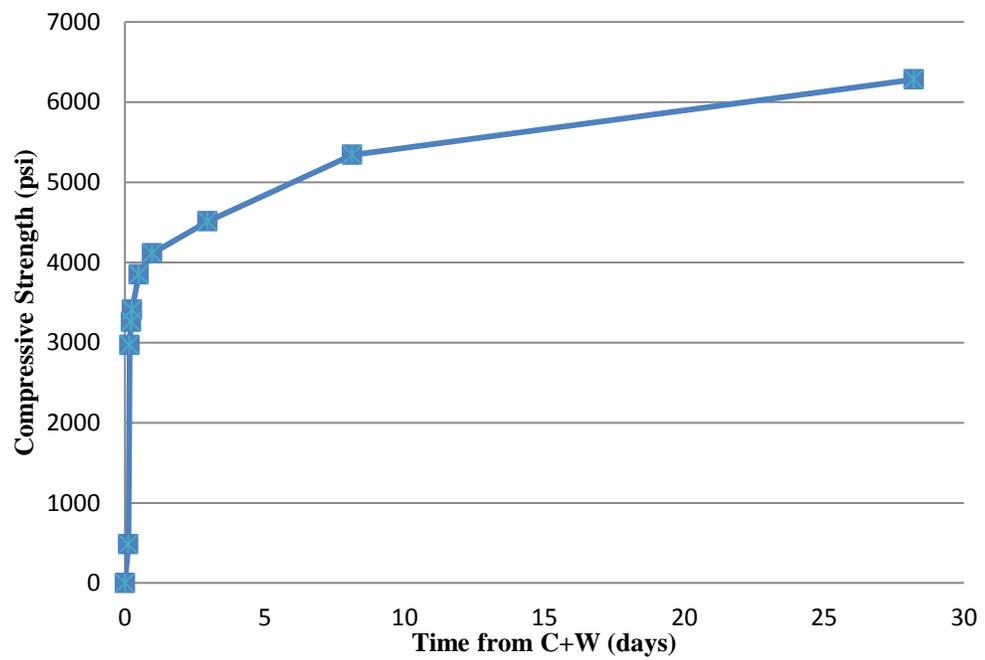


Figure 30: CAC-Latex compressive strength curve

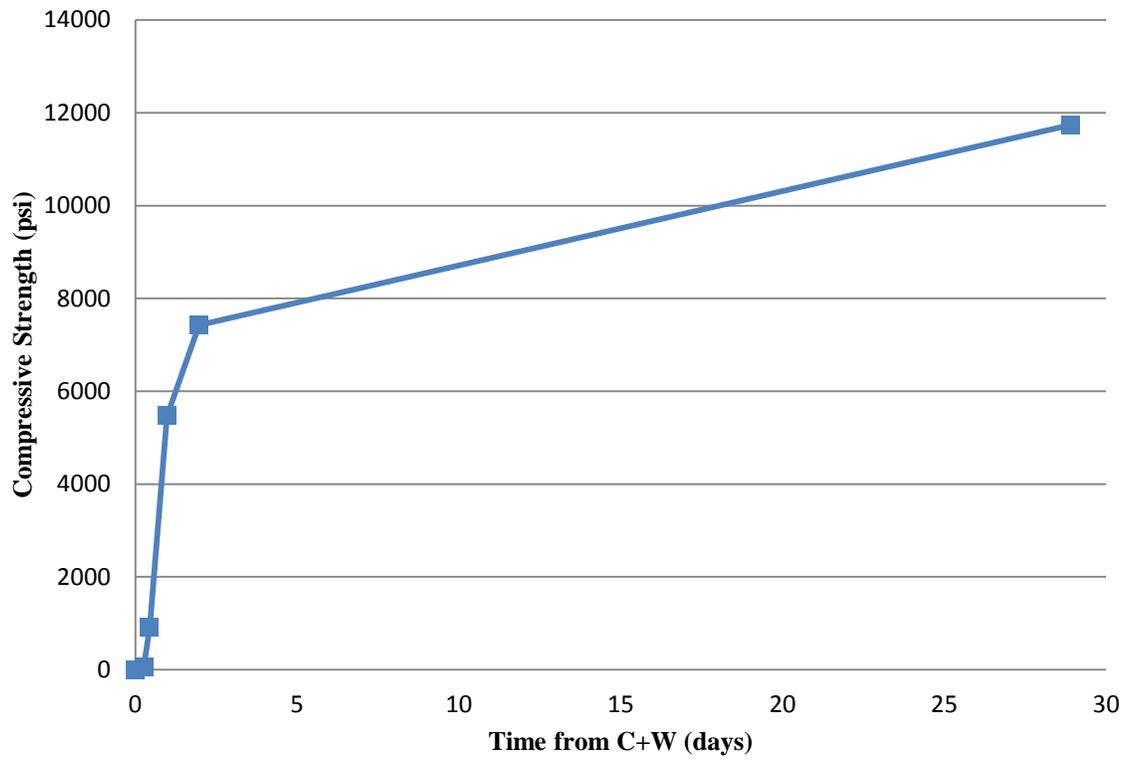


Figure 31: Portland cement compressive strength curve

Appendix B: Accepted Mixture Proportions from Phase I

Table 13: CSA-1 final mixture design

CSA-1	lb/yd ³
Cement	700
Coarse Aggregate	1343
Fine Aggregate	1477
Water	315
Citric Acid	1.4

Table 14: CSA-Latex final mixture design

CSA-LX	lb/yd ³
Cement	700
Coarse Aggregate	1415
Fine Aggregate	1557
Water	152.25
Latex	218.75
Citric Acid	1.4

Table 15: CSA-2 final mixture design

CSA-2	lb/yd ³
Cement	658
Coarse Aggregate	1279
Fine Aggregate	1407
Water	276.4
Citric Acid	1.316

Table 16: CSA-3 final mixture design

CSA-3	lb/yd ³
Cement	658
Coarse Aggregate	1403
Fine Aggregate	1544
Water	296.1
Citric Acid	1.316

Table 17: CAC-1 final mixture design

CAC-1	lb/yd ³
Cement	700
Coarse Aggregate	1418
Fine Aggregate	1560
Water	266
LiSO4 Accelerator	8.75
High Range Water Reducer	2.45

Table 18: CAC-2 final mixture design

CAC-2	lb/yd ³
Cement	752
Coarse Aggregate	1443
Fine Aggregate	1587
Water	263.2

Table 19: CAC-Latex final mixture design

CAC-LX	lb/yd ³
Cement	705
Coarse Aggregate	1397
Fine Aggregate	1645
Water	170.4
Latex	146.9

Table 13: Type III PC final mixture design

Type III PC	lb/yd ³
Cement	658
Coarse Aggregate	1870
Fine Aggregate	1162
Water	223.7
Accelerator	10 oz/100 lbs cement
High Range Water Reducer	13 oz/100 lbs cement
Air-Entrainer	0.15 oz/100 lbs cement

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