EVALUATION OF TERNARY BLENDED CEMENTS FOR USE IN TRANSPORTATION CONCRETE STRUCTURES

by

Amanda Louise Gilliland

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STATEMENT OF THESIS APPROVAL

The thesis of **Amanda Louise Gilliland**

has been approved by the following supervisory committee members:

Paul J. Tikalsky	, Chair	**July 8, 2010** Date Approved
Larry D. Reaveley	, Member	**July 8, 2010** Date Approved
Pedro Romero	, Member	**July 8, 2010** Date Approved

and by **Paul J. Tikalsky** , Chair of

the Department of **Civil and Environmental Engineering**

and by Charles A. Wight, Dean of The Graduate School.

ABSTRACT

This thesis investigates the use of ternary blended cement concrete mixtures for transportation structures. The study documents technical properties of three concrete mixtures used in federally funded transportation projects in Utah, Kansas, and Michigan that used ternary blended cement concrete mixtures. Data were also collected from laboratory trial batches of ternary blended cement concrete mixtures with mixture designs similar to those of the field projects. The study presents the technical, economic, and environmental advantages of ternary blended cement mixtures. Different barriers of implementation for using ternary blended cement concrete mixtures in transportation projects are addressed.

It was concluded that there are no technical, economic, or environmental barriers that exist when using most ternary blended cement concrete mixtures. The technical performance of the ternary blended concrete mixtures that were studied was always better than ordinary portland cement concrete mixtures. The ternary blended cements showed increased durability against chloride ion penetration, alkali silica reaction, and reaction to sulfates. These blends also had less linear shrinkage than ordinary portland cement concrete and met all strength requirements.

The increased durability would likely reduce life cycle costs associated with concrete pavement and concrete bridge decks. The initial cost of ternary mixtures

can be higher or lower than ordinary portland cement, depending on the supplementary cementitious materials used.

Ternary blended cement concrete mixtures produce less carbon dioxide emissions than ordinary portland cement mixtures. This reduces the carbon footprint of construction projects.

The barriers associated with implementing ternary blended cement concrete for transportation projects are not significant. Supplying fly ash returns any investment costs for the ready mix plant, including silos and other associated equipment. State specifications can make designing ternary blended cements more acceptable by eliminating arbitrary limitations for supplementary cementitious materials (SCMs) use and changing to performance-based standards. Performance-based standards require trial batching of concrete mixture designs, which can be used to optimize ternary combinations of portland cement and SCMs. States should be aware of various SCMs that are appropriate for the project type and its environment.

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CHAPTER 1

INTRODUCTION

Supplementary cementitious materials (SCMs) include ground granulated blast furnace slag (GGBFS), fly ash, silica fume, metakaolin, limestone flour, and natural and manufactured pozzolans. Pozzolanic materials are not necessarily cementitious when used alone, but react with the calcium hydroxide (CH) hydration product of portland cement to form calcium silicate hydrate (CSH). CSH is the strongest binding and most durable hydration product of cement. Some materials are not cementitious or pozzolanic but are still considered SCMs. These inert particles and nano seeds serve as catalysts to the formation of CSH. Limestone flour is such a material. The use of SCMs in concrete mixtures has become increasingly important because they increase the durability of concrete, and the economic and environmental advantages of using concrete.

It is important to create concrete structures that will last as long as desired. Concrete bridge decks often fail due to chloride penetration long before they have outlived their design life. Deicing salts are used to enhance the safety of roads and highways in climates that have ice and snow. There is a high concentration of chlorides in deicing salts. The chlorides penetrate the concrete and cause the reinforcement to corrode, which eventually leads to a serviceability failure.

Other common serviceability failures of concrete bridge decks and concrete pavement are alkali silica reaction (ASR) and sulfate expansion. ASR is the reaction of amorphous silica or microsilica found in aggregates and alkali found in the cement paste. The reaction of alkalis and silica creates a gel that expands through the osmotic absorption of moisture and causes the concrete and aggregate to expand (ACI, 2008). It may eventually lead to cracking and a serviceability failure. A common way to avoid ASR is to use aggregates that are not highly susceptible to alkalis. However, this is not always feasible in areas where such aggregates are not readily available. Reducing the permeability of the concrete will help to keep water out of the concrete and will reduce ASR. However, to truly mitigate its effects, the nature of the gel must be changed.

Sulfate expansion occurs in locations exposed to seawater or soils with groundwater high in sulfates. Sulfates react with the hardened cementing materials and form ettringite and gypsum. The formation of ettringite causes expansion and the formation causes the concrete to soften (ACI, 2008). This results in strength loss, and eventually serviceability failure. Reducing the permeability of the concrete will slow the sulfate expansion, but to mitigate the expansion, the chemistry of the hardened cement must be changed.

This thesis will focus on using ternary blended cements to increase concrete durability. The term ternary blended cement refers to a blend of portland cement and two SCMs. Previous laboratory studies (Hammond, 2010; Hanson, 2010; St. Clair, 2004) showed the potential of using ternary blends to improve the service life of concrete. This thesis will investigate the use of ternary blended cements in concrete pavement and concrete bridge deck field applications in Kansas, Michigan, and Utah. When used correctly, ternary blended cement concrete mixtures can greatly increase concrete durability by reducing ASR, sulfate expansion, and chloride permeability. This will greatly extend the life cycle of the concrete. There can also be benefits in strength gain and a reduction of shrinkage. Ternary blended cement mixtures should reduce costs associated with maintenance and repair. Some blends will lower initial capital costs. There are environmental benefits from using ternary blends since these mixtures reduce the amount of expensive raw materials used to manufacture cement and recycle industrial byproducts.

CHAPTER 2

BACKGROUND

2.1 Introduction to Ternary Blended Cements

Using SCMs in binary blended portland cement concrete mixtures has been known for nearly a century. However, using them in ternary combinations has been rare and not considered general practice. The primary reason for this lack of use has been the need for data and the complexity of the materials. There are technical, economic, and environmental benefits to using ternary blended cements. Ternary blends can be even more durable than binary blends because the additional SCM can overcome the shortcomings of the first SCM. However, it should be noted that the properties do not follow a superposition behavior. The SCMs may interact with each other, and properties found in ternary blends may differ from those found in binary blends.

The following subsections summarize some of the previous studies that have been done on the advantages of using ternary blended cements. This section will also discuss some of the barriers that exist for implementing ternary blended cements.

2.2 Technical Advantages

Jones et al. (1997) tested ternary blended cements for resistance to chloride ingress. They used different combinations of GGBFS, fly ash, and silica fume as supplements to portland cement systems. Their study determined that the chloride resistance of ternary blended cements typically performed significantly better than other binary and ordinary portland cement concrete mixtures. However, some ternary blends showed high chloride ingress after 30 days, indicating a need for further study of optimum combinations of materials.

In 1999, Lane and Ozyildirim tested multiple binary and ternary cement blends for alkali silica reaction (ASR). They determined that binary combinations of portland cement and high replacement levels of GGBFS or fly ash had excellent resistance to ASR. However, there was a delay in strength gain. The addition of silica fume to one of the binary combination produced the same high resistance to ASR and maintained high early strength gain.

Shehata and Thomas (2001) also tested blended cements for resistance to ASR. Binary and ternary combinations were tested. The study concluded that binary combinations of silica fume and portland cement had increased alkalinity at ages beyond 28 days. However, ternary blends of portland cement, fly ash, and silica fume maintained low alkalinity for up to 3 years and kept expansion below 0.04%.

Thomas et al. did a long-term study of the durability of ternary blended cements using GGBFS and silica fume (2002). The study consisted of laboratory and outdoor exposure site testing. Slabs of different combinations were cast in harsh Canada environments and were exposed to heavy traffic and deicing salts. Slabs were tested for 2 years. The results showed that ordinary portland cement slabs have high expansion due to ASR. However, none of the ternary blends showed significant expansion from ASR. All slabs performed well in the salt scaling tests with the exception of the slab that had up to 50% GGBFS. This slab showed slight scaling. Ternary blends greatly outperformed all other blends in the rapid chloride penetration tests. The final conclusion of the study was that the ternary blended cement concrete slabs were more durable than all other ordinary and binary concrete slabs.

In 2002, Menendez et al. tested binary and ternary combinations of portland cement, GGBFS, and limestone for strength gain. They concluded that binary combinations of portland cement and GGBFS had low early age strength, but higher strengths at later ages. Binary combinations of portland cement and limestone had high early strengths, but reduced later age strengths. However, ternary combinations of portland cement, limestone, and GGBFS had both high early age and later age strengths.

Khatib and Hibbert (2005) performed similar strength gain tests using portland cement, GGBFS, and metakaolin. They also found that ternary blends of the materials maintained the benefits of each binary combination while overcoming any shortcomings the binary blend experienced.

In 2006, Anwar tested blended cement concretes using fly ash and silica fume for early age properties. The concrete specimens were tested for fresh properties (slump, air content, unit weight) and hardened properties (compressive strength, tensile strength, dynamic elastic modulus, and static young's modulus). Results showed that the ternary blends had desirable fresh properties. This is because the use of fly ash increases the workability of the concrete. The hardened properties showed that fly ash tends to reduce early age strength but the use of silica fume compensated for the early age strength loss.

Ghrici et al. (2007) tested ternary blends of portland cement, limestone, and a natural pozzolana. Control mixtures of ordinary portland cement, portland cement and limestone, and portland cement and natural pozzolana were also tested. Results showed that early age and long-term compressive and flexural strengths of the ternary blend were better than the control mixtures. There was also better resistance to sulfates and chloride-ion penetration in the ternary blend.

Sahmaran et al. tested blended cements for sulfate resistance (2007). Specimens included ordinary portland cement (OPC), sulfate resistant portland cement (SRPC), and blended cements of portland cement, fly ash, and a natural pozzolana. The paper concluded that the blended cements always had less sulfate expansion than the ordinary portland cement mixtures. The ternary blends also performed better than SRPCs at room temperature. In environments exposed to cycles of hot and cold temperatures, the blended cements still performed almost as well as the SRPC mixtures.

Kirca and Erdem (2008) tested binary combinations of portland cement and silica fume for strength gain. Fly ash or GGBFS was then introduced to the binary mixtures to create ternary blended cements. Ternary blends almost always obtained higher early age and later age strengths than the binary mixtures.

In 2008, Hale et al. tested properties of concrete mixtures containing GGBFS and fly ash for use in transportation structures. The goals of the research were to determine if ternary combinations of the materials performed better than binary combinations. Three different types of cements were used in this study. The main conclusions were that the interaction between SCMs and cement varied greatly depending on the chemical composition of the cement. Ternary blends typically performed better than ordinary and binary blends. However, the optimum ranges of SCM replacement varied greatly depending on what cement and type of SCM was used.

2.3 Environmental Advantages

In 1999, Malhotra investigated the use of fly ash in concrete to reduce greenhouse gas emissions. It was estimated that the production of 1 ton of cement produced about 1 ton of CO_2 into the atmosphere. Reducing the amount of cement in concrete mixtures reduces the amount of CO_2 that the cement industry releases into the atmosphere.

Mehta also researched the environmental benefits of using more fly ash and GGBFS in concrete (1999). He estimated at that time that only about 6% of available fly ash was being used as a pozzolan in blended cements, suggesting that it is greatly underused. GGBFS is not as readily available in the Unites States. However, there are still many areas that have access to GGBFS. Mehta concluded that using fly ash and GGBFS as SCMs in concrete mixtures would have a high impact on the future of the concrete industry.

In 2008, Damtoft et al. produced a paper on how the concrete industry was contributing to the Climate Change Initiative. Because hydraulic cements are the most widely used construction material, they can have a huge impact on sustainable development. The research included a section dedicated to SCM replacement in concrete in order to reduce CO_2 emissions from the cement industry. They indicated the importance of using binary, ternary, and quaternary blended cements in order to reduce cement production.

Marquez et al. (2009) researched the CO_2 emissions savings in cement plants that produce ternary blended cements. Results estimated that using ternary blended cements could reduce up to 45% of CO_2 emissions. Reduction of CO_2 emissions varied on the type of SCMs used in the concrete.

2.4 Economic Advantages

The cost of ternary blended cements varies depending on the type of SCMs used and the location of the project. It is difficult to predict exactly how much the mixture will initially cost. Typically the use of fly ash or GGBFS will have no increase in cost, and will likely reduce initial cost (Mehta 1999). Silica fume and metakaolin are not as readily available and will increase the initial cost of the mixture (Damtoft, 2008). However, emphasis should be given to the increased durability of the project and lowered life-cycle costs.

2.5 Barriers to Implementation

Despite all of the laboratory research findings that show ternary blends are superior to ordinary portland cement and binary blends, they are not often used in state transportation projects. There are some barriers that prevent the concrete industry from using them regularly. Some of these barriers are described in the following paragraphs and will be addressed in Chapter 10.

2.5.1 Optimization of SCMs and Implementing Ternary Blends

A major barrier that exists is the lack of understanding about how the different SCMs interact with each other. Optimum combinations of materials require trial batching and analysis of performance criteria. Optimization requires performance-based specifications to be met while keeping mixtures economical and meeting environmental standards. There is hesitation to use ternary blended cement concrete mixtures because it is not a familiar practice. Despite positive results in research, convincing the concrete and cement industry to change to mixture designs with which they are unfamiliar is challenging.

2.5.2 Specification Limitations

There is a lack of performance standards and arbitrary limitations in state DOT specifications for structural concrete and concrete pavements. There are usually limits for SCM replacement. Generally, these limits are not based on performance and can hinder the design of a ternary blended cement concrete mixture. Only four states explicitly accept performance-based ternary blends of cementitious materials.

2.5.3 Supplying SCMs

There are barriers that exist for the broader industry of ready mix plants. In order to supply clients with blended cements, a ready mix plant needs additional silos for storage of SCMs. This can be expensive initially for smaller plants. However, if the plant provides fly ash or GGBFS as one of the SCMs, it is possible that the lowered material cost will eventually pay for the silo. There is also a decision for the ready mix plant to supply preblended cements, or to blend the SCMs in the mixture on site.

2.5.4 Designing Ternary Blended Cements for Specific Projects

Another problem that exists is the want for a “recipe” for a concrete mixture. However, there is no such ternary blended cement concrete mixture. Economic availability and technical specifications with respect to the project should be considered before choosing materials. Environmental standards should also be considered. It is also important to realize that there are different desirable performance properties for different projects. Different projects will have unique optimum ternary blended cement mixtures.

CHAPTER 3

OBJECTIVE

The purpose of this thesis is to show that ternary blended cement concrete mixtures can be used for full-scale transportation structures to improve durability, and reduce environmental impacts of projects. It will also show that the costs of the ternary blended mixtures are comparable, or less than ordinary portland cement concrete mixtures.

Three field projects using ternary blended cement concrete mixtures will be documented. Specimens were taken from the field and tested for performance properties. The data from the specimens will be compared to data from specimens created in the laboratory that have similar mixture designs so that common trends can be observed. The mixture designs used in field projects will be compared to the state specifications to be sure they meet the required standards.

This paper will address the different barriers of implementation of using ternary blended cements in concrete pavements and concrete bridge decks. The different barriers addressed in Chapter 2 will be examined and some basic guidelines will be suggested.

CHAPTER 4

EXPERIMENTS

Data were collected from specimens prepared in the laboratory and from specimens collected in the field. Some of the data used in this thesis are taken from an on-going Pooled Fund Study of the United States Department of Transportation and The Federal Highway Administration. The laboratory data were collected from specimens tested by student technicians at the University of Utah. The field data were collected from state transportation projects in Utah, Kansas, and Michigan. The purpose of this study is to determine best practices for ternary blended cement concrete mixtures for use in transportation structures and pavements. This thesis uses laboratory data from the mixtures in the study that most closely relate to the mixtures used in field projects.

CHAPTER 5

LABORATORY TERNARY BLENDED CEMENT CONCRETE MIXTURES

5.1 Materials

This section will describe the materials that were used in the laboratory experiments that will be presented in this thesis.

5.1.1 Portland Cement

Portland cement is composed of a combination of limestone and either shale, clay, sand, or iron. These materials are ground and blended together and heated in a kiln from $2600°F$ to $3000°F$. This causes the materials to fuse together to create clinker. Cooled clinker is then ground with gypsum ($CaSO_4*2H_20$). The addition of gypsum controls the aluminate chemistry and the setting time of cement concrete. Portland cement reacts with water to form a paste that binds the aggregate particles together to form concrete.

Four of the cements that were used in the laboratory part of the pooled fund study will be presented here. The cements include ASTM C 150 Type I and Type I/II, ASTM C 595 Type IS(20), and ASTM C 1157 MS limestone-blended cement (designated Type E). Type I was used for the mortar mixtures and Type I/II was used for the concrete mixtures. ASTM C 150 defines Type I as a general use portland cement and Type II as a moderate heat and moderate sulfate resistant portland cement. ASTM C 595 defines Type IS(20) as portland-pozzolan cements containing GGBFS meeting ASTM C 989 (ASTM, 2008). The Type IS(20) is 80% Type I cement blended with 20% grade 120 GGBFS. The limestone-blended cement is an ASTM Type II/V cement clinker ground and blended with 10% limestone flour. The limestone-blended cement was also used in the Utah field project and is described more in Chapter 6. The chemical composition of each cement was determined using X-Ray Fluorescence (XRF). The results of the XRF tests are shown in Table 1.

5.1.2 Fly Ash

Fly ash is the byproduct of coal power plants. It is largely the noncombustible material that remains after the coal has been burned. Fly ash particles are very fine smooth spheres that are similar in size to cement particles. Particle size is typically between 5 and 50 μm. Unlike portland cement, Class F fly ash will not react with water. It is pozzolanic, meaning it reacts with calcium hydroxide, a hydration product of portland cement and water, to form cementitious products.

Two types of fly ash used in the laboratory study will be presented in this thesis. The chemical composition of fly ash is dependant on the coal that is burned. ASTM C 618 (ASTM, 2008) classifies fly ash depending on the amount of metallic oxide present. The two fly ashes used in this paper were Class F. The first Class F fly ash came from the Cayuga Generating Station in Cayuga, Indianapolis. The second Class F fly ash came from the Coal Creek Power Station in Underwood, North Dakota. Table 2 shows the chemical composition and ASTM requirements of the fly ashes presented in this thesis.

Table 1. XRF Results for Cements

Chemical (%)	Type I	Type I/II	Type IS(20)	Type E
SiO_2	19.80	20.70	21.66	20.24
Al_2O_3	6.18	3.80	4.55	3.85
Fe_2O_3	2.50	3.50	3.08	3.74
CaO	61.71	63.30	61.46	62.52
Na_2O	0.36	0.05	0.10	0.20
MgO	2.76	2.50	3.45	2.75
P_2O_5	0.21	-	0.10	-
SO_3	2.63	2.70	2.85	2.64
K_2O	0.74	0.66	0.69	0.54
TiO_2	0.28	-	0.36	-
SrO	0.24	-	0.05	-
Mn_2O_3	0.11	-	0.54	-
LOI	2.37	2.10	1.08	2.67
Total	99.91	99.31	99.97	98.21
C_3S	48.10	56.00	-	61.90
C_2S	20.40	27.00	-	11.35
C_3A	12.20	4.00	-	3.87
C_4AF	7.60	11.00	-	11.39

Table 2. XRF Results for Fly Ashes and ASTM C 618 Requirements

Chemical (%)	Coal Creek	Cayuga	ASTM C 618 Requirements Class F	ASTM C 618 Requirements Class C
SiO_2	51.40	45.05	Sum 70% Min	Sum 50% Min
Al_2O_3	16.21	23.71		
Fe_2O_3	6.73	16.43		
CaO	13.15	3.78		
Na_2O	2.86	0.80		
MgO	4.41	0.88		
P_2O_5	0.15	0.24		
SO_3	0.80	0.68	5% Max	5% Max
K_2O	2.33	1.46		
TiO_2	0.63	1.15		
SrO	0.33	0.18		
Mn_2O_3	0.05	0.03		
BaO	0.59	0.10		
LOI	0.05	5.39	6% Max	6% Max
Total	99.69	99.89		

5.1.3 Ground Granulated Blast Furnace Slag

GGBFS is the byproduct of the iron metal industry. During iron production, the molten iron separates from impurities, which are captured by a limestone addition. The slag is drained and cooled very rapidly. The molten iron is tapped from the furnace and the slag remains. The cooled slag is then ground into fine particles. GGBFS has cementitious properties similar to portland cement; however, the reaction is much slower. It also has pozzolanic properties similar to fly ash.

ASTM C 989 (ASTM, 2008) classifies GGBFS into three categories: Grades 80, 100, and 120. The grade of the GGBFS is dependant on the activity index. The activity index is a strength relationship between a portland cement-GGBFS blended cube and an ordinary portland cement cube. This study used 120 GGBFS. Table 3 shows the chemical composition and ASTM requirement of the GGBFS used.

5.1.4 Silica Fume

Silica fume is a byproduct of the ferro-silicon metal industry. Ferro-silicon metals are produced in electric furnaces for sealants, caulk, and other products. The emissions from the furnace are collected and termed silica fume. Silica fume particles are 1/100 the size of cement particles. They are not cementitious but highly pozzolanic.

ASTM C 1240 (ASTM, 2008) defines the requirements of silica fume that can be used in concrete. The chemical composition and ASTM requirement of the silica fume used is shown in Table 4.

Table 3. XRF Results for GGBFS and ASTM C 989 Requirements

Chemical (%)	Grade 120	ASTM C 989 Requirements
SiO_2	36.81	
Al_2O_3	9.66	
Fe_2O_3	0.61	
CaO	36.77	
Na_2O	0.31	
MgO	10.03	
P_2O_5	0.01	
SO_3	2.75	
K_2O	0.35	
SrO	0.05	
TiO_2	0.49	
Mn_2O_3	0.39	
S	1.10	2.5% Max

5.1.5 Admixtures

Chemical admixtures are used to help reach desired concrete mixture properties. The laboratory phase of the study used a water reducing admixture, and an air-entraining agent. The water reducer was a polycarboxolate-based Type A midrange water reducer according to ASTM C 494 (ASTM, 2008). The air-entraining agent meeting ASTM C 260 (ASTM, 2008) used was MBVR, a neutralized vinsol resin.

5.1.6 Coarse Aggregate

The coarse aggregate used was ASTM C 33 #67 (1 inch maximum size and ¾ inch nominal maximum size) limestone aggregate. The aggregate had a fineness modulus of 0.67 and an absorption rate of 0.86.

Table 4. XRF Results for Silica Fume and ASTM C 1240 Requirements

Chemical (%)	Silica Fume	ASTM C 1240 Requirements
SiO_2	97.90	85% Min
Al_2O_3	0.18	
Fe_2O_3	0.07	
CaO	0.42	
Na_2O	0.12	
MgO	0.21	
P_2O_5	0.12	
SO_3	0.17	
K_2O	0.59	
SrO	0.01	
MnO	0.03	
Cl	0.09	
ZnO	0.08	
BaO	0.02	

5.1.7 Fine Aggregate

The fine aggregate used was ASTM C 33 silica concrete sand. The sand had a fineness modulus and absorption of 2.81 and 1.12%, respectively.

5.2 Mixture Designs and Designations

5.2.1 Mixture Designations

This section will describe the different mixture designations used in the laboratory study that most closely relates to the field project mixture designs. Each number represents the percentage of the material used, followed by the material abbreviation. Materials are abbreviated as shown in Table 5. It is restated here that Type I cement was used in mortar mixtures and Type II/I cement was used in the concrete mixtures.

Table 5. Material Abbreviations

Material	Abbreviation
Type I cement	TI
Type I/II cement	TII
Type IS(20) cement	TIS(20)
Limestone-blended cement	E
Cayuga fly ash	F
Coal Creek fly ash	F2
Grade 120 GGBFS	G120S
Silica fume	SF

5.2.2 Mixture Designs

Different combinations of ternary blended cement mortar and concrete mixtures were created during the Pooled Fund Study and tested for performance properties by students at the University of Utah. Some ordinary and binary portland cement mortar and concrete mixtures were also created for comparison. These mixtures are shown in Table 6 and Table 7. Table 8 shows the mixtures containing the limestone-blended cement and fly ash. Tables 9 and 10 show the mixtures containing GGBFS and silica fume.

5.3 Methods

5.3.1 Mortar Specimens

The mortar bars were tested for ASR and sulfate resistance. The bars were tested for resistance to sulfates according to ASTM C 1012: Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution. The bars were tested for resistance to ASR according to ASTM C 1567:

Table 6. Control Mixtures for Mortar Specimens

Mixture ID
100TI
80TI/20F
80TI/20F2
65TI/35G120S
100TIS(20)
100E

Table 7. Control Mixtures for Concrete Specimens

Mixture ID
100TII
80TII/20F
80TII/20F2
65TII/35G120S
100TIS(20)
100E

Table 8. Mortar and Concrete Mixtures Containing Limestone-blended Cement and Class F Fly Ash

Mixture ID
80E/20F
80E/20F2

Table 9. Mortar Mixtures Containing GGBFS and Silica Fume

Mixture ID
65TI/35GGBFS
62TI/35GGBFS/3SF
65TIS(20)/35GGBFS
97TIS(20)/3SF

Table 10. Concrete Mixtures Containing GGBFS and Silica Fume

Mixture ID
65TII/35GGBFS
62TII/35GGBFS/3SF
65TIS(20)/35GGBFS
97TIS(20)/3SF

Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method). Hanson et al. (2010) completed a study investigating the ASR of ternary blended cements. The research results related to the field mixtures will be presented in this thesis.

5.3.2 Concrete Specimens

Concrete specimens were tested for fresh properties and early performance properties. This thesis will focus on the concrete specimens tested for strength gain, linear shrinkage, and resistance to chloride-ion penetration. Strength gain was tested according to ASTM C 39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Linear shrinkage was tested following ASTM C 157: Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete. Resistance to chloride-ion permeability was tested according to ASTM C 1202: Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride-ion Penetration. Hammond (2010) completed a study including the chloride-ion penetration resistance of ternary blended cements. Some of his data will be presented in this thesis.

CHAPTER 6

FIELD TERNARY BLENDED CEMENT CONCRETE MIXTURES

Three field projects have been completed for Phase III of the Pooled Fund Study. This thesis primarily addresses the results of these projects located in Salt Lake City, Utah; Lawrence, Kansas; and Battle Creek, Michigan. Each project used a unique ternary blended cement concrete mixture. The specimens that were collected during construction vary depending on the project site. Each field project will be described in the remainder of this section.

The environmental impact of the ternary mixtures will be based on the carbon dioxide emissions associated with the mixture. The environmental advantages of these mixtures will be addressed in Chapter 9. Cost analysis of ternary blended cement mixtures will be presented in Chapter 10.

6.1 Concrete Pavement Salt Lake City, Utah

This project was unique because a portion of the pavement was a binary blended cement concrete mixture and a portion was a ternary blended cement concrete mixture. This allowed for comparisons to be made between the two mixtures. The binary blended cement concrete pavement will be referred to as the control section of the pavement. The contractor paid the same amount per yd^3 for both concrete mixtures. This project was cast in warm weather conditions.

6.1.1 Location

The pavement was placed along 10400 South between Bangerter Highway (A) and Redwood Road (B). The control mixture was placed from Bangerter Highway to 3350 West, and from 3200 West to Redwood Road. The ternary mixture was placed in the two westbound travel lanes from 3350 West to 3200 West. The locations of the project and the ternary pavement are shown in Figure 1. The stars on the figure indicate the location of the ternary blended cement concrete pavement.

6.1.2 Mixture Design

The control pavement used a 7-sack mixture with a local Type II/V blend with 25% Class F fly ash as a portion of the cementitious material. The ternary blend

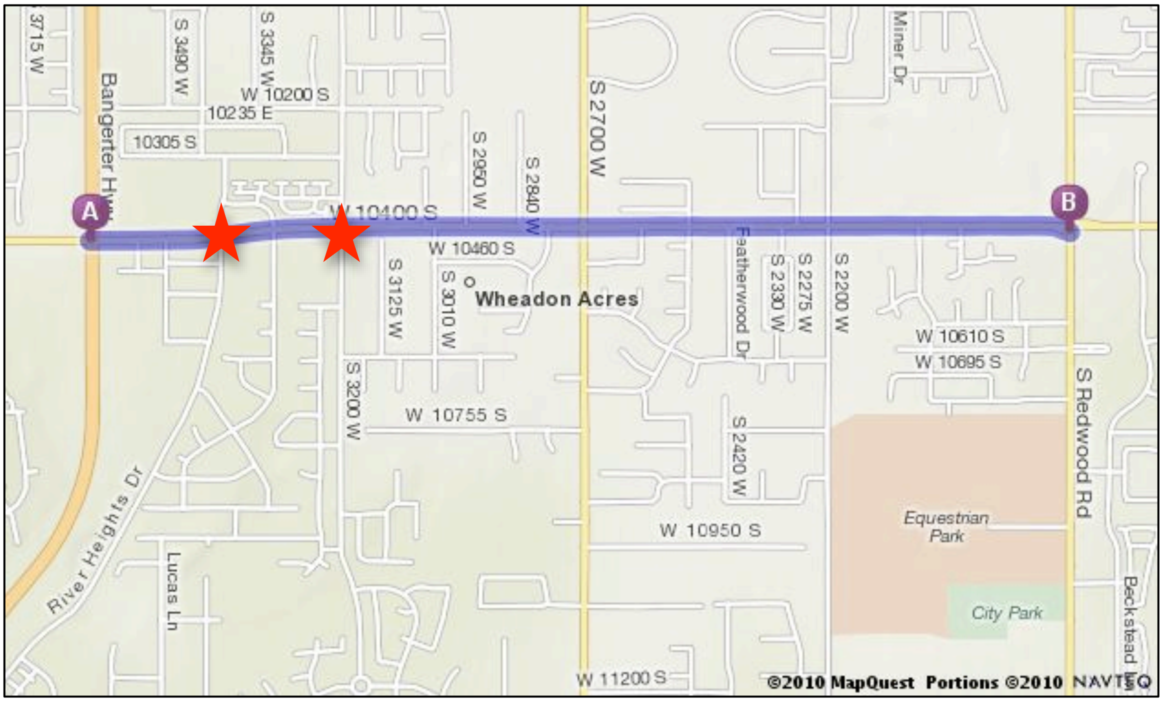

Figure 1. Location of Utah Pavement and Location of Ternary Mixture Portion of Pavement

used a performance-based cement meeting ASTM C 1157 containing 10% ground limestone flour. The C 1157 cement used the same clinker as the control cement and blended it with 10% limestone flour. 25% of the C 1157 cement (E) was replaced with the Class F fly ash. Table 11 shows the mixture designs for the control and ternary concrete pavements.

6.1.3 State Specifications for Cement Content and SCM Replacement

Utah requires a minimum cementitious material content of 470 lbs/yd^3 for pavements and 564 lbs/yd^3 for bridge decks (UDOT, 2008). They also limit the amount of Class F fly ash replacement to a minimum of 20%. Maximum limits for Class F fly ash are specified at 30% if the fly ash is replacing a blended hydraulic cement. Class C fly ash is not permitted in Utah. Other pozzolans are permitted as long as they expand less than 0.1% in ASR testing according to ASTM C 1567. The mixture designs used for the Utah pavement met the state requirements.

Table 11. Mixture design for Control and Ternary Portion of Salt Lake City, Utah Pavement

Mixture design W/C 0.37		Control (75TII-V/25FA)	Ternary (75E/25FA)
Total cementitious materials	(lb/yd^3)	657.5	657.5
Type II/V cement	(lb/yd^3)	493.0	0.0
ASTM 1157 limestone blended cement	(lb/yd^3)	0.0	493.0
Fly ash	(lb/yd^3)	164.5	164.5
Water	(lb/yd^3)	245.0	245.0
Fine aggregate	(lb/yd^3)	1373.0	1373.0
Coarse aggregate #67	(lb/yd^3)	1022.0	1022.0
Coarse aggregate #467	(lb/yd^3)	498.0	498.0
Air entraining agent	(oz/yd^3)	5.9	5.9
Midrange water reducer	(oz/yd^3)	30.2	30.2

6.1.4 Sampling and Testing

Specimens were collected during the casting of the control pavement on May 18, 2009. Times of sampling and ambient weather conditions during the control casting are shown in Table 12. Specimens were collected during the casting of the ternary pavement on July 28, 2009. Table 13 shows the times of sampling and ambient weather conditions for the ternary concrete specimens. Slump, air content, and concrete temperature were collected during each sampling. The average slump, air content, and concrete temperature for the control and ternary casting are presented in Table 14.

Specimens were collected and cured in laboratory conditions. Specimens were collected from the control and the ternary pavements for strength gain, and rapid chloride permeability (CIPT). Shrinkage specimens were collected for the ternary pavement only. Tests were performed according to the ASTM standards described in Chapter 5.

6.1.5 Qualitative Comments

The edges of the pavement were clean and held their shape very well. The suppliers had no problems achieving slump. The paving crew was impressed with the workability of the mixture. The finishing crew noticed no difference between the ternary blended cement concrete mixture and the control mixture.

6.2 Concrete Bridge Deck Lawrence, Kansas

The Kansas bridge deck is a 3-span concrete bridge deck with steel girders. The concrete was cast in cool to moderate conditions.

Table 12. Conditions of Sample Collection for Control Mixture Specimens in Salt Lake City, Utah

Sample Date	Sample Time	Comments	Ambient Temperature
May 18, 2009	10:00 am	Sunny, warm. Sample taken from outbound truck at ready mix plant.	~75° F
May 18, 2009	10:45 am	Sunny, warm. Sample taken from outbound truck at ready mix plant.	~75°F

Table 13. Conditions of Sample Collection for Ternary Mixture Specimens in Salt Lake City, Utah

Sample Date	Sample Time	Comments	Ambient Temperature
July 28, 2009	5:49 am	Warm. Sample taken from outbound truck at ready mix plant.	~60° F
July 28, 2009	6:12 am	Warm. Sample taken from outbound truck at ready mix plant.	~60°F
July 28, 2009	6:41 am	Warm. Sample taken from outbound truck at ready mix plant.	~60°F
July 28, 2009	7:15 am	Warm. Sample taken from outbound truck at ready mix plant.	~60°F

Table 14. Slump, Air Content, and Temperature for Control and Ternary Concrete Mixtures for Samples in Salt Lake City, Utah

Test	Control Mixture	Ternary Mixture
Slump (in)	1.25	1.13
Air Content (%)	5.6	5.4
Concrete Temperature (°F)	69	77

6.2.1 Location

The bridge deck is located on US-59. It is a northbound bridge located just south of US-56. The location of the bridge deck is shown in Figure 2.

6.2.2 Mixture Design

The ternary blended cement mixture was a 5.7-sack mixture. The mixture used a Type I/II cement with 35% GGBFS and 5% silica fume as SCM additions. The SCMs were added on site at the ready mix plant. The mixture design is shown in Table 15.

6.2.3 State Specifications for Cement Content and SCM Replacement

Kansas requires a minimum cementitious material content of 564 lbs/yd^3 for pavements and 480 lbs/yd^3 for bridge decks (KDOT, 2008). Kansas limits the total amount of SCM replacement to 40%. The maximum amount of Class C or Class F fly ash permitted is 25%, GGBFS is limited to 35%, and silica fume is limited from 3% to 7%. The specifications for using SCMs in concrete require trial batching. Strength tests must be performed on specimens created during trial batching. The ternary blend used in the Kansas bridge deck meets all of the state requirements for bridge decks.

6.2.4 Sampling and Testing

Specimens were collected during the casting of the bridge deck on October 28, 2009. The sampling and ambient weather conditions are given in Table 16. Slump, air content, and concrete temperature were collected during sampling. The average slump, air content, and concrete temperature values from the ternary

Figure 2. Location of Kansas Bridge Deck

concrete casting are presented in Table 17. Samples were collected and cured in laboratory conditions. Specimens were collected and tested for compressive strength, CIPT, and compressive strength, and CIPT were tested according to ASTMs described in Chapter 5.

6.2.5 Qualitative Comments

The contractor was impressed with the workability of the lean mixture. Typical mixtures in Kansas use a 2-inch overlay on bridge decks high in silica fume. He preferred using the ternary blend that only required one cast.

Table 15. Mixture Design for Ternary Bridge Deck in Lawrence, Kansas

Mixture design W/C 0.42 5.7-sack mixture		Ternary (60TI-II/35GGBFS/5SF)
Total cementitious materials	(lb/yd^3)	535.0
Portland cement	(lb/yd^3)	321.0
GGBFS	(lb/yd^3)	187.0
Silica fume	(lb/yd^3)	27.0
Water	(lb/yd^3)	225.0
Fine aggregate	(lb/yd^3)	1217.0
Coarse aggregate	(lb/yd^3)	1371.0
Intermediate aggregate	(lb/yd^3)	463.0
Air entraining agent	(oz/yd^3)	4.0
Admixture Type F	(oz/yd^3)	1.0
Admixture Type C	(oz/yd^3)	1.0
Admixture Type D	(oz/yd^3)	1.0

Table 16. Conditions of Sample Collection for Ternary Bridge Deck in Lawrence, Kansas

Sample Date	Sample Time	Comments	Ambient Temperature
October 28, 2009	8:20 am	Sample taken at truck discharge	~48^{o}F
October 28, 2009	10:50 am	Sample taken at truck discharge	~57^{o}F

Table 17. Slump, Air Content, and Temperature for Samples in Lawrence, Kansas

Test	Ternary Mixture
Slump (in)	5.4
Air Content (%)	7.3
Concrete Temperature (^{o}F)	62

6.3 Concrete Bridge Deck Battle Creek, Michigan

The Michigan concrete bridge deck was constructed using a 6.4-sack cementitious material mixture with preblended ternary C 595 cement. The cost of this mixture was \$175.00/yd^3. The average cost per cubic yard for a concrete mixture acceptable for a bridge deck ranges from \$135.00/yd^3 to \$200.00/yd^3. This placement was done under winter conditions and cold weather practices.

6.3.1 Location

The location of the bridge deck was on I-94 over riverside drive, between the I-194 and Capital Avenue interchanges. The location of the bridge deck is shown in Figure 3.

6.3.2 Mixture Design

The cement used in this mixture was on demand preblended ternary cement. This blended cement was 71% Type I cement, 25% GGBFS, and 4% silica fume by mass. The cement is preblended at a cement terminal and shipped to the ready mix concrete plant. The cement meets the requirements of ASTM C 595: Blended Hydraulic Cement, and ASTM C 1157: Standard Performance Specification for Hydraulic Cement. The mixture design for the bridge deck is shown in Table 18.

6.3.3 State Specifications for Cement Content and SCM Replacement

Michigan requires a minimum cementitious material content of 526 lbs/yd^3 for pavements and 611 lbs/yd^3 for bridge decks (MDOT, 2003). The total permitted amount of SCM is 40% of the total cementitious material. The maximum amount of fly ash that can be used as a cementitious material is 25%. GGBFS is permitted

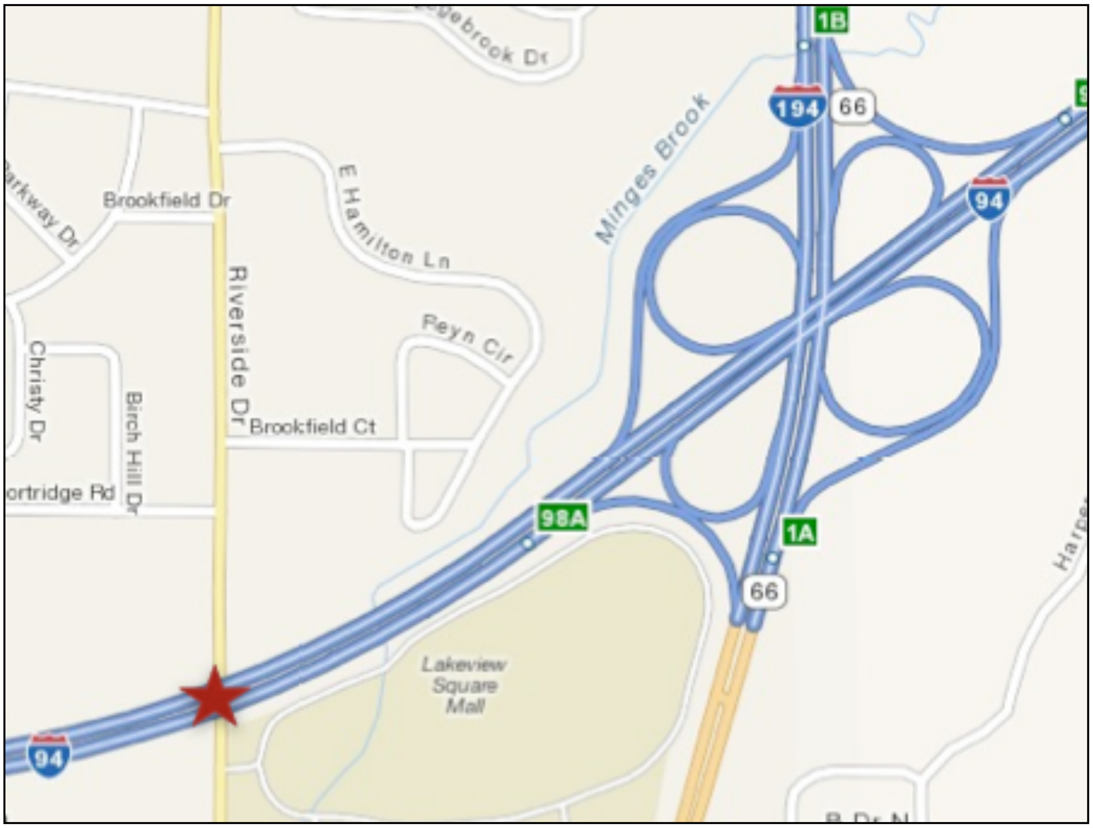

Figure 3. Location of Michigan Bridge Deck

up to 35% of the cementitious material. If the SCM content exceeds these limits, a trial batch must be created and tested for 28-day compressive strength, slump, and air content.

The mixture design used for the Michigan bridge deck does not meet the 611 lbs/yd^3 limit, but met all of the technical specifications.

6.3.4 Sampling and Testing

The specimens were collected during the casting on December 18, 2009. The specimens were taken from the sixth truck and the ambient temperature was 33° F. Specimens were collected and cured in laboratory conditions. Samples were tested for strength gain, CIPT, and shrinkage according to the ASTMs described in Chapter

5. Temperature sensors were also placed in the deck prior to the pour and curing temperatures were monitored. Slump, air content, and concrete temperature were collected during sampling and are shown in Table 19.

6.3.5 Qualitative Comments

The ternary blended bridge deck performed well under cold weather curing practices.

Table 18. Mixture Design for Ternary Bridge Deck in Battle Creek, Michigan

Mixture design W/C 0.46		Ternary (71TI/25GGBFS/4SF)
Total cementitious materials	(lb/yd^3)	600.0
Portland cement	(lb/yd^3)	426.0
GGBFS	(lb/yd^3)	150.0
Silica fume	(lb/yd^3)	24.0
Water	(lb/yd^3)	270.0
Fine aggregate	(lb/yd^3)	1234.0
Coarse aggregate MDOT 6AA	(lb/yd^3)	1435.0
Coarse aggregate MDOT 29A	(lb/yd^3)	299.0
Air entraining agent	(oz/yd^3)	11.4
Admixture Type D	(oz/yd^3)	18.0
Admixture Type MR	(oz/yd^3)	64.0

Table 19. Slump, Air Content, and Concrete Temperature for Samples in Battle Creek, Michigan

Test	Ternary Mixture
Slump (in)	4.0
Air Content (%)	5.1
Concrete Temperature (^{o}F)	81

CHAPTER 7

RESULTS

This section will include the results from the laboratory trial batches and from the field sampled concrete. Because ASR and sulfate tests were tested on mortar bars, specimens could not be taken from the field. Therefore, no direct comparisons can be made between the laboratory and field specimens for ASR and sulfate tests. However, the performance in the field would likely be similar to the performance of the laboratory trial batches of mortar bars.

The data collected from the field specimens will be displayed with the concrete specimen laboratory data in order to observe trends between different SCM combinations. The data gathered from the field specimens will be designated as UT, KS, and MI followed by the abbreviated mixture design. The field data will be placed with the laboratory data with similar mixture designs. However, it should be noted that the SCMs used in the field are locally obtained and not from the same source as those used in the laboratory tests. Therefore, exact behavior of the mixtures will vary, but trends can still be observed. Control mixtures of ordinary and binary blended cements will also be displayed. In cases where there are no laboratory data available for comparison, the field data will be displayed alone.

7.1 Mortar specimens

7.1.1 Sulfate Expansion

Table 20 displays the sulfate expansion values at 6, 12, and 15 months of mixtures containing limestone cement and Class F fly ash. Table 21 displays the sulfate expansion values of mixtures containing silica fume and grade 120 GGBFS. The values are the average of 6 specimens. According to ASTM C 1012, the maximum allowable expansion for moderate sulfate resistance is 0.10% at 6 months. The maximum allowable expansion for high sulfate resistance is 0.05% and 0.10% at 6 and 12 months, respectively (ASTM, 2008). A discussion of the test results is presented in Chapter 8.

7.1.2 ASR Expansion

Tables 22-23 show the values of expansion at 14 days from ASR. Methods presented in ASTM C 1567 were followed with the exception of the fine aggregate. Fine aggregate was a blend of 25% highly reactive Pyrex glass and 75% sand by mass. This combination was used in order to increase the ASR potential. An expansion of less than 0.10% is considered a passing value (ASTM, 2008). A discussion of the test results is presented in Chapter 8.

7.2 Concrete Specimens

7.2.1 Strength Development

The compressive strengths (f'_c) of each specimen at 7 and 28 days are shown in Tables 24-25. The compressive strength is the average of three concrete cylinders.

Table 20. Sulfate Expansion for Mixtures Containing Limestone-blended Cement and Class F Fly Ash

Mixture ID	Expansion (%) 6 months	12 months	15 months
Laboratory Control Mixtures			
100TI	0.31	0.50	0.50
100E	0.05	0.08	0.11
80TI/20F	0.03	0.04	0.04
80TI/20F2	0.04	0.05	0.06
Laboratory Ternary Mixtures			
80E/20F	0.03	0.03	0.05
80E/20F2	0.04	0.04	0.05

Table 21. Sulfate Expansion for Mixtures Containing GGBFS and Silica Fume

Mixture ID	Expansion (%) 6 months	12 months	15 months
Laboratory Control Mixtures			
100TI	0.31	0.50	0.50
100TIS(20)	0.04	0.06	0.07
65TI/35G120S	0.03	0.04	0.07
Laboratory Ternary Mixtures			
62TI/35GGBFS/3SF	0.02	0.03	0.03
65TIS(20)/35GGBFS	0.02	0.02	0.02
97TIS(20)/3SF	0.03	0.04	0.04

Table 22. ASR Expansion for Mixtures Containing Limestone-blended Cement and Class F Fly Ash

Mixture ID	Expansion (%)
Laboratory Control Mixtures	
100TI	0.55
100E	0.62
80TI/20F	0.10
80TI/20F2	0.24
Laboratory Ternary Mixtures	
80E/20F	0.05
80E/20F2	0.04

The 28/7 f'$_c$ ratio is also shown. A value of at least 1.25 for the 28/7 day f'$_c$ ratio is desirable. A discussion of the test results is presented in Chapter 8.

7.2.2 Shrinkage

Figures 4-5 show the shrinkage trend of specimens for up to 28 days. Values less than 500 με are desirable for linear shrinkage. The shrinkage results are the average of two specimens. Field specimens in Kansas and Michigan were not tested for shrinkage. However, the laboratory results of similar mixtures are still presented here. A discussion of the test results is presented in Chapter 8.

7.2.3 Chloride-ion Penetration

Chloride penetration of a concrete mixture was estimated using ASTM C1202. The test method determines a concrete mixture's electrical conductance by subjecting a specimen to a 60 volt DC for 6 hours. The total charge that is passed through the specimen is correlated to ponding studies that test for chloride penetration. The rapid test is faster and more convenient than ponding studies.

Table 23. ASR Expansion for Mixtures Containing GGBFS and Silica Fume

Mixture ID	Expansion (%)
Laboratory Control Mixtures	
100TI	0.55
100TIS(20)	0.17
65TI/35G120S	0.20
Laboratory Ternary Mixtures	
62TI/35GGBFS/3SF	0.02
65TIS(20)/35GGBFS	0.03
97TIS(20)/3SF	0.06

Table 24. Compressive Strengths at 7 and 28 days for Mixtures Containing Limestone-blended Cement and Class F Fly Ash

	f'$_c$ (psi)		f'$_c$ ratio
Mixture ID	7 Day	28 Day	28 day/7 day
Laboratory Control Mixtures			
100TI	5359	6354	1.19
80TII/20F	5381	7260	1.35
80TII/20F2	5321	6717	1.26
100E	4932	5881	1.19
Laboratory Ternary Mixtures			
80E/20F	4925	6148	1.25
80E/20F2	4069	5229	1.29
Field Mixtures			
UT 75TII-V/25F	3495	4454	1.27
UT 75E/25F	3303	5396	1.63

Table 25. Compressive Strengths at 7 and 28 days for Mixtures Containing GGBFS and Silica Fume

Mixture ID	f'$_c$ (psi) 7 Day	f'$_c$ (psi) 28 Day	f'$_c$ ratio 28 day/7 day
Laboratory Control Mixtures			
100TII	5359	6354	1.19
100TIS(20)	3100	5215	1.68
65TII/35G120S	5568	7955	1.43
Laboratory Ternary Mixtures			
62TII/35GGBFS/3SF	4902	6466	1.32
65TIS(20)/35GGBFS	2171	5176	2.38
97TIS(20)/3SF	4491	7315	1.63
Field Mixtures			
KS 60TI-II/35GGBFS/5SF	3225	5640	1.75
MI 71TI/25GGBFS/4SF	6180	8380	1.36

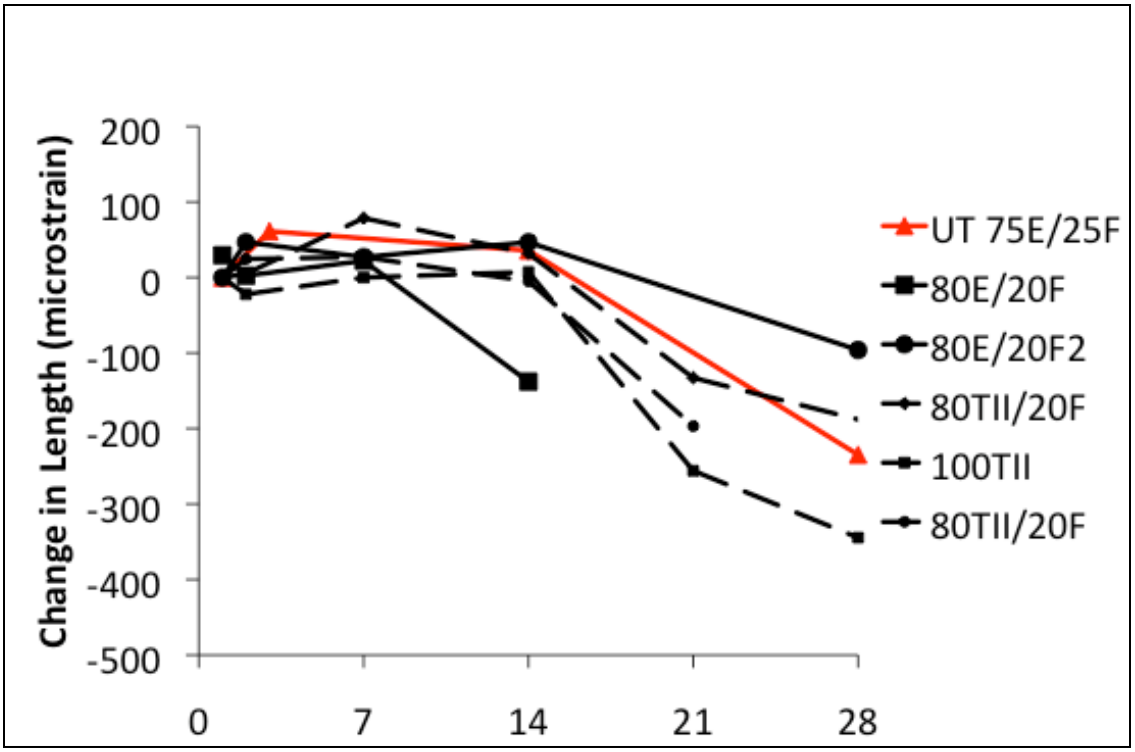

Figure 4. Linear Shrinkage for Mixtures Containing Limestone-blended Cement and Class F Fly Ash

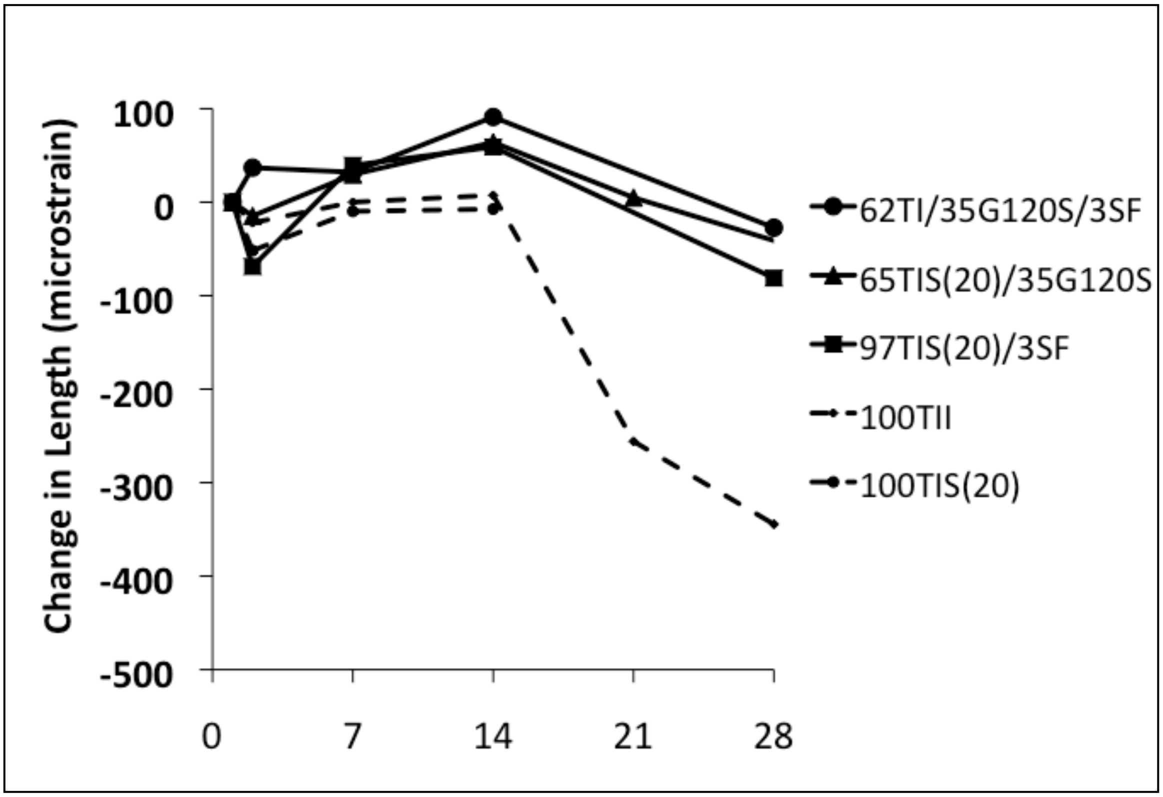

Figure 5. Linear Shrinkage for Mixtures Containing GGBFS and Silica Fume

All of the laboratory specimens were tested for chloride-ion penetration after wet curing for 14 days and dry curing for 77 days. The charge passed for the laboratory specimens is the average of 4 samples. The Utah specimens were tested after wet curing for 14 days and dry curing for 77 days. The Kansas specimens were tested after wet curing for 56. The Michigan specimens were tested after wet curing for 56 days. Curing regimes were consistent with state specifications. Each of these procedures allows for longer hydration times to better estimate the properties of the mature concrete. Table 26 summarizes the relationship between the charge passed during the test and the chloride penetration of the concrete (ASTM, 2008). Tables 27 and 28 give the data for the CIPT of all the laboratory and field mixtures. A discussion of the test results is presented in Chapter 8.

Table 26. Relationship Between Charge Passed and Chloride Penetration

Charge passed (coulombs)	Chloride penetration
0-1000	Very low
1000-2000	Low
2000-4000	Moderate
4000 +	High

Table 27. CIPT Results for Mixtures Containing Limestone-blended Cement and Class F Fly Ash

Mixture ID	Charge Passed (coulombs)
Laboratory Control Mixtures	
100TII	4243
100E	5890
80TII/20F2	2200
Laboratory Ternary Mixtures	
80E/20F	4530
80E/20F2	4169
Field Mixtures	
UT 75TII-V/25F	463
UT 75E/25F	1862

Table 28. CIPT Results for Mixtures Containing GGBFS and Silica Fume

Mixture ID	Charge Passed (coulombs)
Laboratory Control Mixtures	
100TII	4243
100TIS(20)	4355
65TII/35G120S	1348
Laboratory Ternary Mixtures	
62TII/35GGBFS/3SF	984
65TIS(20)/35GGBFS	1567
97TIS(20)/3SF	935
Field Mixtures	
KS 60TI-II/35GGBFS/5SF	480
MI 71TI/25GGBFS/4SF	868

7.2.4 Curing Temperatures

Temperature sensors were placed in the Michigan bridge deck prior to pouring in order to monitor curing temperatures. Sensors were placed in the middle at the top and bottom of the mat, and at the top and bottom of the fascia. There was also a sensor placed over the beam. Ambient temperature was also recorded. The data were gathered for 7 days. The recorded temperatures are shown in Figure 6. The difference in temperature did not exceed 10 ◦F at any time between top and bottom mats, and the maximum temperature did not exceed 110 ◦F. A discussion of the results is presented in Chapter 8.

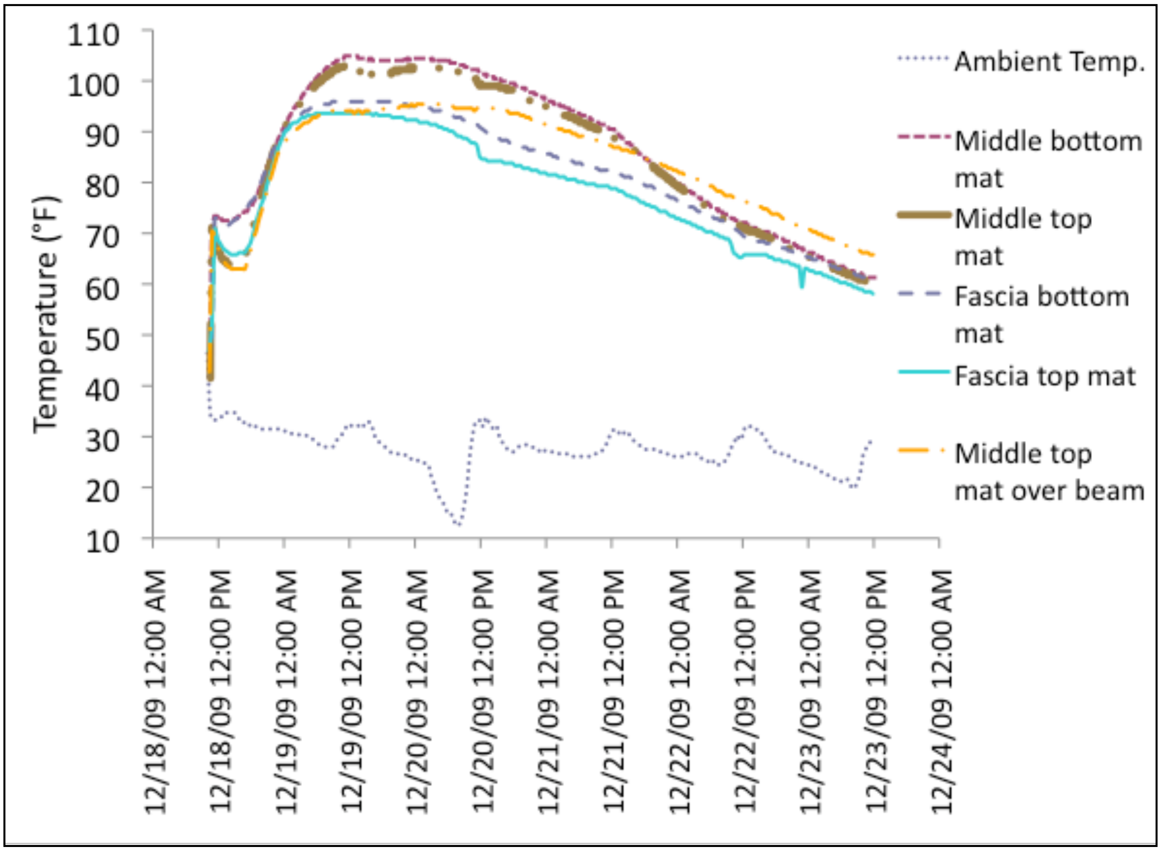

Figure 6. Curing Temperatures for Michigan Bridge Deck

CHAPTER 8

DISCUSSION OF RESULTS

8.1 Mortar Results

8.1.1 Sulfate Expansion Results

The only ordinary portland cement mixture was the 100TI. ASTM C 150 Type I cement is not considered to have any significant resistance to sulfate attack. The 100TI mixture expanded more than the permissible value within 6 months. The change in length of 0.31% had already exceeded the permissible value of 0.10% for moderate sulfate attack.

The other control mixtures performed better than the ordinary portland cement concrete mixture. The 100TIS(20) had a high resistance to sulfate with a 12-month expansion of 0.06%. The 100E blend had a 6-month expansion of 0.05%. The addition of limestone flour to the Type II/V cement does not help reduce sulfate expansion, but maintains a high sulfate resistance standard (HS). The 80TI/20F2 also met the HS standard with an expansion of 0.06%. The 65TI/35GGBFS performed even better with a 15-month expansion of 0.07%. The addition of GGBFS or fly ash consistently made Type I cement highly resistant to sulfate attack.

The ternary blended cement mixtures performed better than the ordinary portland cement mixtures. The mixtures containing the limestone-blended cement and Class F fly ash met the standard for HS and would likely perform well in concentrated sulfate environments. The control mixture (100E) had an expansion of 0.05% at 6 months and 0.08% at 12 months. The values of the ternary limestone-blended cement and Class F fly ash mixtures were nearly half of these values. The addition of Class F fly ash reduced the sulfate expansion. The fly ash deprives the pore solution of calcium ions and prevents the aluminosulfate transformations associated with sulfate attack (ACI, 2008).

The GGBFS and silica fume ternary mixtures all met the HS standards. The addition of silica fume to the cement and GGBFS mixtures also reduced the sulfate expansion as compared to the control mixtures. The 65TIS(20)/35GGBFS mixture had the lowest expansion of only 0.02%. The high amount of GGBFS greatly reduced sulfate expansion. This combination of materials is effective in controlling aluminosulfate transformations. Silica fume and GGBFS in combination formed additional CSH, which reduces the pore size in concrete and consumes calcium hydroxide ($Ca(OH)_2$) (ACI, 2008).

8.1.2 ASR Expansion Results

The only control mixture to meet the ASR requirements according to ASTM C 1567 was the 80TI/20F mixture, which had an expansion of 0.10%, the limit for ASR mitigation. The 100E mixture had the highest expansion of 0.62%. The 100TI mixture also had a high expansion of 0.55%. The other control mixtures had moderate expansion ranging from 0.17%-0.24%. The binary mixtures helped reduce ASR expansion with the exception of the limestone-blended cement. The addition of limestone did not reduce ASR expansion.

The ternary mixtures containing Class F fly ash and limestone-blended cement both easily met the 0.10% expansion limit according to ASTM C 1567. The expansion for the 80TI/20F was 0.05% and expansion for 80TI/20F2 was 0.04%. The addition of Class F fly ash to the limestone-blended cement seemed to greatly reduce ASR expansion. This is due to the consumption of $Ca(OH)_2$ by the fly ash through pozzolanic hydration (ACI, 2008).

The ternary mixture containing GGBFS and silica fume had very low expansions at 14 days. The 62TI/35GGBFS/3SF had an expansion of 0.02%. The addition of silica fume to the binary mixture of 65TI/35GGBFS greatly reduced expansion. The 65TIS(20)/35GGBFS had an expansion of 0.03%. The 97TIS(20)/3SF had an expansion of 0.06%. Both of these ternary mixtures had lower expansions than the 100TIS(20) mixture. The addition of GGBFS or silica fume seemed to reduce ASR expansion.

8.2 Concrete Results

8.2.1 Strength Development

Compressive strength ratios (28 day/7 day) greater than 1.25 are desirable. This ratio is an indication of the speed of hydration. Slower hydration leads to a more refined microstructure. Compressive strength ratios that are less than 1.25 indicate higher strength gain before 7 days. Accelerated strength gain leads to more cracking and higher permeability.

State specifications generally do not specify any relationship between 7 and 28-day strengths. Instead, a minimum 28-day strength is specified. Table 29 shows the state specified 28-day strengths for Utah, Kansas, and Michigan. Each of the

Table 29. State Requirements for 28-day Compressive Strength

State	Year of Specification	Required Minimum 28-day Strength (psi)
Utah	2008	3000 (pavement) 4000 (bridge deck)
Kansas	2008	4000 (bridge deck and pavement) 5000 (when silica fume is used)
Michigan	2003	3500 (pavement) 4000 (bridge deck)

mixtures tested for strength gain met the requirements for all pavement and bridge deck specifications.

The control mixture using 100% Type I cement and the control mixture using 100% of the limestone-blended cement had compressive strength ratios of less than 1.25. The blended and binary control mixtures had compressive strength ratios greater than 1.25. The mixture containing 100% TIS(20) and the mixture containing 35% GGBFS both had the highest ratios of 1.68 and 1.43, respectively.

The mixtures containing limestone-blended cement and Class F fly ash had compressive strength ratios greater than 1.25. The values ranged from 1.25 to 1.63. The Utah ternary blend had the highest compressive strength ratio. Fly ash tends to slow down early age strength gain but boosts later age strength. This is because the pozzolanic behavior starts later than the hydration of the cement, and continues even after the cement stops hydrating (ACI, 2008). The mixtures containing limestone-blended cement and Class F fly ash followed this trend.

The mixtures containing GGBFS and silica fume, like those used in the Kansas and Michigan field projects, had compressive strength ratios greater than 1.25. The values ranged from 1.32 to 2.38. The mixture containing Type TIS(20) and GGBFS had the highest strength ratio. This ratio of 2.38 was the result of the high mass of GGBFS (48%) in the mixture, which tends to retard early strength and boost later age strength (ACI 2008). The Kansas bridge deck mixture design had a ratio of 1.75, and the Michigan bridge deck mixture design had a ratio of 1.36.

The Michigan bridge deck had much higher strengths at 7 and 28 days than the other mixtures. This is possibly because the cement was preblended at the cement plant. This allows the cement plant to optimize the gypsum content, which controls the rate of hydration. This is also a result of the amount of cementitious materials in the mixture. The amount of cementitious materials could have been reduced and the mixture still would have met the technical specifications.

8.2.2 Shrinkage

At 28 days, linear shrinkage should remain less than 500 με (0.05% change in length) (ACI, 2008). This indicates that the concrete will not be highly susceptible to drying shrinkage cracking. All of the mixtures tested had a change in length of less than 500 με. The control mixtures experienced the most shrinkage. The 100TI mixture had the highest change in length at 28 days at about -344 με. The binary control mixtures performed slightly better than the ordinary portland cement mixture.

The mixtures containing the limestone-blended cement and the Class F fly ash all had a change in length of less than 500 με. The control mix of 100E had a change in length of -221 $\mu\varepsilon$. The ternary blends containing Class F fly ash change in lengths ranged from -95 $\mu\varepsilon$ to -234 $\mu\varepsilon$. The 80E/20F mixture was not tested at 28 days, but had a change in length of -137 $\mu\varepsilon$ at 14 days. The addition of fly ash to the limestone-blended cement did not greatly change the amount of shrinkage that occurred. The Utah pavement had a change in length of -234 $\mu\varepsilon$. This meets the ASTM requirement for linear shrinkage (ACI, 2008).

The GGBFS and silica fume mixtures experienced very little shrinkage. The Kansas and Michigan bridge decks were not tested for linear shrinkage. However, it is reasonable to assume that they would behave similarly to the laboratory data. At 28 days, the values ranged from -27 $\mu\varepsilon$ to -81 $\mu\varepsilon$. These values are very low and suggest that little to no shrinkage cracking will occur.

8.2.3 Chloride-ion Penetration

Resistance to chloride penetration is particularly important for structures that are reinforced. Chlorides travel through the pore structure in the concrete from diffusion, absorption, and freely through cracks and cause the steel reinforcement to corrode. Kansas specifies a maximum charge passing of 3500 coulombs. Utah and Michigan do not specify chloride penetration in their specifications but targeted a charge of less than 2000 coulombs for the field studies.

The control mixtures had charges ranging from 1800 to 5890. The ordinary Type II cement, limestone-blended cement, and Type TIS(20), all had high charges, indicating a high chance of chloride penetration. The 80TII/20F2 and 65TII/35GGBFS had low charges, indicating a low chance of chloride penetration.

The limestone-blended cement and Class F fly ash mixtures had charges passing from 1800 to 4500. The control mixture for the Utah pavement had a much lower charge of only 463. The addition of limestone to the cement clinker did not improve the resistance to chloride penetration. The CIPT results were improved when fly ash was added to the limestone-blended cement. Since pavements are not heavily reinforced, resistance to chloride penetration is not a major design factor. The ternary blend used for the Utah is ideal for a pavement, but would not be the best mixture for a bridge deck.

The GGBFS and silica fume mixtures had charges ranging from 480 to 980. The 65TIS(20)/35GGBFS mixture had a charge of 1500 coulombs. The addition of silica fume in a mixture improved the resistance to chloride permeability. The GGBFS and silica fume mixtures all had a very low charges pass, and would be effective in reducing chloride permeability.

The Kansas bridge deck had a charge passing of 480 coulombs. The mixture met the state specifications and would reduce chloride permeability. The Michigan bridge deck had a charge passing of 868 coulombs. There is no specification for chloride penetration in Michigan, but there is a very high resistance to chloride penetration in this mixture.

8.2.4 Curing Temperatures

The sensors were placed in various locations throughout the Michigan bridge deck. Some of the sensors were placed in the middle of the deck, and others closer to the outer edge. There should not be a large difference in temperatures throughout the bridge deck. A high range in temperatures suggests that thermal cracking could occur. The greatest difference in temperatures during the curing of the Michigan bridge deck occurred around the 3rd and 4th day. The maximum temperature difference between the middle and the top of the deck was only about 10°F, and the maximum temperature did not exceed 110°F. This indicates that thermal cracking would not likely occur.

CHAPTER 9

CO_2 SIGNATURES OF TERNARY BLENDED CEMENT MIXTURES

Marquez, Hanson, and Tikalsky (2008) presented a method on determining the amount of carbon dioxide emissions for a concrete mixture. There are three things that contribute to the concrete industry's carbon dioxide emissions: the calcination of the limestone to create cement clinker, the emissions related to grind the clinker into cement, and the carbon dioxide emissions from transporting the limestone and other materials to the cement plant. There are also carbon emissions associated with transporting the materials to the project site; however, those will not be considered here. Unlike cement, SCMs do not require calcination. This significantly reduces the amount of CO_2 that is emitted. This chapter will use the methods presented by Marquez et al. to determine the CO_2 signatures of the mixtures presented in this paper.

9.1 Summary of CO_2 Intensities by Material

It is reasonable to assume that the CO_2 emitted by transporting materials to the cement plant is the same for all three state projects and for the laboratory mixtures. Cement clinker can be produced in either a wet kiln or a dry kiln. Wet kilns emit about 1.02 pounds of CO_2 emissions and dry kilns emit about 0.9 pounds of CO_2 emissions (Marquez et al. 2008). This paper will include the CO_2 signatures for cement created in both types of kilns. The CO_2 that is emitted per pound of cementitious material is shown in Table 30. It will be assumed that the CO_2 from Class F fly ash will be the same for all ashes used in this paper. The CO_2 signatures for mixtures presented in the previous chapters are shown in Table 31.

9.2 Discussion of Carbon Dioxide Intensities

The ternary blended cements lower the amount of carbon dioxide emitted from concrete mixtures. This is particularly important for projects that use a lot of concrete, such as pavements.

Consider the Utah pavement project. Approximately 9000 feet were paved in the binary control mixture, and 1000 feet were paved with the ternary blended cement mixture. The pavement had two lanes for traffic in each direction. The ternary blend was paved only in the westbound travel lanes. Approximately one cubic yard of concrete paved one foot of the two-lane road, so about two cubic yards of concrete paved one foot for all four lanes of the road. This means it took about 20,000 yd^3 of concrete to complete the project. For a 7-sack mixture (658 lbs cementitious material/yd^3), the total amount of cement for this project was about 6,500 tons. Using the appropriate dry kiln signatures from Table 31 for the Utah control and ternary mixtures, it is estimated that about 4,450 tons of CO_2 were emitted from the project. Had the project been 100% portland cement, the total emissions would have been about 5,920 tons. These numbers become even more significant on larger pavement projects. The Utah pavement project presented in this paper was only about 2 miles.

Table 30. Carbon Dioxide Emissions by Material

Material	CO_2 emissions (lb/lb material)	
Silica fume	0.030	
Grade 120 GGBFS	0.032	
Class F fly ash	0.012	
	Dry kiln	Wet kiln
Portland cement	0.90	1.02
Limestone blended cement (10% limestone)	0.81	0.92
TIS(20) cement (20% GGBFS)	0.69	0.78

Table 31. Carbon Dioxide Emissions for all Mixtures

Mixture ID	Dry CO_2 emissions (lb/lb cementitious material)	Wet CO_2 emissions (lb/lb cementitious material)
100TI	0.90	1.02
100TIS(20)	0.69	0.78
100E	0.81	0.92
80TI/20F	0.72	0.82
65TI/35G120S	0.53	0.47
80E/20F	0.65	0.74
UT 75TII-V/25F	0.68	0.77
UT 75E/25F	0.61	0.70
62TII/35GGBFS/3SF	0.57	0.64
65TIS(20)/35GGBFS	0.45	0.52
97TIS(20)/3SF	0.66	0.76
KS 60TI-II/35GGBFS/5SF	0.55	0.62
MI 71TI/25GGBFS/4SF	0.65	0.73

Larger interstate projects would require many miles of pavement with more travel lanes. Using less cementitious material in the mixture can even further reduce these numbers. Assume a 5.5 sack mixture (517 lbs cementitious material/yd^3) for the Utah concrete pavement. If the project reduced the amount of cementitious materials to 517 lbs/yd^3, the total carbon dioxide emissions would have been about 3500 tons.

CHAPTER 10

ECONOMIC ANALYSIS OF TERNARY BLENDED CEMENT MIXTURES

10.1 Initial Costs

The initial cost for the ternary blended cement mixture used for the Utah pavement was the same as the binary blend. The contractor and paving crew noticed no difference in the workability or finishing of the ternary blend compared to the binary blend. No technical advantages were sacrificed, and the CO_2 signature determined in Chapter 9 was reduced by 0.07 lbs/lbs cementitious material.

The initial cost for the ternary blended cement mixture used for the Michigan bridge deck was \$175.00/yd^3. This falls in the typical range of \$135.00/yd^3 to \$200.00/yd^3 (MDOT, 2010). The contractors were pleased with the performance of the ternary blended cement bridge deck during a cold-weather cast.

The initial cost of the Kansas bridge deck is unknown. However, typical bridge decks in Kansas use two different concrete mixtures per bridge. The first mixture is usually an ordinary or binary portland cement mixture. This mixture is capped with a mixture high in silica fume. This requires the contractor to have a construction crew for two separate castings. Only having to cast a concrete bridge deck once will cut the labor costs in half.

10.2 Increased Durability

It is reasonable to believe that the increased durability of ternary blended cement mixtures will extend the life of concrete used in transportation projects. This will likely reduce life-cycle costs typically associated with the upkeep of these structures.

The increased durability of ternary blended cement concrete mixtures allows for less cementitious material to be used. Specifications heavily enforce 28-day strength. Although fly ash and GGBFS tend to slow early age strength gain, they boost strength prior to 28 days. This allows 28-day age strength to be met using less cementitious materials. If necessary, early age strength can be achieved using metakaolin or silica fume.

The Michigan bridge deck used a 6.4 sack cementitious material mixture. Specifications generally require a 6.5 sack mixture. The 28-day strength requirement for a Michigan bridge deck is 4000 psi. The actual 28-day strength of the Michigan bridge deck was over 8000 psi. Even though Michigan used less cementitious materials than the specifications required, the 28-day strength was more than double the requirement. The cementitious materials could have been reduced further. Reducing the amount of cementitious materials in a concrete mixture will reduce the initial cost.

CHAPTER 11

DISCUSSION OF BARRIERS OF IMPLEMENTATION

This section describes some of the barriers that keep ternary blended cement concrete mixtures from being used for pavements and transportation structures.

11.1 Optimization of SCMs and Implementing Ternary Blends

The interaction between SCMs varies depending on the type and source of SCM used. SCMs also interact differently with different types of cements. It is important to create ternary blended cement concrete mixtures that will create long lasting structures. Trial mixture designs using the materials that will be used in the field should be created in the laboratory and tested for performance prior to being used for a project.

Rupnow (2008) studied ternary blended cement mixtures containing fly ash and GGBFS for use in transportation structures. They tested ternary mixtures using different types of cements and admixture combinations. The pozzolans reacted very differently with each of the cements and admixtures. There were not always trends between the different cement types and admixture combinations. This suggests that it is difficult to predict exactly how a mixture will behave without a trial batch that uses the materials that will be used for the project.

Sources of SCMs vary by type. For instance, most sources of silica fume and GGBFS in the United States are on the East Coast. It is important for people in the concrete industry to know which SCMs are practical to use for different locations. Economic and environmental considerations should also be considered when doing initial trial batching for a project.

Convincing the cement and concrete industry to change from using ordinary or binary portland cement mixtures to ternary cement mixtures is challenging. Ternary blends are unfamiliar to most areas of the United States. Using ternary blended cements can appear to have an element of risk. Changing specifications to require or at least include using multiple SCMs in the mixture can help to overcome this issue. Education on using ternary blended cements would reduce some unfamiliarity. Meeting the target specifications for concrete pavements and structures during trial batching when using ternary blended cement mixtures would reduce the sense of risk.

11.2 Specification Limitations

Trial batching can be used to ensure that ternary blended cement mixtures meet all the state specifications. However, some of the state specifications place limits on the amount of SCMs that can replace cement in a mixture. These limits are generally not based on performance and can make it difficult to design a ternary blended cement concrete mixture. The limitations for the state projects used in this paper were presented in Chapter 6.

In some state specifications, the limits placed on SCMs can be overridden if a trial batch is completed and passes the required performance standards. Some states, like Kansas, require trail batching if SCMs are used. Other states, like Michigan, have limits on SCMs but allow them to be overridden if a trail batch is made and tested for performance properties.

State specifications should use SCM content guidelines rather than limits, and require trial batching for all concrete mixtures before every state project. The guidelines would give states a starting point for designing a ternary blended cement mixture. Trial batching could be used to determine optimum combinations of SCMs and test compatibility with the other materials in the mixture.

There are also limitations on how much cementitious material must be used in a mixture. The limitations for cementitious materials for Utah, Kansas, and Michigan were presented in Chapter 6. Chapter 10 discussed the economic advantages of using less cementitious materials in a mixture. If specifications are performance based and require trial batching, the appropriate amount of cementitious materials required can be determined. This will reduce the initial cost of the mixture.

11.3 Supplying SCMs

Fly ash is commonly used in concrete pavements, and many ready mix plants already have at least one additional storage silo for fly ash or another SCM. However, in order to supply a client with a ternary blended cement concrete mixture, the plant will need at least 3 storage silos. A storage silo that holds up to 4800 ft^3 of materials costs around \$40,000. This can be a large expense for a ready mix plant.

Supplying fly ash will lower the cost of materials for a concrete mixture. This allows the ready mix plant to adjust the price of a mixture to satisfy clients while turning a profit. GGBFS is approximately the same price as cement, and will not increase the initial cost of a mixture. If the ready mix plant produces concrete containing fly ash, they could quickly pay off the cost of the silo.

For example, the cost of fly ash is approximately 40% the cost of cement. Assuming cement is $100.00/ton, replacing 25% of a six-sack mixture with fly ash would save $4.50/yd^3. Assuming a truck can carry 10 yd^3 of concrete per trip, the ready mix plant will have paid for the silo after sending out just 890 trucks.

A plant also has the option to supply cements that are preblended with one or more SCMs or to blend them on site. Preblended cements are advantageous because they have been optimized at the cement plant. The cement plant will add the optimum gypsum content for the cement and SCM blend. The cement and SCM particles will also be uniformly distributed. It is difficult to ensure that cement and SCM particles get evenly distributed when mixing on site. However, using pre-blended cements limits the combinations that the plant can supply to a client.

If a ready mix plant has a wide variety of clients, it is likely that the demand of type of cement will also vary. A homebuilder will have different demands than someone working on a state project. A homebuilder will not want to pay for any additional materials and might not need the durability that a state project would require. If a ready mix plant stores SCMs and cement in separate silos they will have a better selection of concrete mixtures for their clients.

11.4 Designing Ternary Blended Cements for Specific Projects

There is no such thing as a “recipe” for a ternary blended cement concrete mixture. States should not develop just one mixture to use for everything. Different projects will require different performance properties. For example, the ternary blended cement mixture for the Utah pavement would not be ideal for a bridge deck. The limestone blended cement and Class F fly ash mixtures had moderate to high chances of chloride permeability. This is perfectly acceptable for a pavement; however, this would not be an optimum mixture for a bridge deck.

There is a need for some initial guidelines to follow when designing ternary blended cements. These guidelines should give information about different SCM combinations and their typical performance. This will give states a starting point for designing a mixture appropriate for their project. The mixtures used in this thesis can be used as a starting point for some ternary blended cement mixtures.

States should also not adopt another state’s mixture design because it worked well for that state. Availability of SCMs varies by location. It can cost a lot of money to transport materials long distances. It also diminishes the environmental benefits of using SCMs as a cement replacement.

For example, silica fume is only produced in plants on the East Coast and Midwest. Figure 7 shows the locations of plants that produced silica fume in February 2010. The locations are listed below.

Figure 7. Locations of Silica Fume Production for February 2010

1. Niagara Falls, New York
2. Beverley, Ohio
3. Alloy, West Virginia
4. Selma, Alabama
5. Mt. Meigs, Alabama

It would not make economic sense for Utah to import silica fume to use in a bridge deck. The closest silica fume source to Salt Lake City, Utah is the plant in Beverley, Ohio. The driving distance from Beverley, Ohio to Salt Lake City, Utah is about 1800 miles. The average cost of silica fume is \$0.20 per pound. The cost to transport a truckload (22 tons) of bagged pellets of silica fume is about \$1.50/mile (Kojundic, 2010). This is only the cost to ship the silica fume. It does not include any costs associated with labor. If 5% of cement was replaced in a 6-sack mix (564 lbs/yd^3 of cementitious material), this would increase the cost of a mixture by about

$43.00/yd^3 of concrete. It would also cost the plant additional labor costs to open the bagged pellets.

The driving distance from the bridge deck in Lawrence, Kansas to Selma, Alabama is only about 780 miles. If 5% of cement was replaced in a 6-sack mix (564 lbs/yd^3 of cementitious material), it would increase the cost of a mixture by about $22.00/yd^3. This is only half of the cost of silica fume in Salt Lake City, Utah. Fly ash and GGBFS are more readily available than silica fume. However, there are still some locations in the United States that do not have access to both of these SCMs. It is important to consider the SCMs that make the most economic and environmental sense that also meet technical specifications.

CHAPTER 12

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the early age concrete properties of ready mix concrete containing ternary blended cement. The concrete was placed in three state projects (Utah, Kansas, and Michigan). The results were compared to specimens with similar mixture designs that were created in the laboratory. The mixture designs and results were also compared to the state specifications to ensure compliance with the requirements of each state. This study also reported the cost factors of ternary mixtures, and carbon dioxide signatures of the ternary mixtures.

The barriers of implementation of using ternary blended cement mixtures for all state projects were discussed. The following conclusions and recommendations are determined for this study:

1. There are no technical barriers that exist when using most ternary blended cement mixtures. The mixtures can be designed to meet state requirements and outperform ordinary portland cement concrete mixtures.
2. Ternary blended cement concrete mixtures greatly reduce the carbon dioxide emissions related to the concrete industry. These mixtures can save over nearly 1500 tons of carbon dioxide from being emitted into the atmosphere for just 2 miles of a 4 lane concrete pavement.

3. The initial cost of a ternary blended cement concrete pavement is dependant on the SCMs used and their proximity to the project location. The initial cost can generally be lowered if fly ash is used. The increased durability of ternary blended cement mixtures allows less cementitious materials to be used. This will reduce initial costs. Life-cycle costs of ternary blended cement mixtures will likely be reduced due to both initial cost and increased durability.
4. The interaction between SCMs varies depending on different materials that are used. Optimum combinations will vary with the selection of materials and relative quantities of each constituent in the concrete mixture. The best way to optimize a ternary concrete mixture is through trial batching using the mixture designs in this thesis, or other successful projects, as a starting point.
5. Convincing the cement and concrete industry to implement using ternary blended cement concrete mixtures can be done through education and updating specifications.
6. Ready mix plants can easily receive a return of their investment of adding additional silos for storage of SCMs if they provide fly ash. If they blend on site, the investment in the silo and associated equipment can be recovered in less than 9000 yd^3 of concrete.
7. Preblended cements can be beneficial because the SCMs are evenly distributed and the gypsum content has been optimized during the cement production. These cements also meet all applicable codes.

8. State specifications often limit the use of SCMs in concrete and are not performance-based. States should update their specification to be performance-based and make it acceptable to design ternary blended cement concrete mixtures. The specifications should also give guidelines that show trends for different combinations of SCMs.
9. There is no such thing as a “recipe” for a ternary blended cement concrete mixture. Different SCMs are appropriate for general use and others for special projects. States should develop guidelines that will give a starting point for designing ternary blended cement mixtures for both cases. Different SCMs are also appropriate for different environments. Each state should use SCMs that best suits the project and its environment.

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