# Development of Performance Properties of Ternary Mixtures: Laboratory Study on Concrete

National Concrete Pavement Technology Center

Tech Center

## Final Report
## March 2011

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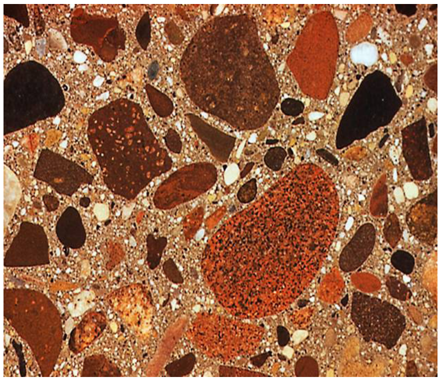
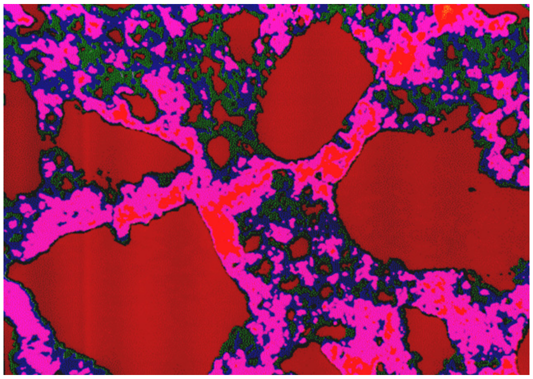
Federal Highway Administration (DTFH61-06-H-00011 (Work Plan 12))
Pooled Fund Study TPF-5(117): California, Illinois, Iowa (lead state), Kansas, Mississippi, New Hampshire, Oklahoma, Pennsylvania, Wisconsin, and Utah; the Portland Cement Association; Headwaters Resources; the American Coal Ash Association; and the Slag Cement Association





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The preparation of this (report, document, etc.) was financed in part through funds provided by the Iowa Department of Transportation through its "Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation," and its amendments.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Iowa Department of Transportation.

## Technical Report Documentation Page

| | | |
|---|---|---|
| **1. Report No.**<br>DTFH61-06-H-00011 Work Plan 12<br>Pooled Fund Study TPF-5(117) | **2. Government Accession No.** | **3. Recipient's Catalog No.** |
| **4. Title and Subtitle**<br>Development of Performance Properties of Ternary Mixtures: Laboratory Study on Concrete | | **5. Report Date**<br>March 2011<br>**6. Performing Organization Code** |
| **7. Author(s)**<br>Paul Tikalsky, Peter Taylor, Shannon Hanson, and Pratanu Ghosh | | **8. Performing Organization Report No.** |
| **9. Performing Organization Name and Address**<br>National Concrete Pavement Technology Center<br>Iowa State University<br>2711 South Loop Drive, Suite 4700<br>Ames, IA 50010-8664 | | **10. Work Unit No. (TRAIS)**<br>**11. Contract or Grant No.** |
| **12. Sponsoring Organization Name and Address**<br>Federal Highway Administration<br>U.S. Department of Transportation<br>1200 New Jersey Avenue SE Washington, DC 20590 | | **13. Type of Report and Period Covered**<br>Final Report<br>**14. Sponsoring Agency Code** |
| **15. Supplementary Notes**<br>Visit www.cptechcenter.org for color PDF files of this and other research reports. | | |

**16. Abstract**

This research project is a comprehensive study of how supplementary cementitious materials (SCMs) can be used to improve the performance of concrete mixtures. This report summarizes the findings of the Laboratory Study on Concrete phase of this work.

The earlier "paste and mortar phase" of this work considered several sources of each type of SCM (fly ash, slag, and silica fume) so that the material variability issues could be addressed. Several different sources of portland cement and blended cement were also used in the experimental program. This phase of the research used an experimental matrix of 48 different mortar and concrete mixtures, which were identified in the earlier work as potential ternary mixtures that could benefit department of transportation (DOT) goals for long-lasting transportation bridges and pavements.

This report contains test results from durability testing on mortar and concrete containing ternary cementitious materials and standard coarse and fine aggregates. Limited testing was also conducted on select mixtures for performance in hot and cold climates, to determine the potential to design ternary mixtures in adverse conditions.

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|---|---|---|---|
| **17. Key Words**<br>fly ash— portland cement—silica fume— slag—ternary mixtures | | **18. Distribution Statement**<br>No restrictions. | |
| **19. Security Classification (of this report)**<br>Unclassified. | **20. Security Classification (of this page)**<br>Unclassified. | **21. No. of Pages**<br>226 | **22. Price**<br>NA |

**Form DOT F 1700.7 (8-72)** **Reproduction of completed page authorized**

# DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXTURES: LABORATORY STUDY ON CONCRETE

**FINAL REPORT**
**March 2011**

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Sponsored through
Federal Highway Administration DTFH61-06-H-00011 Work Plan 12;
FHWA Pooled Fund Study TPF-5(117): California, Illinois, Iowa (lead state), Kansas,
Mississippi, New Hampshire, Oklahoma, Pennsylvania, Wisconsin, Utah;
the Portland Cement Association; Headwaters Resources; the American Coal Ash Association;
and the Slag Cement Association

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# ACKNOWLEDGEMENTS

This research was conducted under Federal Highway Administration (FHWA) DTFH61-06-H-00011 Work Plan 12 and the FHWA Pooled Fund Study TPF-5(117), involving the following State Departments of Transportation (DOTs):

- California
- Illinois
- Iowa (lead state)
- Kansas
- Mississippi
- New Hampshire
- Oklahoma
- Pennsylvania
- Wisconsin
- Utah

The researchers recognize the following partners for sponsoring this research:

- American Coal Ash Association
- Headwaters Resources
- Portland Cement Association
- Slag Cement Association

Finally, the researchers recognize the following companies for their in-kind contributions to this research:

- BASF Admixtures
- Elkem
- Engelhard
- Geneva Rock
- Giant Cement
- Holcim Cement
- Keystone Cement
- Lafarge Cement

# INTRODUCTION

Supplementary cementitious materials (SCMs), such as fly ash, ground granulated blast-furnace slag (GGBFS), natural pozzolans, calcined kaolinite, and silica fume, have become common parts of modern concrete practice (PCA, 2002; Transportation Research Board, 1990; ACI, 2007). The blending of two or three cementitious materials to optimize durability, strength, or economics provides owners, engineers, materials suppliers, and contractors with substantial advantages over mixtures containing only portland cement. However, these advances in concrete technology and engineering have not been adequately captured in the specifications of concrete.

Usage is often curtailed because of prescriptive concerns or historical comparisons about how such materials should perform. In addition, SCMs can exhibit significant variation in chemical and physical properties, within both a given source and, more commonly, between sources. Hence, current literature contains contradictory reports concerning the "optimal use" of supplementary cementitious materials.

Users need specific guidance to assist them in defining the performance requirements for a concrete application and the selection of optimal proportions of the cementitious materials needed to produce the required durable concrete. The selection process is complicated by the fact that blended cements are currently available in selected regions. Both portland and blended cements have already been optimized by the manufacturer to provide specific properties (such as setting time, shrinkage, and strength gain). The addition of SCMs (as binary, ternary, or even more complex mixtures) can alter these properties, and, hence, has the potential to impact the overall performance and applications of concrete.

Research is needed to identify and quantify the major factors that govern the performance of mixtures containing multiple SCMs. The focus of the research should be directed at ensuring that the use of these various materials always has a positive impact on the overall durability of the concrete.

## Project Goals

The goal of this project is to provide the quantitative information needed to make sound engineering judgments pertaining to the selection and use of SCMs in conjunction with portland or blended cement. This will lead to a more effective utilization of supplementary materials and/or blended cements, enhancing the life-cycle performance and minimizing the cost of transportation pavements and structures.

The efforts of this work were directed at producing test results to support the following specific goals:

- Provide quantitative guidance for ternary mixtures that can be used to enhance the performance of structural and pavement concrete
- Provide a solution to the cold weather issues that are currently restricting the use of blended cements and/or SCMs
- Identify how to best use ternary mixes when rapid strength gain is needed
- Develop performance-based specifications for concrete used in transportation pavements and structures

**Background**

Engineers for state departments of transportation (DOTs) throughout the US have used fly ash and GGBFS or slag cement as a partial replacement for portland cement in concrete production on a regular basis since the implementation of the Resource Conservation and Recovery Act in 1986. The Texas DOT (TxDOT) was one of the few states that conducted work to optimize the use of fly ash or slag cement to produce concrete mixtures that meet specific performance objectives prior to 1990 (Tikalsky et al., 1988).

For many years, most states implemented a strategy that was meant to produce concrete mixtures that exhibit performance similar to mixtures employing only portland cement. With the growing availability of slag cement and silica fume, and the limited supply of fly ash in some markets, the selection of materials for any given job has become more complicated.

SCMs have the potential to dramatically improve the overall performance, by increasing the longevity of the transportation infrastructure and decreasing the life-cycle cost of that infrastructure. The introduction of fly ash silica fume and slag cement in ternary combinations has periodically provided the following benefits to DOT and associated agencies:

- Excellent long-term strength
- Lower clinker and lower environmental emissions associated with concrete
- Mitigation of Alkali Silica Reaction (ASR)
- Mitigation of sulfate attack
- Resistance to corrosion
- Durability for highways and bridges
- Reduction of construction issues related to binary concrete mixtures

Closer inspection of the list and the technical literature suggests that the issues appear to be related to selection of material combinations, ranges of proportions of cementitious materials, constructability, ambient weather conditions, and materials variability.

## Outline of Research Phases

The paste and mortar phase of this study consisted of laboratory experiments to study the influence of multiple combinations and proportions of cement, slag, silica fume, calcined kaolinite, and fly ash on specific performance properties of mortar specimens. The testing program used a wide range of different materials and many different dosage levels.

Test results were evaluated to identify material combinations for potential optimums in the various performance responses. Chemical admixtures (water reducers, air entraining agents, and accelerators) were included in the paste and mortar phase of the study to compare setting time, water demand, and air content variation with ternary mixtures. The architecture for predicting the performance of ternary systems, based on the material properties of the total cementitious system, was created in the paste and mortar phase of the study.

All of the materials used in the study were characterized with bulk chemical and physical testing in accordance with the appropriate ASTM International or American Association of State Highway and Transportation Officials (AASHTO) specifications. In addition, X-ray diffraction and X-ray fluorescence was used to determine the minerals and bulk chemistry present in the cementitious materials.

This concrete phase of the study used the information obtained from the paste and mortar work to select a range of materials and dosages to investigate the effects of cold, hot, and ambient environmental conditions for use in laboratory concrete mixtures. The thrust of this phase was to build on the data from the paste and mortar work, and test concrete mixtures to evaluate the performance characteristics of pavement and structural mixtures.

The materials used in both phases were identical, so that the mortar test results could be directly compared to the test results obtained from concrete test specimens. This comparison is needed to provide information pertaining to the selection of appropriate mixture design and performance tests for specification development. It was desirable to develop mixture design tests using the behavior of mortar specimens that translate well into the performance of concrete. The results of this phase were performance-based measures for concrete in transportation applications.

A subsequent phase will be field demonstrations, in which contractors and states will have on-site technical support for using ternary mixtures. After each trial, the performance-based specifications will be reviewed and revised if necessary. The National Concrete Pavement Technology Center (National CP Tech Center) at Iowa State University (ISU) will seek to help conduct at least one project for each participant state using its mobile research laboratory.

## CEMENTITIOUS AND SUPPLEMENTARY CEMENTITIOUS MATERIALS

The primary cement used for the paste and mortar work was an ASTM C150 Type I cement from Keystone Cement. An ASTM C150 Type I/II cement from Davenport, Iowa was also used. These cement sources were chosen due to their frequent use in research to increase the credibility of this study's findings. The Keystone Cement plant was reconstructed with a new precalcining dry kiln before the start of this concrete phase and no longer makes the same clinker as used for the paste and mortar work.

This phase also used an ASTM C150 Type II/V cement from the Holcim Cement plant in Devil's Slide, Utah. This cement is widely used in the Western US and also used a clinker for blended cements.

### Blended Hydraulic Cements

Three blended hydraulic cements conforming to ASTM C595 were used in this study. Mixture designs, which include blended hydraulic cement, require one additional SCM to qualify as a ternary mixture.

A portland-pozzolan cement (Type IP or TIP) has a cement replacement of 15 to 40% by mass of a pozzolan constituent. This study used a Type IP with a combination of 75% TI portland cement from Florence, Kansas and 25% Class F fly ash from Sugar Creek, Missouri.

A slag-modified portland cement (Type IS(20) or TISM) has a cement replacement of less than 25% by mass of a slag constituent. This study used a TISM with a combination of 80% Type I/II portland cement from Davenport, Iowa and 20% Grade 100 GGBFS.

A pozzolan-modified cement (Type IP(6) or TIPM) has a cement replacement of less than 15% by mass of a pozzolan constituent. This study used a Type IPM with a combination of 94.05% Type I/II portland cement from Davenport, Iowa and 5.95% silica fume.

### Limestone Blended Cement

A limestone blended cement (E) was also used in this study. This particular cement is a Type II/V cement with 10% cement replacement by mass of crushed limestone. The limestone is a filler material and not expected to significantly enhance the concrete performance. Cement used for this study came from Devils Slide, Utah. The limestone replacement with one SCM qualifies the mixtures as a ternary blend. Table 1 shows the chemical composition for the portland and blended cements used in this study.

### Pozzolans

This study used a Class C fly ash (C) from the Port Neal #4 Power Station located in Sioux City, Iowa and two Class F fly ashes. The first Class F fly (F) ash came from the Cayuga Generating Station in Cayuga, Indiana. The second Class F fly ash (F2) came from the Coal Creek Power Station in Underwood, North Dakota. Table 2 shows the chemical composition of the fly ashes, along with ASTM C618 specification requirements.

**Table 1. Chemical compositions of portland and blended cements used**

| **Chemical (%)** | **Type I** | **Type I/II** | **Type IP(25)** | **Type IS(20)** | **Type IP(6)** | **Type E** |
|---|---|---|---|---|---|---|
| **CaO** | 61.71 | 63.00 | 50.88 | 61.46 | 59.15 | 62.52 |
| **$SiO_2$** | 19.80 | 20.70 | 28.88 | 21.66 | 24.91 | 20.24 |
| **$Al_2O_3$** | 6.18 | 4.16 | 8.19 | 4.55 | 4.38 | 3.85 |
| **$Fe_2O_3$** | 2.50 | 3.13 | 3.70 | 3.08 | 3.12 | 3.74 |
| **MgO** | 2.76 | 3.02 | 1.60 | 3.45 | 1.36 | 2.75 |
| **$K_2O$** | 0.74 | 0.75 | 0.90 | 0.69 | 0.56 | 0.54 |
| **$Na_2O$** | 0.36 | 0.09 | 0.35 | 0.10 | 0.22 | 0.20 |
| **$SO_3$** | 2.63 | 2.84 | 2.74 | 2.85 | 3.33 | 2.64 |
| **LOI** | 2.37 | 1.26 | 1.14 | 1.08 | 1.60 | 2.67 |
| **Total** | 99.91 | 99.99 | 99.40 | 99.97 | 99.31 | 98.21 |
| **$C_3S$** | 48.1 | 58.7 | -- | -- | -- | 61.9 |
| **$C_2S$** | 20.4 | 15.1 | -- | -- | -- | 11.4 |
| **$C_3A$** | 12.2 | 5.7 | -- | -- | -- | 3.9 |
| **$C_4AF$** | 7.6 | 9.5 | -- | -- | -- | 11.39 |

**Table 2. Chemical compositions of the fly ashes with ASTM C618 requirements**

| **Chemical (%)** | **Class C (C)** | **Class F (F)** | **Class F (F2)** | **Class C** | **Class F** |
|---|---|---|---|---|---|
| **$SiO_2$** | 34.02 | 45.05 | 51.40 | Sum 50% Min | Sum 70% Min |
| **$Al_2O_3$** | 18.20 | 23.71 | 16.21 | | |
| **$Fe_2O_3$** | 6.59 | 16.43 | 6.73 | | |
| **CaO** | 27.18 | 3.78 | 13.15 | | |
| **$Na_2O$** | 1.56 | 0.80 | 2.86 | | |
| **MgO** | 5.06 | 0.88 | 4.41 | | |
| **$SO_3$** | 2.70 | 0.68 | 0.80 | 5.0% Max | 5.0% Max |
| **$K_2O$** | 0.35 | 1.46 | 2.33 | | |
| **LOI, %** | 0.27 | 5.39 | 0.05 | 6.0% Max | 6.0% Max |
| **Total** | 100.17 | 99.89 | 99.69 | | |

GGBFS conforming to ASTM C989 at Grades 100 and 120 were used in this study. Table 3 shows the chemical composition of these, along with ASTM C989 specification requirements.

The silica fume used in this study was Elkem Microsilica EMS 965, which is a powder product. Table 4 shows the chemical composition of the silica fume, along with ASTM C1240 specification requirements.

Metamax metakaolin produced by Englehand Corporation was used in this study. Table 5 shows the chemical composition of the metakaolin, along with ASTM C618 specification requirements.

**Table 3. Chemical compositions for the Grade 100 and 120 GGBFS with ASTM C989 requirements**

| Chemical (%) | Grade 100 | Grade 120 | ASTM C989 |
|---|---|---|---|
| $SiO_2$ | 37.40 | 36.81 | |
| $Al_2O_3$ | 8.98 | 9.66 | |
| $Fe_2O_3$ | 0.76 | 0.61 | |
| CaO | 36.86 | 36.77 | |
| MgO | 10.60 | 10.03 | |
| S | 1.03 | 1.10 | 2.5% Max |
| $Na_2O$ | 0.29 | 0.31 | |
| $K_2O$ | 0.40 | 0.35 | |
| SrO | 0.04 | 0.05 | |

**Table 4. Chemical compositions for the silica fume with ASTM C1240 requirements**

| Chemical (%) | Silica Fume | ASTM C1240 |
|---|---|---|
| $SiO_2$ | 97.90 | 85.0% Min |
| $Na_2O$ | 0.12 | |
| MgO | 0.21 | |
| $Al_2O_3$ | 0.18 | |
| $SO_3$ | 0.17 | |
| Cl | 0.09 | |
| $K_2O$ | 0.59 | |
| CaO | 0.42 | |
| MnO | 0.03 | |
| $Fe_2O_3$ | 0.07 | |
| ZnO | 0.08 | |

**Table 5. Chemical compositions for the metakaolin with ASTM C618 requirements**

| Chemical (%) | Metakaolin | ASTM C618 |
|---|---|---|
| **$SiO_2$** | 51.95 | Sum 70% Min |
| **$Al_2O_3$** | 44.27 | |
| **$Fe_2O_3$** | 0.41 | |
| **$Na_2O$** | 0.16 | |
| **MgO** | 0.05 | |
| **$SO_3$** | 0.02 | 4.0% Max |
| **$K_2O$** | 0.14 | |
| **CaO** | 0.06 | |
| **LOI** | 0.31 | 10.0% Max |
| **Total** | 98.91 | |

**Aggregate**

The fine aggregate used was ASTM C33 concrete sand from Geneva Rock Products in Utah. The sand had a fineness modulus and absorption of 2.90 and 1.9%, respectively. Figure 1 shows the gradation of the sand used with the ASTM C33 gradation limits.

Coarse aggregate used in this phase's concrete specimens was from Geneva Rock Products in Utah with a nominal diameter, fineness modulus, and absorption of 1 in., 2.8, and 0.86%, respectively.

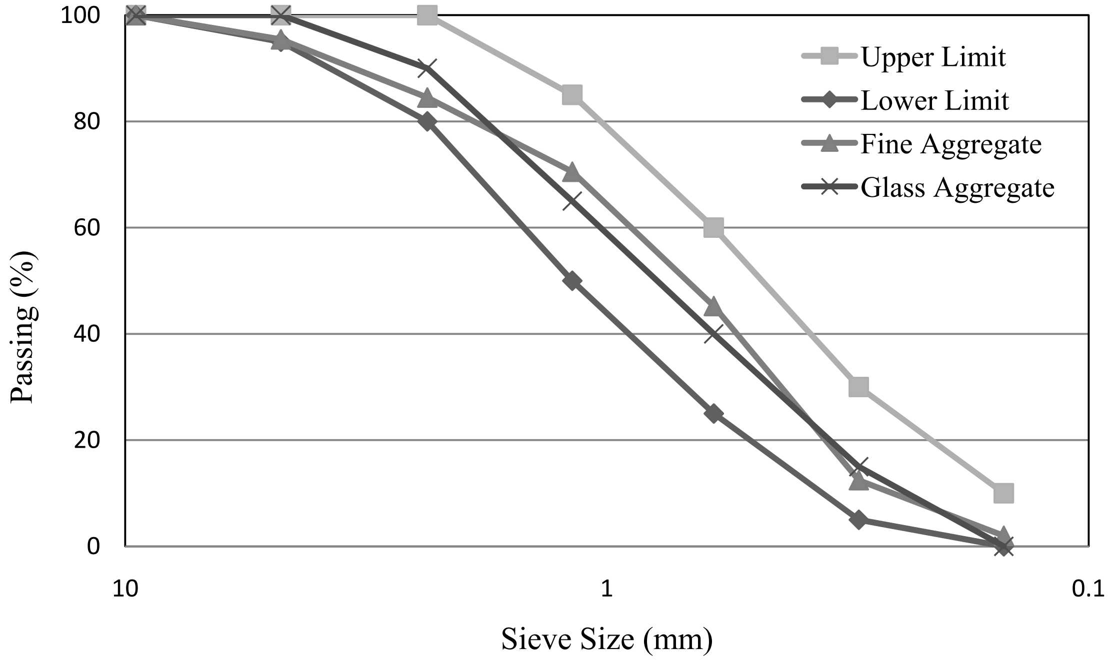

Figure 1. Gradation of fine aggregates

## Chemical Admixtures

Chemical admixtures are used to modify the characteristics of the concrete. During the course of the study, two admixtures were used. Glenium 3030 is a polycarboxylate-based, mid-range, water-reducing admixture that meets the ASTM C494 requirements for a Type A water-reducing and a Type F high-range water-reducing admixture. MB VR is an air-entraining admixture and meets the requirements in ASTM C260.

## Mixture Designs

This study consisted of 12 control mixtures and 105 ternary mixtures. Six of the control mixtures were 100% Type I, Type I-II, and blended cements. Binary mixtures formed the other six control mixtures. Ternary mixtures contain either cement with two SCMs or hydraulic blended cement with one SCM.

Each mixture was uniquely identified using numbers and symbols. The number before each symbol represents the percentage of cementitious material by mass. Each material is separated by a slash. For example, the Mixture ID 60TI/20C/20F contains 60% by mass of ASTM C150 Type I cement, 20% by mass of ASTM C618 Class C fly ash, and 20% by mass of ASTM C618 Class F fly ash. Table 6 shows each constituent, identification symbol, specific gravity, and equivalent alkali content used in this study.

**Table 6. Material identification**

| Material (Source) | Symbol | Specific Gravity | Equivalent Alkali (%) |
|---|---|---|---|
| **Type I** | TI | 3.04 | 0.85 |
| **Type I/II** | TI-II | 3.13 | 0.58 |
| **Type IS(20)** | TISM | 2.95 | 0.35 |
| **Type IP** | TIP | 3.11 | 0.55 |
| **Type IP(6)** | TIPM | 3.08 | 0.59 |
| **Blended Lime** | E | 3.25 | 0.55 |
| **Class C Fly Ash** | C | 2.62 | 1.79 |
| **Class F Fly Ash** | F | 2.37 | 1.76 |
| **Class F Fly Ash** | F2 | 2.41 | 4.39 |
| **GGBFS 100** | G100S | 2.82 | 0.55 |
| **GGBFS 120** | G120S | 2.96 | 0.54 |
| **Silica Fume** | SF | 2.21 | 0.51 |
| **Metakaolin** | M | 2.52 | 0.25 |

# LABORATORY STUDY ON PASTE AND MORTAR SUMMARY

## Introduction

The first phase of this work, the “Laboratory Study on Mortar,” focused on determining durability properties of mortar specimens with ternary cementitious mixture designs. Cementitious material used to develop 117 ternary mixture designs included: Type I, Type I/II, Type ISM, Type IP, Type IPM and a high lime portland cement, Class C fly ash, moderate and low calcium Class F fly ashes, grades 100 and 120 GGBFS, silica fume, and metakaolin. All cementitious materials were subjected to bulk chemical and physical testing. Mixing and testing were performed at the University of Utah and Iowa State University under the supervision of Dr. Paul Tikalsky. Testing began fall of 2006 and was completed summer of 2008. Findings for each of the nine properties tested and analyzed for this phase are briefly summarized below.

## Setting Time and Mortar Flow

Blended cements increased the time to initial and final set and the introduction of SCMs to replace Type I portland cement increased the time to initial and final set, as well as increased the workability. Mixtures containing Class F fly ash had an unexpected decrease in set time, which could be due to the increased fineness of the Class F fly ashes. The grade 120 GGBFS tended to have a decreased flow and time to initial and final set, compared to the grade 100 GGBFS, due to the finer grind. A weak relationship exists between the flow value and time to initial set.

## Compatibility

A low-range water reducer, Pozzolith 200N, showed significant reduction in time to initial and final set when used at a doubled dosage rate. Mixtures containing Class C fly ash generally set quicker and show the incompatibility of some Class C fly ashes with water reducers. A high-range water reducer, PS-1466, was also tested. Increasing the dose of the PS-1466, the time to initial set is affected to a greater degree than the time to final set. These results show that careful planning and engineering judgment must be exercised when designing field concrete mixes. Using the Vicat test may flag a potential incompatibility issues before field construction begins.

## Air Void System

A combination of water reducer and an air-entraining agent, AEA, was studied with two Air Void Analyzer (AVA) samples for an average. As expected, a decrease in spacing factor leads to an increase of specific surface. Also, increasing the $\% D < 300$ μm in the mortar increases the specific surface. Both trends indicate a finer air void system may be more resistant to freeze-thaw. General trends also show an increase in compressive strength with a decrease in the percent of air voids less than 300 μm. A decrease in the finer fraction of air voids indicates lower air content or larger air voids within the mix. The blended cements (TIP, TISM, TIPM) generally produced better air void structure.

Although most mixtures meet the threshold of 0.2 mm (0.008 in.) spacing factor, the majority of mixtures do not meet the minimum criteria of 23 –43 mm-1 (600 –1000 in.-1) for specific surface. This does not necessarily mean the corresponding concrete would fail in freeze-thaw, but steps should be taken to increase the specific surface and create a finer air void system.

### Mortar Compressive Strength

Following ASTM C109, 2 in. mortar cubes were tested for compressive strength. Most strengths correlated well with the bulk chemistry of the mixture, especially the chemical percentages of CaO and Al2O3. The highest 7 and 28 day strengths were observed with mixtures containing type PM cement and metakaolin. The lowest 7 and 28 day strengths were observed with mixtures containing Type IP cement and Class F fly ash.

The effect of exceeding the recommended dosage of water reducer (Pozzolith 200N) on the mortar's early strength was also investigated on a sample of mixture designs. The 3 day compressive strengths were greatly decreased when the recommendations were exceeded. However, by 28 days, the compressive strength of the over dosed mortars was approximately the same as the mixtures with properly-dosed water reducers, which suggests the retardation effect of the water reducer has no long term effects.

### Heat Signature

The heat signature of concrete mixtures is important, as it defines the hydration process and gives estimates of the time to initial and final set. The heat liberated during hydration is important especially during cold and hot weather concreting applications. It was observed that when incorporating SCMs, a reduction in maximum temperature rise and a time delay to maximum heat generation was experienced. With the decrease in heat generated, the general tradeoff is a longer time to initial and final set.

The heat signature of mixtures containing Grade 120 GGBFS is significantly larger than mixtures containing grade 100 GGBFS. This is expected due to grade 120 GGBFS having a finer particle size than grade 100 GGBFS. The results also show the influence of the silica fume replacement (3 or 5%) is negligible when comparing the respective heat signatures. This shows that a 5% replacement rate may be used if needed in high-performance concreting applications with no noticeable effect on the heat signature.

### Shrinkage

Each mixture consists of a 28 day shrinkage value or length change of hardened hydraulic-cement mortar. In comparison to a 100% Type I portland cement mixture, shrinkage was reduced when type I cement was blended with any other constituents. However, when Type I/II portland cement was blended, higher shrinkage results were observed than the 100% Type I/II mixture. Type IP and Type PM portland cements saw both higher and lower shrinkage results than when blended with an additional constituent.

## SULFATE MORTAR BAR TESTING

### Methods for Sulfate Testing

Following ASTM C1012, six 1x1x11.25 in. mortar bars and twelve 2x2x2 in. cubes were formed for each mixture. The 2 in. cubes were used to determine the compressive strength of the mixtures. When a mixture reached a compressive strength of 2,850 psi, the bars for the mixture were measured for length and placed into a sealed container containing a sodium sulfate solution at room temperature. Length change measurements were taken at 1, 2, 3, 4, 8, 13, and 15 weeks and 4, 6, 9, 12, 15, and 18 months. New sulfate solution was placed in the sealed container after each measurement.

### Sulfate Results

See Table 7 for control mixture results. The remaining sulfate expansion results are broken down by specific SCM and are shown in Table 8 to Table 14.

**Table 7. Sulfate expansion at 6, 12, and 15 months for control mixtures**

| Mixture ID | Expansion (%)<br>6 Months | 12 Months | 15 Months |
|---|---|---|---|
| **100TI** | **0.31** | **0.50** | **0.50** |
| **80TI/20C** | **0.11** | **0.50** | **0.50** |
| **80TI/20F** | 0.03 | 0.04 | 0.04 |
| **80TI/20F2** | 0.04 | 0.05 | 0.06 |
| **65TI/35G100S** | 0.02 | 0.02 | 0.03 |
| **65TI/35G120S** | 0.03 | 0.04 | 0.05 |
| **100TI-II** | **0.04** | **0.06** | **0.07** |
| **80TI-II/20G120S** | 0.03 | 0.04 | 0.05 |
| **100TIP** | 0.02 | 0.03 | 0.03 |
| **100TISM** | 0.04 | 0.06 | 0.07 |
| **100TIPM** | 0.02 | 0.02 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

Charts of expansion at 6, 12, and 15 months were plotted to compare long-term expansion. The sulfate expansion of all mortar mixtures with ternary cementitious combinations were separated into individual SCMs and are presented in the Appendix. According to ASTM C1012, 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. Mixtures that are classified as moderate sulfate resistance are in boldface type, and mixtures that are not classified as moderate or high sulfate resistant are in boldface and shaded gray.

**Table 8. Sulfate expansion at 6, 12, and 15 months for Class C fly ash**

| | **Expansion (%)** | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **60TI/20C/20F2** | **0.10** | **0.23** | **0.35** |
| **75TI/20C/5SF** | 0.04 | 0.08 | 0.12 |
| **77TI/20C/3SF** | 0.04 | 0.13 | 0.39 |
| **65TI/30C/5SF** | 0.03 | 0.04 | 0.04 |
| **67TI/30C/3SF** | 0.04 | 0.10 | 0.09 |
| **60TI/20C/20G100S** | **0.06** | **0.11** | **0.17** |
| **60TI/20C/20G120S** | 0.04 | 0.06 | 0.10 |
| **50TI/35G100S/15C** | 0.04 | 0.06 | 0.06 |
| **50TI/30C/20G120S** | 0.05 | 0.20 | 0.38 |
| **75TI/20C/5M** | 0.09 | 0.31 | 0.50 |
| **65TI/30C/5M** | **0.13** | **0.42** | **0.50** |
| **60TI/30C/10F** | 0.06 | 0.13 | 0.20 |
| **60TI/30C/10F2** | **0.17** | **0.29** | **0.40** |
| **68TI-II/17G120S/15C** | -0.06 | -0.05 | -0.04 |
| **60TI-II/25C/15G120S** | **0.06** | **0.28** | **0.46** |
| **50TI/35G120S/15C** | 0.04 | 0.09 | 0.25 |
| **50TI/30C/20G100S** | 0.04 | 0.06 | 0.09 |
| **85TIP/15C** | 0.04 | 0.04 | 0.09 |
| **75TIP/25C** | 0.04 | 0.06 | 0.13 |
| **85TISM/15C** | 0.03 | 0.10 | 0.12 |
| **75TISM/25C** | 0.04 | 0.08 | 0.11 |
| **85TIPM/15C** | 0.02 | 0.02 | 0.03 |
| **75TIPM/25C** | 0.03 | 0.03 | 0.04 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 9. Sulfate expansion at 6, 12, and 15 months for Class F fly ash**

| | Expansion (%) | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **60TI/20F/20F2** | 0.04 | 0.05 | 0.05 |
| **75TI/20F/5SF** | 0.02 | 0.03 | 0.03 |
| **77TI/20F/3SF** | 0.02 | 0.03 | 0.03 |
| **60TI/20F/20G100S** | 0.03 | 0.03 | 0.03 |
| **60TI/20F/20G120S** | 0.03 | 0.04 | 0.04 |
| **75TI/20F/5M** | 0.04 | 0.05 | 0.05 |
| **60TI/30C/10F** | **0.06** | **0.13** | **0.20** |
| **60TI/30F/10F2** | 0.04 | 0.05 | 0.05 |
| **65TI/30F/5SF** | 0.00 | 0.00 | 0.00 |
| **67TI/30F/3SF** | 0.03 | 0.04 | 0.08 |
| **50TI/30F/20G100S** | 0.03 | 0.04 | 0.03 |
| **50TI/30F/20G120S** | 0.04 | 0.05 | 0.04 |
| **65TI/30F/5M** | 0.04 | 0.05 | 0.04 |
| **50TI/35G100S/15F** | 0.03 | 0.04 | 0.04 |
| **50TI/35G120S/15F** | 0.02 | 0.05 | 0.05 |
| **68TI-II/17G120S/15F** | -0.06 | -0.06 | -0.06 |
| **60TI-II/25F/15G120S** | 0.02 | 0.03 | 0.03 |
| **85TIP/15F** | 0.01 | 0.06 | 0.06 |
| **75TIP/25F** | 0.03 | 0.03 | 0.03 |
| **85TISM/15F** | 0.02 | 0.03 | 0.03 |
| **75TISM/25F** | 0.03 | 0.04 | 0.04 |
| **85TIPM/15F** | 0.01 | 0.01 | 0.02 |
| **75TIPM/25F** | 0.02 | 0.02 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 10. Sulfate expansion at 6, 12, and 15 months for Class F2 fly ash**

| | Expansion (%) | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **60TI/20C/20F2** | **0.10** | **0.23** | **0.35** |
| **60TI/20F/20F2** | 0.04 | 0.05 | 0.05 |
| **75TI/20F2/5SF** | 0.04 | 0.04 | 0.04 |
| **77TI/20F2/3SF** | 0.06 | 0.07 | 0.06 |
| **60TI/20F2/20G100S** | 0.04 | 0.04 | 0.04 |
| **60TI/20F2/20G120S** | 0.04 | 0.06 | 0.07 |
| **75TI/20F2/5M** | 0.05 | 0.06 | 0.06 |
| **60TI/30C/10F2** | **0.17** | **0.29** | **0.40** |
| **60TI/30F/10F2** | 0.04 | 0.05 | 0.05 |
| **65TI/30F2/5SF** | 0.02 | 0.03 | 0.03 |
| **67TI/30F2/3SF** | 0.02 | 0.03 | 0.03 |
| **50TI/30F2/20G100S** | 0.03 | 0.04 | 0.04 |
| **50TI/30F2/20G120S** | 0.03 | 0.05 | 0.04 |
| **65TI/30F2/5M** | 0.04 | 0.07 | 0.08 |
| **50TI/35G100S/15F2** | 0.02 | 0.03 | 0.03 |
| **50TI/35G120S/15F2** | 0.03 | 0.04 | 0.04 |
| **68TI-II/17G120S/15F2** | -0.06 | -0.05 | -0.05 |
| **60TI-II/25F2/15G120S** | 0.02 | 0.03 | 0.03 |
| **85TIP/15F2** | 0.01 | 0.07 | 0.07 |
| **75TIP/25F2** | 0.03 | 0.04 | 0.04 |
| **85TISM/15F2** | 0.02 | 0.03 | 0.03 |
| **75TISM/25F2** | 0.03 | 0.02 | 0.03 |
| **85TIPM/15F2** | 0.02 | 0.02 | 0.02 |
| **75TIPM/25F2** | 0.02 | 0.02 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 11. Sulfate expansion at 6, 12, and 15 months for Grade 100 GGBFS**

| | Expansion (%) | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **60TI/20C/20G100S** | **0.06** | **0.11** | **0.17** |
| **60TI/20F/20G100S** | 0.03 | 0.03 | 0.03 |
| **60TI/20F2/20G100S** | 0.04 | 0.04 | 0.04 |
| **50TI/30C/20G100S** | 0.04 | 0.06 | 0.09 |
| **50TI/30F/20G100S** | 0.03 | 0.04 | 0.03 |
| **50TI/30F2/20G100S** | 0.03 | 0.04 | 0.04 |
| **50TI/35G100S/15C** | 0.04 | 0.06 | 0.06 |
| **50TI/35G100S/15F** | 0.03 | 0.04 | 0.04 |
| **50TI/35G100S/15F2** | 0.02 | 0.03 | 0.03 |
| **60TI/35G100S/5SF** | 0.02 | 0.03 | 0.03 |
| **62TI/35G100S/3SF** | 0.03 | 0.03 | 0.03 |
| **60TI/35G100S/5M** | 0.00 | 0.03 | 0.03 |
| **64TI-II/20G100S/16G120S** | 0.02 | 0.03 | 0.03 |
| **52TI-II/35G100S/13G120S** | 0.02 | 0.03 | 0.02 |
| **80TIP/20G100S** | 0.03 | 0.02 | 0.03 |
| **65TIP/35G100S** | 0.03 | 0.03 | 0.03 |
| **80TISM/20G100S** | 0.03 | 0.03 | 0.03 |
| **65TISM/35G100S** | 0.03 | 0.02 | 0.02 |
| **80TIPM/20G100S** | 0.02 | 0.02 | 0.02 |
| **65TIPM/35G100S** | 0.02 | 0.01 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 12. Sulfate expansion at 6, 12, and 15 months for Grade 120 GGBFS**

|  | **Expansion (%)** |  |  |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **60TI/20C/20G120S** | 0.04 | 0.06 | 0.10 |
| **60TI/20F/20G120S** | 0.04 | 0.06 | 0.07 |
| **60TI/20F2/20G120S** | 0.03 | 0.04 | 0.04 |
| **50TI/30C/20G120S** | **0.05** | **0.20** | **0.38** |
| **50TI/30F/20G120S** | 0.04 | 0.05 | 0.04 |
| **50TI/30F2/20G120S** | 0.03 | 0.05 | 0.04 |
| **50TI/35G120S/15C** | 0.04 | 0.09 | 0.25 |
| **50TI/35G120S/15F** | 0.02 | 0.05 | 0.05 |
| **50TI/35G120S/15F2** | 0.03 | 0.04 | 0.04 |
| **60TI/35G120S/5SF** | 0.02 | 0.03 | 0.02 |
| **62TI/35G120S/3SF** | 0.02 | 0.03 | 0.03 |
| **60TI/35G120S/5M** | 0.02 | 0.04 | 0.03 |
| **68TI-II/17G120S/15C** | -0.06 | -0.05 | -0.04 |
| **68TI-II/17G120S/15F** | -0.06 | -0.06 | -0.06 |
| **68TI-II/17G120S/15F2** | -0.06 | -0.05 | -0.05 |
| **76TI-II/19G120S/5SF** | -0.06 | -0.05 | -0.05 |
| **78TI-II/19G120S/3SF** | 0.02 | 0.03 | 0.03 |
| **64TI-II/20G100S/16G120S** | 0.02 | 0.03 | 0.03 |
| **76TI-II/19G120S/5M** | 0.03 | 0.04 | 0.05 |
| **60TI-II/25C/15G120S** | **0.06** | **0.28** | **0.46** |
| **60TI-II/25F/15G120S** | 0.02 | 0.03 | 0.03 |
| **60TI-II/25F2/15G120S** | 0.02 | 0.03 | 0.03 |
| **52TI-II/35G100S/13G120S** | 0.02 | 0.03 | 0.02 |
| **80TIP/20G120S** | 0.03 | 0.03 | 0.04 |
| **65TIP/35G120S** | 0.03 | 0.03 | 0.04 |
| **80TISM/20G120S** | 0.03 | 0.04 | 0.04 |
| **65TISM/35G120S** | 0.02 | 0.02 | 0.02 |
| **80TIPM/20G120S** | 0.03 | 0.03 | 0.03 |
| **65TIPM/35G120S** | 0.02 | 0.02 | 0.03 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 13. Sulfate expansion at 6, 12, and 15 months for silica fume**

| | Expansion (%) | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **75TI/20C/5SF** | 0.04 | 0.08 | 0.50 |
| **77TI/20C/3SF** | **0.04** | **0.13** | **0.39** |
| **75TI/20F/5SF** | 0.02 | 0.03 | 0.03 |
| **77TI/20F/3SF** | 0.02 | 0.03 | 0.03 |
| **75TI/20F2/5SF** | 0.04 | 0.04 | 0.04 |
| **77TI/20F2/3SF** | **0.06** | **0.07** | **0.06** |
| **65TI/30C/5SF** | 0.03 | 0.04 | 0.04 |
| **67TI/30C/3SF** | 0.04 | 0.10 | 0.09 |
| **65TI/30F/5SF** | 0.00 | 0.00 | 0.00 |
| **67TI/30F/3SF** | 0.03 | 0.04 | 0.08 |
| **65TI/30F2/5SF** | 0.02 | 0.03 | 0.03 |
| **67TI/30F2/3SF** | 0.02 | 0.03 | 0.03 |
| **60TI/35G100S/5SF** | 0.02 | 0.03 | 0.03 |
| **62TI/35G100S/3SF** | 0.03 | 0.03 | 0.03 |
| **60TI/35G120S/5SF** | 0.02 | 0.03 | 0.02 |
| **62TI/35G120S/3SF** | 0.02 | 0.03 | 0.03 |
| **90TI/5M/5SF** | 0.01 | 0.03 | 0.03 |
| **92TI/5M/3SF** | 0.02 | 0.04 | 0.06 |
| **76TI-II/19G120S/5SF** | -0.06 | -0.05 | -0.05 |
| **78TI-II/19G120S/3SF** | 0.02 | 0.03 | 0.03 |
| **95TIP/5SF** | 0.02 | 0.02 | 0.02 |
| **97TIP/3SF** | 0.02 | 0.03 | 0.02 |
| **95TISM/5SF** | 0.02 | 0.03 | 0.03 |
| **97TISM/3SF** | 0.03 | 0.04 | 0.04 |
| **95TIPM/5SF** | 0.01 | 0.01 | 0.02 |
| **97TIPM/3SF** | 0.01 | 0.01 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

**Table 14. Sulfate expansion at 6, 12, and 15 months for metakaolin**

| | Expansion (%) | | |
|---|---|---|---|
| **Mixture ID** | **6 Months** | **12 Months** | **15 Months** |
| **75TI/20C/5M** | **0.09** | **0.31** | **0.50** |
| **75TI/20F/5M** | 0.05 | 0.06 | 0.06 |
| **75TI/20F2/5M** | 0.05 | 0.06 | 0.06 |
| **65TI/30C/5M** | **0.13** | **0.42** | **0.50** |
| **65TI/30F/5M** | 0.04 | 0.05 | 0.04 |
| **65TI/30F2/5M** | 0.04 | 0.07 | 0.08 |
| **60TI/35G100S/5M** | 0.00 | 0.03 | 0.03 |
| **60TI/35G120S/5M** | 0.02 | 0.04 | 0.03 |
| **76TI-II/19G120S/5M** | 0.03 | 0.04 | 0.05 |
| **95TIP/5M** | 0.02 | 0.02 | 0.03 |
| **95TISM/5M** | 0.04 | 0.05 | 0.06 |
| **95TIPM/5M** | 0.02 | 0.01 | 0.02 |

Mixture designs that are classified as moderate sulfate resistant are in **boldface** type; mixtures that are not classified as moderate or high sulfate resistant are **shaded and in boldface**.

## Discussion of Sulfate Resistance

### *Control Mixtures*

The sulfate resistance for control mortars had a wide range of expansions. The mixture with 100% Type I cement and the mixture with 80% Type I cement and 20% Class C fly ash experienced extensive cracking by 6 months. By 12 months, all bars were broken. The 100% IPM cement had the least expansion of 0.02% at 6 months and maintained this expansion through 15 months.

### *Class C Fly Ash*

The least expansion at all reading intervals was the mixture design containing 85% Type IPM cement and 15% Class C fly ash. Complete fracture of all six bars by 15 months was seen by both mixtures that contained Type I cement, Class C fly ash, and metakaolin.

Class C fly ash drastically reduced the mortar resistance to sulfate expansion over an extended time period. Many of the mixture designs would be considered moderate sulfate resistant, because expansion was less than 0.1% at 6 months. But by 15 months, 7 of the 22 mixture designs had severe damage, bowing, or complete fracture.

### *Class F Fly Ash*

The Class F fly ash was found to be very good in mitigating the sulfate reaction. The least expansion occurred in the mixture containing 68% Type I-II with 17% Grade 120 GGBFS and 15% Class F fly ash. This mixture design actually had a reduction in length due to shrinkage, which was not overcome by sulfate expansion. The maximum expansion occurred with the mixture design of 60% Type I, 30% Class C fly ash, and 10% Class F fly ash with expansions of 0.06%, 0.13%, and 0.20% at 6, 12, and 15 months, respectively.

### *Class F2 Fly Ash*

The expansion results for mixtures containing Class F2 fly ash was more or less similar to the mixtures containing Class F fly ash. A negative expansion was found in the mixture containing 68% Type I-II, 17% Grade 120 GGBFS, and 15% Class F2 fly ash. The maximum expansion, and only mixtures not classified as high sulfate resistant, occurred with the mixture designs that contained Class C fly ash.

### *Grade 100 GGBFS*

The mortar mixtures containing Grade 100 GGBFS showed almost the same pattern as the mixtures containing fly ashes. The combination of Class C fly ash with slag showed the maximum expansions of 0.06%, 0.11%, and 0.17% at 6, 12, and 15 months, respectively. The binary mixtures containing Type IPM cement and GGBFS showed the least expansion of 0.02% expansion for all three readings.

### *Grade 120 GGBFS*

Grade 120 GGBFS was one of the most widely used SCMs in this study. Out of the 114 mixtures under study, more than 30 mixtures contained Grade 120 GGBFS. The mixtures containing Type I-II cement with slag and Class F or F2 fly ash had the least expansion, while the mixtures containing Class C fly ash experienced the most expansion.

The mixture design with 50% Type I cement, 35% Grade 120 GGBFS, and 15% Class C fly ash had an expansion of less than 0.1% at 12 months, classifying it as high sulfate resistance. However, over the next 3 months of testing, the expansion rate drastically increased leading to an average expansion of 0.25%.

### *Silica Fume*

Ternary mixtures containing silica fume had either 3 or 5% silica fume. The maximum expansion was found with the mixtures containing 75 and 77% Type I cement, 20% Class C fly ash, and silica fume. Both mixtures experienced expansions above 0.35% by 15 months. The rest of the mixtures still had less than 0.1% expansion at 15 months.

*Metakaolin*

Again, the mixtures that contained Class C fly ash experienced very high expansions. The two mixtures with Class C fly ash had expansions 0.09% and 0.31% at 6 and 12 months with complete fracture by 15 months. All other mix designs had expansions under 0.1% for all readings with minimum expansion for the binary blend of Type IP and metakaolin.

*Photos of Sulfate Bars*

Sulfate attack caused some mixture designs to experience severe damage. Figure 2 shows two different mixtures that were tested in the same container. This photo was taken immediately after opening the curing container at 15 months. The top two bars, 1-054-2-05 and 1-054-2-06, had the mixture design 50TI/35G230S/15C and by 15 months, 3 of the 6 mortar bars had completely fractured. The bottom bar, 1-041-2-01, had a mixture design of 65TI/30F2/5M. The average expansion of this mixture design was 0.08% at 15 months, which is evident in this intact specimen. Figure 3 and Figure 4 are images of the 1-054 mixture after being removed from the solution.

**Figure 2. Damage due to sulfate attack**

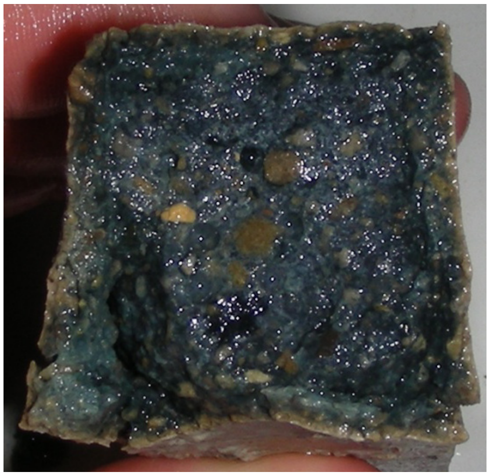

**Figure 3. Internal sulfate attack damage**

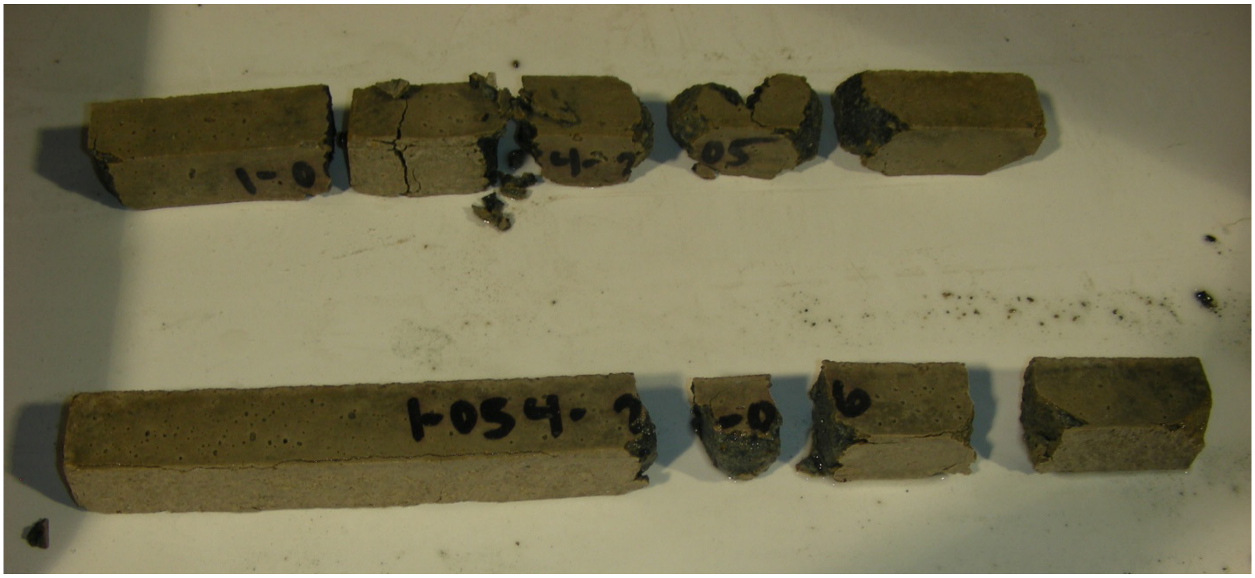

**Figure 4. Severe sulfate damage**

## ALKALI SILICA REACTION

### Methods and Materials

ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method) and ASTM C441 Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction were combined for this study. The process of ASTM C1567 was followed with the exception of aggregate. The fine aggregate used in the study was only moderately reactive, so Pyrex glass from ASTM C441 was blended at 25% Pyrex glass and 75% sand by weight, thus increasing the ASR potential. By using highly reactive aggregates, submerging in NaOH solution, and storing at 176°F, an extremely harsh testing environment was created. Figure 1 shows the gradation of the fine aggregates, along with ASTM C33 gradation limits used for ASR testing. According to ASTM C1567, if the expansion at 14 days is ≤0.10%, the mixture passes and is successful in mitigating ASR.

*Canadian Standards Association CSA A23.2-27A*

Using Tables 2 through 6 of CSA A23.2-27A, the required SCM replacement levels can be determined. The first step is to use Table 2 to identify the aggregate reactivity. The Pyrex glass and sand blend of fine aggregate is classified as *Highly Reactive* aggregate. The next step is to determine the level of risk associated with the structure using Table 3. This risk level is a factor of concrete element size and environmental exposure. The study specimens are small, but the elevated temperature and immersion during the ASTM C1567 curing procedure qualify the specimens to be *All concrete exposed to humid air, buried, or immersed,* putting this study at a *Risk Level 4*. Table 4 is then used to determine the level of prevention. For a *Risk Level 4* and a service life between 5 and 75 years a *Preventive Measure Y* is required. Moving to Table 5, a *Preventive Measure Y* requires the use of either a low alkali cement, sufficient amounts of SCMs (found in Table 6), or rejection of aggregate.

For *Prevention Measure Y*, Table 6 identifies the minimum cement replacement level for each SCM. All cements used in the study have a total alkali content less than 1.00%, so the level of SCMs do not need to be increased by one prevention level. The Class F fly ash used in this study has a total alkali content of 1.76% and a CaO content of 3.78%, which leads to a minimum cement replacement of 25%. The Class F2 fly ash has a total alkali content of 4.39% and CaO content of 13.15%, which leads to a minimum cement replacement of 35%. The Class C fly ash has a total alkali content of 1.79% and a CaO content of 27.18. Due to these mineral characteristics, the Class C fly ash would require further investigation before being approved for use, but for comparison purposes in this study, a minimum cement replacement level of 45% was used. Grade 100 and Grade 120 GGBFS have total alkali contents of 0.55 and 0.54%, respectively, so a minimum cement replacement level of 50% is required. The total alkali content of silica fume is 0.51%,so the minimum cement replacement level is three times the total equivalent alkali content of the mixture design. Metakaolin falls into the natural pozzolans category, which requires additional testing. A minimum cement replacement level of 10% was used for metakaolin for comparison purposes in this study (Ramlochan et al., 2000). The total equivalent alkali content was calculated for the blended cements and then the blended cements were broken into their two constituents for SCM replacement level requirement calculations.

With the required cement replacement levels determined from CAS A23.2-27A Table 6, the mixture designs can be applied to equation (1). The sum of the replacement level of each SCM divided by the minimum required must total ≥1 for the mixture to pass CSA A23.2-27A and be expected to be adequately resistant to ASR.

$$\frac{\text{SCM1 PRL}}{\text{SCM1 MRL}} + \frac{\text{SCM2 PRL}}{\text{SCM2 MRL}} \geq 1 \tag{1}$$

where:
SCM1 = first SCM
SCM2 = second SCM
PRL = proposed replacement level
MRL = minimum replacement level

*California Department of Transportation Section 90*

The California Department of Transportation (Caltrans) 2009 Section 90 specification has a straightforward equation based on minimum replacement levels for binary mixtures. Current binary minimum SCM replacement levels for silica fume, low calcium fly ash, moderate calcium fly ash, and GGBFS are 12%, 25%, 30%, and 50%, respectively. These percentages were algebraically manipulated using the least common denominator and a coefficient was determined for each. This equation has an underlying assumption that when multiple SCMs are used, each contributes to ASR mitigation in proportion to its minimum required replacement level (Caltrans, 2010).

If the equality of equation (2) is satisfied, the concrete mixture will be resistant to ASR expansion (Caltrans, 2009). Caltrans also requires equation (3) to be satisfied for the mixture design to be acceptable.

$$\frac{(25\times\text{UF})+(12\times\text{FA})+(10\times\text{FB})+(6\times\text{SL})}{\text{MC}} \geq \text{X} \tag{2}$$

where:
UF = silica fume, metakaolin, or ultrafine fly ash, including the amount in blended cement, lbs/yd$^3$
FA = fly ash or natural pozzolan, Class F or N with CaO content less than 10%, including the amount in blended cement, lbs/yd$^3$
FB = fly ash or natural pozzolan Class F or N with CaO content up to 15%, including the amount in blended cement, lbs/yd$^3$
SL = GGBFS, including the amount in blended cement, lbs/yd$^3$
MC = Minimum amount of cementitious material specified, lbs/yd$^3$
X = 1.8 for innocuous aggregate; 3.0 for all other aggregate

$$\text{MC} - \text{MSCM} - \text{PC} \geq 0 \tag{3}$$

where:
MC = minimum amount of cementitious material specified, lbs/yd$^3$
MSCM = minimum sum of SCMs that satisfies equation (2), lbs/yd$^3$
PC = amount of portland cement, including the amount in blended cements, lbs/yd$^3$

Equation (2) (the SCM equation) and equation (3) (the cementitious equation) were applied to the mixture designs tested in this study. The study Class F fly ash has a CaO content of 3.8%, while the Class F2 fly ash has a CaO content of 13.2%. This classifies the fly ashes as FA (CaO contents < 10%) and FB (CaO contents <15%), respectively. Class C fly ashes are not permitted according to Section 90, but study mixture designs containing Class C fly ash were still applied to the equations with no mitigation capability being applied to the Class C fly ash cement replacement level. The mixtures containing blended hydraulic cement were properly divided so the overall percentage of cement and pozzolan were applied to the equation. The minimum amount of cementitious material specified (MC) was selected to be 100, so the mixture design percentages of each cementitious material could be applied directly. The aggregates in this study were not innocuous aggregates, so X was set to 3. Therefore, if the equated value is ≥3, the mixture is expected to be adequately ASR resistant.

For equation (3), MC is dependent on application. For example, the range for bridge deck slabs is 675 to 800 pounds per cubic yard (Caltrans, 2009). If a study mixture design fails equation (2), equation (3) is not applicable. If the mixture design passes equation (2), equation (3) will also pass. Therefore, no equated value is given in the result tables for each mixture.

### *Mixture Designs*

This study consisted of 12 control mixtures and 105 ternary mixtures. Six of the control mixtures were 100% Type I, Type I/II, and blended cements. Binary mixtures formed the other six control mixtures. Ternary mixtures contain either cement with two SCMs or hydraulic blended cement with one SCM.

Each mixture was uniquely identified using numbers and symbols. The number before each symbol represents the percentage of cementitious material by mass. Each material is separated by a slash. For example, the Mixture ID 60TI/20C/20F contains 60% by mass of ASTM C150 Type I cement, 20% by mass of ASTM C618 Class C fly ash, and 20% by mass of ASTM C618 Class F fly ash. Table 15 shows each constituent, identification symbol, specific gravity, and equivalent alkali content used in this study.

**Table 15. Material identification**

| Material<br>(Source) | Symbol | Specific Gravity | Equivalent Alkali (%) |
|---|---|---|---|
| **Type I** | TI | 3.04 | 0.85 |
| **Type I/II** | TI-II | 3.13 | 0.58 |
| **Type IS(20)** | TISM | 2.95 | 0.35 |
| **Type IP** | TIP | 3.11 | 0.55 |
| **Type IP(6)** | TIPM | 3.08 | 0.59 |
| **Blended Lime** | E | 3.25 | 0.55 |
| **Class C Fly Ash** | C | 2.62 | 1.79 |
| **Class F Fly Ash** | F | 2.37 | 1.76 |
| **Class F Fly Ash** | F2 | 2.41 | 4.39 |
| **GGBFS 100** | G100S | 2.82 | 0.55 |
| **GGBFS 120** | G120S | 2.96 | 0.54 |
| **Silica Fume** | SF | 2.21 | 0.51 |
| **Metakaolin** | M | 2.52 | 0.25 |

### Alkali Silica Reaction Results

For each mixture, Table 16 through Table 27 show the ASTM C1567 14 day expansion value, the calculated value when applying CSA 23.2-27A, and the calculated value using the Caltrans equation. The tables are divided into groups by SCM. Each ternary mixture can be found on both tables associated with its SCMs. To make the tables easier to analyze, the values that failed a specification are shaded and in boldface type.

**Table 16. ASR expansion and predictions of control mixtures**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| **100TI** | **0.55** | **0.00** | **0.00** |
| **100TI-II** | **0.39** | **0.00** | **0.00** |
| **80TI/20C** | **0.51** | **0.44** | **0.00** |
| **80TI/20F** | 0.10 | **0.80** | **2.40** |
| **80TI/20F2** | **0.24** | **0.57** | **2.00** |
| **65TI/35G100S** | 0.08 | **0.70** | **2.10** |
| **65TI/35G120S** | **0.20** | **0.70** | **2.10** |
| **80TI-II/20G120S** | **0.19** | **0.40** | **1.20** |
| **100TIP** | 0.04 | 1.00 | 3.00 |
| **100TISM** | **0.17** | **0.40** | **1.20** |
| **100TIPM** | **0.11** | 3.37 | **1.49** |
| **100E** | **0.62** | **0.00** | **0.00** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 17. ASR expansion and predictions of mixtures containing Class C fly ash**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| 60TI/30C/10F | **0.11** | 1.07 | **1.20** |
| 60TI/20C/20F2 | **0.17** | 1.02 | **2.00** |
| 60TI/30C/10F2 | **0.20** | **0.95** | **1.00** |
| 50TI/35G100S/15C | 0.02 | 1.03 | **2.10** |
| 60TI/20C/20G100S | **0.12** | **0.84** | **1.20** |
| 50TI/30C/20G100S | 0.04 | 1.07 | **1.20** |
| 50TI/35G120S/15C | 0.02 | 1.03 | **2.10** |
| 60TI/20C/20G120S | **0.26** | **0.84** | **1.20** |
| 50TI/30C/20G120S | 0.06 | 1.07 | **1.20** |
| 68TI-II/17G120S/15C | **0.14** | **0.67** | **1.02** |
| 60TI-II/25C/15G120S | 0.05 | **0.86** | **0.90** |
| 77TI/20C/3SF | **0.29** | 1.42 | **0.75** |
| 75TI/20C/5SF | **0.13** | 2.08 | **1.25** |
| 67TI/30C/3SF | **0.25** | 1.56 | **0.75** |
| 65TI/30C/5SF | 0.09 | 2.16 | **1.25** |
| 75TI/20C/5M | **0.31** | **0.94** | **1.25** |
| 65TI/30C/5M | **0.15** | 1.17 | **1.25** |
| 85TIP/15C | 0.10 | 1.18 | **2.55** |
| 75TIP/25C | 0.04 | 1.31 | **2.25** |
| 85TISM/15C | 0.09 | **0.67** | **1.02** |
| 75TISM/25C | 0.06 | **0.86** | **0.90** |
| 85TIPM/15C | 0.09 | 2.50 | **1.25** |
| 75TIPM/25C | 0.02 | 2.24 | **1.13** |
| 80E/20C | **0.26** | **0.44** | **0.00** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 18. ASR expansion and predictions of mixtures containing Class F fly ash**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| 60TI/30C/10F | **0.11** | 1.07 | **1.20** |
| 60TI/20F/20F2 | 0.04 | 1.37 | 4.40 |
| 60TI/30F/10F2 | 0.05 | 1.49 | 4.60 |
| 50TI/35G100S/15F | 0.03 | 1.30 | 3.90 |
| 60TI/20F/20G100S | 0.03 | 1.20 | 3.60 |
| 50TI/30F/20G100S | 0.04 | 1.60 | 4.80 |
| 50TI/35G120S/15F | 0.03 | 1.30 | 3.90 |
| 60TI/20F/20G120S | 0.02 | 1.20 | 3.60 |
| 50TI/30F/20G120S | 0.04 | 1.60 | 4.80 |
| 68TI-II/17G120S/15F | 0.04 | **0.94** | **2.82** |
| 60TI-II/25F/15G120S | 0.03 | 1.30 | 3.90 |
| 77TI/20F/3SF | 0.04 | 1.78 | 3.15 |
| 75TI/20F/5SF | 0.06 | 2.45 | 3.65 |
| 67TI/30F/3SF | 0.06 | 2.10 | 4.35 |
| 65TI/30F/5SF | 0.05 | 2.71 | 4.85 |
| 75TI/20F/5M | 0.03 | 1.30 | 3.65 |
| 65TI/30F/5M | 0.04 | 1.70 | 4.85 |
| 85TIP/15F | 0.02 | 1.45 | 4.35 |
| 75TIP/25F | 0.01 | 1.75 | 5.25 |
| 85TISM/15F | 0.06 | **0.94** | **2.82** |
| 75TISM/25F | 0.05 | 1.30 | 3.90 |
| 85TIPM/15F | 0.03 | 2.81 | 3.06 |
| 75TIPM/25F | 0.01 | 2.69 | 4.12 |
| 80E/20F | 0.05 | **0.80** | **2.40** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 19. ASR expansion and predictions of mixtures containing Class F2 fly ash**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| **60TI/30C/10F2** | **0.20** | **0.95** | **1.00** |
| **60TI/20C/20F2** | **0.17** | 1.02 | **2.00** |
| **60TI/30F/10F2** | 0.05 | 1.49 | 4.60 |
| **60TI/20F/20F2** | 0.04 | 1.37 | 4.40 |
| **50TI/35G100S/15F2** | 0.04 | 1.13 | 3.60 |
| **60TI/20F2/20G100S** | 0.05 | **0.97** | 3.20 |
| **50TI/30F2/20G100S** | 0.03 | 1.26 | 4.20 |
| **50TI/35G120S/15F2** | 0.05 | 1.13 | 3.60 |
| **60TI/20F2/20G120S** | 0.07 | **0.97** | 3.20 |
| **50TI/30F2/20G120S** | 0.03 | 1.26 | 4.20 |
| **68TI-II/17G120S/15F2** | 0.05 | **0.77** | **2.52** |
| **60TI-II/25F2/15G120S** | 0.05 | 1.01 | 3.40 |
| **77TI/20F2/3SF** | 0.07 | 1.22 | **2.75** |
| **75TI/20F2/5SF** | 0.04 | 1.65 | 3.25 |
| **67TI/30F2/3SF** | 0.04 | 1.16 | 3.75 |
| **65TI/30F2/5SF** | 0.04 | 1.36 | 4.25 |
| **75TI/20F2/5M** | **0.16** | 1.07 | 3.25 |
| **65TI/30F2/5M** | 0.04 | 1.36 | 4.25 |
| **85TIP/15F2** | 0.02 | 1.28 | 4.05 |
| **75TIP/25F2** | 0.01 | 1.46 | 4.75 |
| **85TISM/15F2** | 0.06 | **0.77** | **2.52** |
| **75TISM/25F2** | 0.05 | 1.01 | 3.40 |
| **85TIPM/15F2** | 0.10 | 1.88 | **2.76** |
| **75TIPM/25F2** | 0.02 | 1.68 | 3.62 |
| **80E/20F2** | 0.04 | **0.57** | **2.00** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 20. ASR expansion and predictions of mixtures containing Grade 100 GGBFS**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| **60TI/20C/20G100S** | **0.12** | **0.84** | **1.20** |
| **50TI/30C/20G100S** | 0.04 | 1.07 | **1.20** |
| **50TI/35G100S/15C** | 0.02 | 1.03 | **2.10** |
| **60TI/20F/20G100S** | 0.03 | 1.20 | 3.60 |
| **50TI/30F/20G100S** | 0.04 | 1.60 | 4.80 |
| **50TI/35G100S/15F** | 0.03 | 1.30 | 3.90 |
| **60TI/20F2/20G100S** | 0.05 | **0.97** | 3.20 |
| **50TI/30F2/20G100S** | 0.03 | 1.26 | 4.20 |
| **50TI/35G100S/15F2** | 0.04 | 1.13 | 3.60 |
| **64TI-II/20G100S/16G120S** | 0.05 | **0.72** | **2.16** |
| **52TI-II/35G100S/13G120S** | 0.04 | **0.96** | **2.88** |
| **62TI/35G100S/3SF** | 0.02 | 2.06 | **2.85** |
| **60TI/35G100S/5SF** | 0.04 | 2.99 | 3.35 |
| **60TI/35G100S/5M** | 0.02 | 1.20 | 3.35 |
| **80TIP/20G100S** | 0.02 | 1.20 | 3.60 |
| **65TIP/35G100S** | 0.02 | 1.35 | 4.05 |
| **80TISM/20G100S** | 0.06 | **0.72** | **2.16** |
| **65TISM/35G100S** | 0.03 | **0.96** | **2.88** |
| **80TIPM/20G100S** | 0.02 | 3.13 | **2.39** |
| **65TIPM/35G100S** | 0.02 | 2.94 | 3.07 |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 21. ASR expansion and predictions of mixtures containing Grade 120 GGBFS**

| **Mixture ID** | **ASTM C 1567 (Pass ≤ 0.10)** | **CSA A23.2-27A (Pass ≥ 1.0)** | **Caltrans Equation (Pass ≥ 3.0)** |
|---|---|---|---|
| **60TI/20C/20G120S** | **0.26** | **0.84** | **1.20** |
| **50TI/30C/20G120S** | 0.06 | 1.07 | **1.20** |
| **50TI/35G120S/15C** | 0.03 | 1.03 | **2.10** |
| **60TI-II/25C/15G120S** | 0.05 | **0.86** | **0.90** |
| **68TI-II/17G120S/15C** | **0.14** | **0.67** | **1.02** |
| **60TI/20F/20G120S** | 0.02 | 1.20 | 3.60 |
| **50TI/30F/20G120S** | 0.04 | 1.60 | 4.80 |
| **50TI/35G120S/15F** | 0.03 | 1.30 | 3.90 |
| **60TI-II/25F/15G120S** | 0.03 | 1.30 | 3.90 |
| **68TI-II/17G120S/15F** | 0.04 | **0.94** | **2.82** |
| **60TI/20F2/20G120S** | 0.07 | **0.97** | 3.20 |
| **50TI/30F2/20G120S** | 0.03 | 1.26 | 4.20 |
| **50TI/35G120S/15F2** | 0.05 | 1.13 | 3.60 |
| **60TI-II/25F2/15G120S** | 0.05 | 1.01 | 3.40 |
| **68TI-II/17G120S/15F2** | 0.05 | **0.77** | **2.52** |
| **52TI-II/35G100S/13G120S** | 0.04 | **0.96** | **2.88** |
| **64TI-II/20G100S/16G120S** | 0.05 | **0.72** | **2.16** |
| **62TI/35G120S/3SF** | 0.05 | 2.07 | **2.85** |
| **60TI/35G120S/5SF** | 0.04 | 3.01 | 3.35 |
| **78TI-II/19G120S/3SF** | 0.06 | 2.13 | **1.89** |
| **76TI-II/19G120S/5SF** | 0.04 | 3.30 | **2.39** |
| **60TI/35G120S/5M** | 0.04 | 1.20 | 3.35 |
| **76TI-II/19G120S/5M** | 0.04 | **0.88** | **2.39** |
| **80TIP/20G120S** | 0.01 | 1.20 | 3.60 |
| **65TIP/35G120S** | 0.05 | 1.35 | 4.05 |
| **80TISM/20G120S** | 0.06 | **0.72** | **2.16** |
| **65TISM/35G120S** | 0.03 | **0.96** | **2.88** |
| **80TIPM/20G120S** | 0.01 | 3.14 | **2.39** |
| **65TIPM/35G120S** | 0.04 | 2.96 | 3.07 |
| **80E/20G120S** | 0.05 | **0.40** | **1.20** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 22. ASR expansion and predictions of mixtures containing silica fume**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| **77TI/20C/3SF** | **0.29** | 1.42 | **0.75** |
| **67TI/30C/3SF** | **0.25** | 1.56 | **0.75** |
| **75TI/20C/5SF** | **0.13** | 2.08 | **1.25** |
| **65TI/30C/5SF** | 0.09 | 2.16 | **1.25** |
| **77TI/20F/3SF** | 0.04 | 1.78 | 3.15 |
| **67TI/30F/3SF** | 0.06 | 2.10 | 4.35 |
| **75TI/20F/5SF** | 0.06 | 2.45 | 3.65 |
| **65TI/30F/5SF** | 0.05 | 2.71 | 4.85 |
| **77TI/20F2/3SF** | 0.07 | 1.22 | **2.75** |
| **67TI/30F2/3SF** | 0.04 | 1.38 | 3.75 |
| **75TI/20F2/5SF** | 0.04 | 1.65 | 3.25 |
| **65TI/30F2/5SF** | 0.04 | 1.74 | 4.25 |
| **62TI/35G100S/3SF** | 0.02 | 2.06 | **2.85** |
| **60TI/35G100S/5SF** | 0.04 | 2.99 | 3.35 |
| **78TI-II/19G120S/3SF** | 0.06 | 2.13 | **1.89** |
| **62TI/35G120S/3SF** | 0.05 | 2.07 | **2.85** |
| **76TI-II/19G120S/5SF** | 0.04 | 3.30 | **2.39** |
| **60TI/35G120S/5SF** | 0.04 | 3.01 | 3.35 |
| **92TI/5M/3SF** | 0.07 | 1.74 | **2.00** |
| **90TI/5M/5SF** | 0.04 | 2.58 | **2.50** |
| **95TIP/5SF** | 0.01 | 5.61 | 4.10 |
| **97TIP/3SF** | 0.03 | 3.79 | 3.66 |
| **95TISM/5SF** | 0.05 | 3.40 | **2.39** |
| **97TISM/3SF** | 0.06 | 2.20 | **1.91** |
| **95TIPM/5SF** | 0.04 | 6.07 | **2.66** |
| **97TIPM/3SF** | 0.03 | 4.99 | **2.19** |
| **95E/5SF** | 0.06 | 3.04 | **1.25** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 23. ASR expansion and predictions of mixtures containing metakaolin**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| 75TI/20C/5M | **0.31** | **0.94** | **1.25** |
| 65TI/30C/5M | **0.15** | 1.17 | **1.25** |
| 75TI/20F/5M | 0.03 | 1.30 | 3.65 |
| 65TI/30F/5M | 0.04 | 1.70 | 4.85 |
| 75TI/20F2/5M | **0.16** | 1.07 | 3.25 |
| 65TI/30F2/5M | 0.04 | 1.36 | 4.25 |
| 60TI/35G100S/5M | 0.02 | 1.20 | 3.35 |
| 76TI-II/19G120S/5M | 0.04 | **0.88** | **2.39** |
| 60TI/35G120S/5M | 0.04 | 1.20 | 3.35 |
| 92TI/5M/3SF | 0.07 | 1.74 | **2.00** |
| 90TI/5M/5SF | 0.04 | 2.58 | **2.50** |
| 95TIP/5M | 0.02 | 1.03 | **1.25** |
| 95TISM/5M | 0.06 | **0.88** | **2.39** |
| 95TIPM/5M | 0.02 | 3.97 | **2.73** |
| 95E/5M | **0.16** | **0.50** | **1.25** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 24. ASR expansion and predictions of mixtures containing Type IP cement**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| 100TIP | 0.04 | 1.56 | 3.00 |
| 85TIP/15C | 0.10 | 1.32 | **2.55** |
| 75TIP/25C | 0.04 | 1.17 | **2.25** |
| 85TIP/15F | 0.02 | 2.26 | 4.35 |
| 75TIP/25F | 0.01 | 2.72 | 5.25 |
| 85TIP/15F2 | 0.02 | 1.75 | 4.05 |
| 75TIP/25F2 | 0.01 | 1.88 | 4.75 |
| 80TIP/20G100S | 0.02 | 1.64 | 3.60 |
| 65TIP/35G100S | 0.02 | 1.71 | 4.05 |
| 80TIP/20G120S | 0.01 | 1.64 | 3.60 |
| 65TIP/35G120S | 0.05 | 1.71 | 4.05 |
| 95TIP/5SF | 0.01 | 6.13 | 4.10 |
| 97TIP/3SF | 0.03 | 4.33 | 3.66 |
| 95TIP/5M | 0.02 | 1.98 | 4.10 |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 25. ASR expansion and predictions of mixtures containing Type IS(20) cement**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10) | CSA A23.2-27A (Pass ≥ 1.0) | Caltrans Equation (Pass ≥ 3.0) |
|---|---|---|---|
| **100TISM** | **0.17** | **0.40** | **1.20** |
| **85TISM/15C** | 0.09 | **0.67** | **1.02** |
| **75TISM/25C** | 0.06 | **0.86** | **0.90** |
| **85TISM/15F** | 0.06 | **0.94** | **2.82** |
| **75TISM/25F** | 0.05 | 1.30 | 3.90 |
| **85TISM/15F2** | 0.06 | **0.77** | **2.52** |
| **75TISM/25F2** | 0.05 | 1.01 | 3.40 |
| **80TISM/20G100S** | 0.06 | **0.72** | **2.16** |
| **65TISM/35G100S** | 0.03 | **0.96** | **2.88** |
| **80TISM/20G120S** | 0.06 | **0.72** | **2.16** |
| **65TISM/35G120S** | **0.16** | **0.96** | **2.88** |
| **95TISM/5SF** | 0.05 | 3.40 | **2.39** |
| **97TISM/3SF** | 0.06 | 2.20 | **1.91** |
| **95TISM/5M** | 0.06 | **0.88** | **2.39** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 26. ASR expansion and predictions of mixtures containing Type IP(6) cement**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10[*]) | CSA A23.2-27A (Pass ≥ 1.0[*]) | Caltrans Equation (Pass ≥ 3.0[*]) |
|---|---|---|---|
| **100TIPM** | **0.11** | 3.37 | **1.49** |
| **85TIPM/15C** | 0.09 | 2.53 | **1.26** |
| **75TIPM/25C** | 0.02 | 2.23 | **1.12** |
| **85TIPM/15F** | 0.03 | 2.81 | 3.06 |
| **75TIPM/25F** | 0.01 | 2.69 | 4.12 |
| **85TIPM/15F2** | 0.10 | 1.88 | **2.76** |
| **75TIPM/25F2** | 0.02 | 1.68 | 3.62 |
| **80TIPM/20G100S** | 0.02 | 3.13 | **2.39** |
| **65TIPM/35G100S** | 0.02 | 2.94 | 3.07 |
| **80TIPM/20G120S** | 0.01 | 3.14 | **2.39** |
| **65TIPM/35G120S** | 0.04 | 2.96 | 3.07 |
| **95TIPM/5SF** | 0.04 | 6.07 | **2.66** |
| **97TIPM/3SF** | 0.03 | 4.99 | **2.19** |
| **95TIPM/5M** | 0.02 | 3.97 | **2.73** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

**Table 27. ASR expansion and predictions of mixtures containing limestone blended cement**

| Mixture ID | ASTM C 1567 (Pass ≤ 0.10*) | CSA A23.2-27A (Pass ≥ 1.0*) | Caltrans Equation (Pass ≥ 3.0*) |
|---|---|---|---|
| **100E** | **0.62** | **0.00** | **0.00** |
| **80E/20C** | **0.26** | **0.44** | **0.00** |
| **80E/20F** | 0.05 | **0.80** | **2.40** |
| **80E/20F2** | 0.04 | **0.57** | **2.00** |
| **80E/20G120S** | 0.05 | **0.40** | **1.20** |
| **95E/5SF** | 0.06 | 3.04 | **1.25** |
| **95E/5M** | **0.16** | **0.50** | **1.25** |

Mixture designs that do not pass the standard are **shaded and in boldface type**.

## ASTM C1567 Accelerated Mortar-Bar Testing Discussion

### *Control Mixtures*

Of the 12 control mixtures, 9 had expansions greater than the maximum 0.10% allowable. The limestone blended cement had the highest ASR expansion (0.62%), followed by 100% Type I (0.55%), the binary blend of 80% Type I cement and 20% Class C fly ash (0.52%), and 100% Type I/II cement (0.39%). The blended and binary mixtures, with the exception of the mixture containing 20% Class C fly ash, all experienced expansions less than 0.25%. The control mixtures performed as expected with 14 day expansions >0.10%, because of the harsh environment and highly reactive aggregate. The SCM replacement was beneficial as it lowered the expansion compared to the 100% Type I, but higher levels of replacement are required to mitigate ASR for binary mixtures. Figure 5 shows the 14 day expansions for the control mixtures.

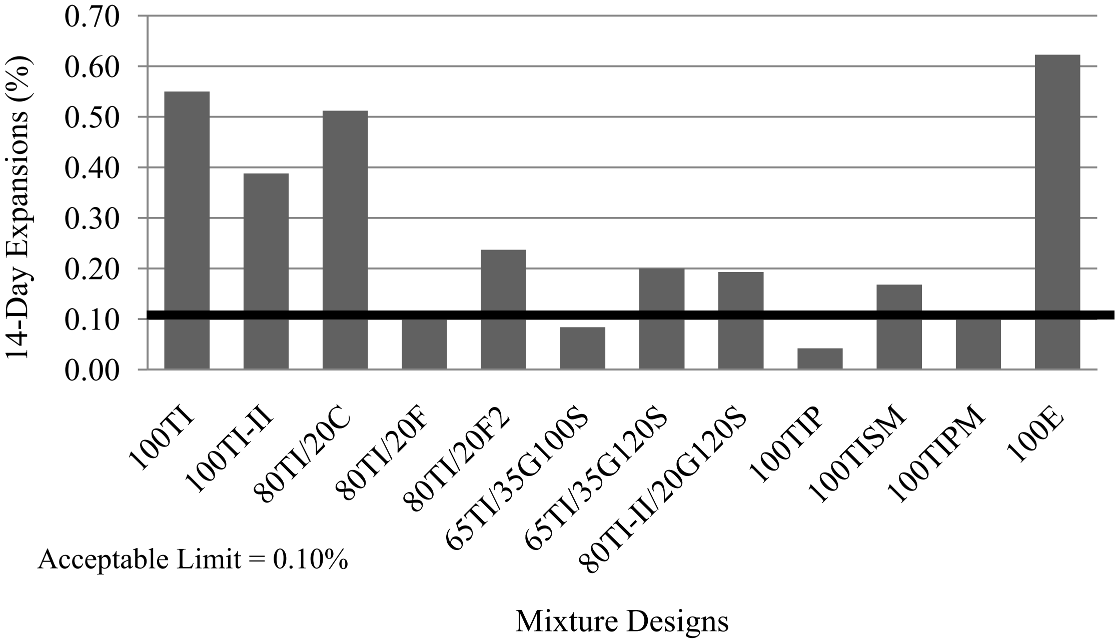

**Figure 5. ASTM C1567 ASR expansion for control mixtures**

*Class C Fly Ash*

The 14 day mortar bar expansion for the mixtures containing Class C fly ash ranged between 0.02% and 0.31%. Only 12 of the 24 mixture designs had expansions less than the accepted limit of 0.10%. Of the 8 mixtures containing Class C fly ash and GGBFS, 7 had expansions of 0.14% or less. The 1 mixture containing Class C fly ash and GGBFS with an expansion higher than 0.14% had an expansion of 0.29%. This mixture contained 20% Grade 120 GGBFS and 20% Class C fly ash. Both SCMs could have led to the significantly higher expansion. The Grade 120 GGBFS is more reactive than the Grade 100 GGBFS. By being more reactive, the alkalis within the GGBFS are released faster into the pore water of the concrete leading to an increased ASR expansion. The Class C fly ash has a high CaO content of 27.18%, which requires higher replacement levels to mitigate ASR, so with only a 20% cement replacement, it has lower migration capabilities than a cement replacement level of 30%. Both of these concepts are supported throughout the study. Two mixtures tested contained 20% Class C fly ash and 20% GGBFS. These mixtures had higher ASR expansions than the 2 mixtures that contained 30% Class C fly ash and 20% GGBFS. The same effect was seen for the mixtures containing Class C fly ash and silica fume. The mixtures with higher replacement levels of Class C fly ash had lower ASR expansions.

None of the mixtures with Class C and Class F or F2 fly ashes had ASR expansions ≤0.10%. The mixture with Class C and Class F fly ash did have less ASR expansion than the Class C and Class F2 mixtures. The probable cause of the expansion difference is the higher CaO and alkali content of the Class F2 fly ash. Figure 6 shows the 14 day ASR expansions of the mixtures containing Class C fly ash blended with Class F fly ash, Class F2 fly ash, Grade 100 GGBFS, or

Grade 120 GGBFS. Figure 7 shows the 14 day ASR expansions of the mixtures containing Class C fly ash blended with silica fume, metakaolin, or blended cement.

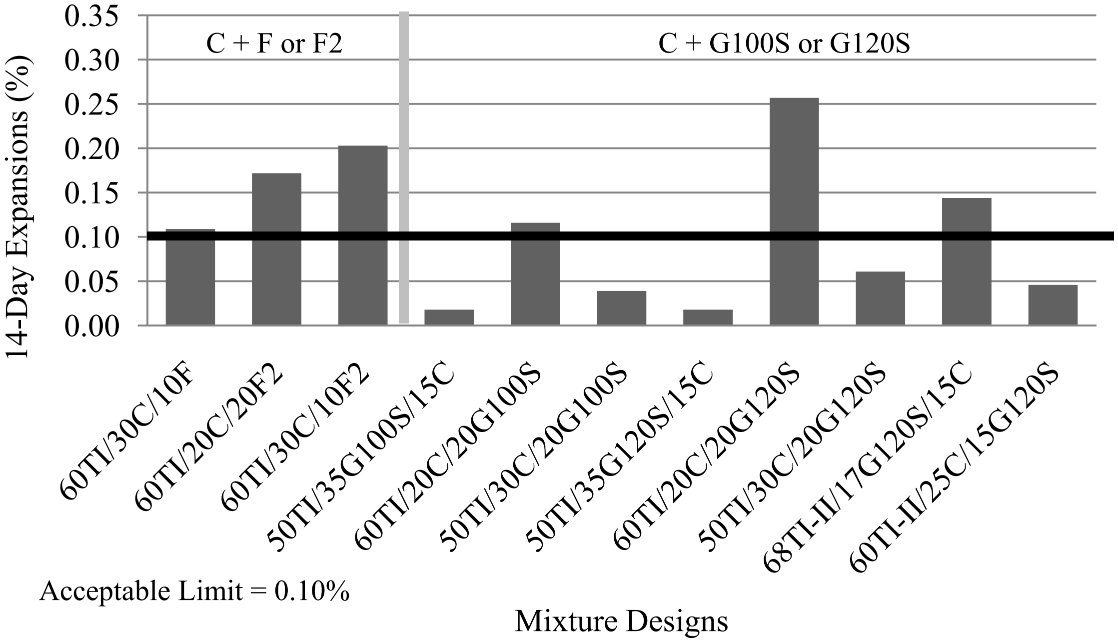

**Figure 6. ASTM C1567 ASR expansion for mixtures containing Class C fly ash blended with Class F or F2 fly ash or Grade 100 or 120 GGBFS**

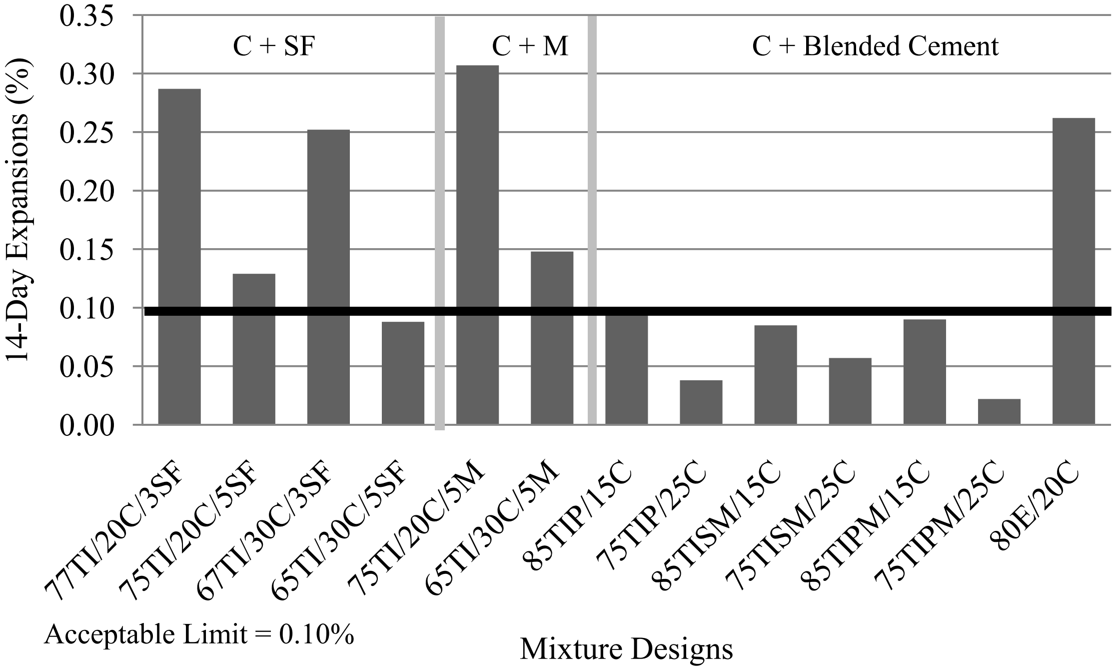

**Figure 7. ASTM C1567 ASR expansion for mixtures containing Class C fly ash blended with silica fume, metakaolin, or blended cement**

*Class F Fly Ash*

Class F fly ash is highly effective at mitigating ASR. The largest ASR expansion, with the exception of the mixture containing Class C fly ash, was 0.06% with an average ASR expansion of 0.037%. The mixture with Class C fly ash had an expansion of 0.11% and is the only mixture that did not have an expansion less than 0.10%.

Figure 8 shows the 14 day ASR expansions for mixtures containing Class F fly ash blended with Class C or F2 fly ash or Grade 100 or 120 GGBFS. Figure 9 shows the 14 day ASR expansions of the mixtures containing Class F fly ash blended with silica fume, metakaolin, or blended cement.

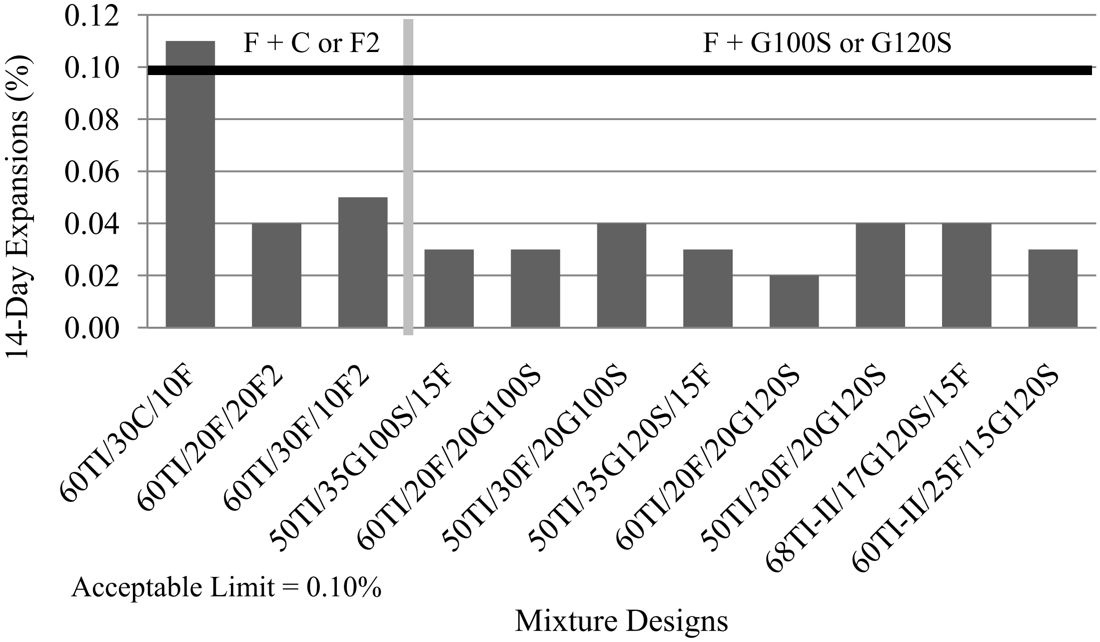

**Figure 8. ASTM C1567 ASR expansion for mixtures containing Class F fly ash blended with Class C or F2 fly ash or Grade 100 or 120 GGBFS**

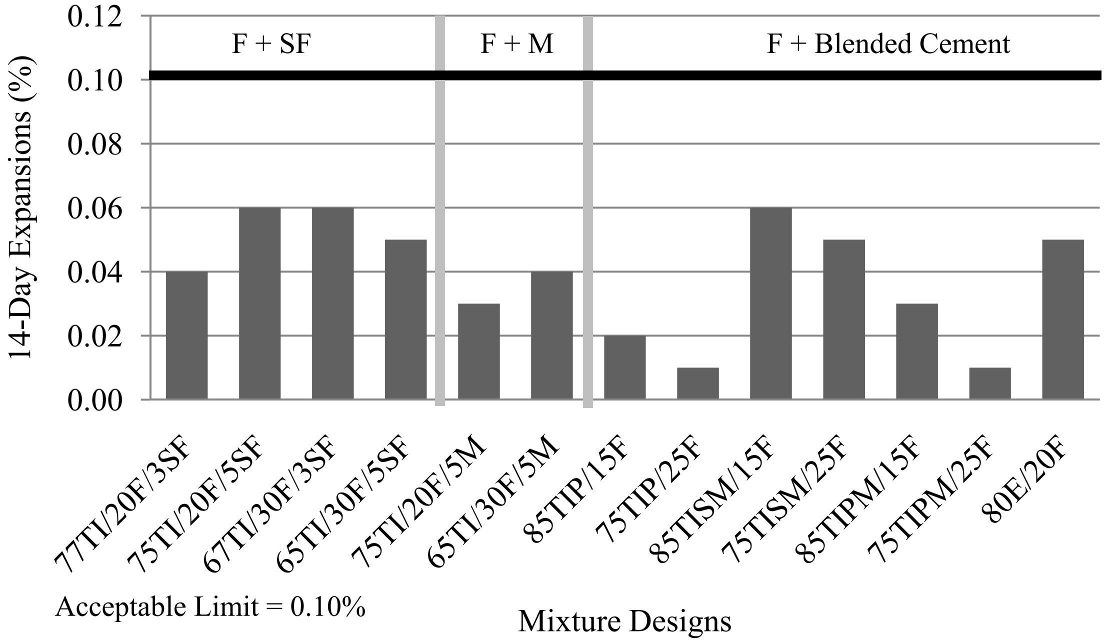

**Figure 9. ASTM C1567 ASR expansion for mixtures containing Class F fly ash blended with silica fume, metakaolin, or blended cement**

*Class F2 Fly Ash*

The ASR expansion results for mixtures containing Class F2 fly ash are similar to the mixtures containing Class F fly ash, but with a slightly higher average expansion of 0.044%. An expansion of ≤0.10% was seen in all mixture except the 2 mixtures containing Class C fly ash and the mixture with 20% Class F2 fly ash and 5% metakaolin. The 2 mixtures that contain Class C fly ash presented a different trend than the other study mixtures containing Class C fly ash. Instead of the higher Class C fly ash replacement level having a lower expansion, the higher replacement level of Class C fly ash had a higher expansion. The mixture with 30% Class C and 10% Class F2 fly ash had an expansion of 0.20%, while the mixture with 20% Class C and 20% Class F2 fly ash had an expansion of 0.17%. It is likely that the lower mitigating capability of Class F2 fly ash used at only 10% cement replacement could not overcome the trend of Class C fly ash having less ASR expansion with higher cement replacement. It is expected that a mixture with 30% Class C fly ash and 20% Class F2 fly ash would have a lower expansion than either of the two study mixture designs discussed above.

The third mixture that failed ASTM C1567 contained 20% Class F2 fly ash and 5% metakaolin with an expansion of 0.16%. The low replacement levels of this mixture could not adequately mitigate ASR. The low replacement levels also caused the mixture of 15% Class F2 fly ash and Type IP(6) to have an expansion of 0.10%, which is the limit of ASTM C1567. Figure 10 shows the 14 day ASR expansions for mixtures containing Class F2 fly ash blended with Class C or F fly ash or Grade 100 or 120 GGBFS. Figure 11 shows the 14 day ASR expansions of the mixtures containing Class F2 fly ash blended with silica fume, metakaolin, or blended cement.

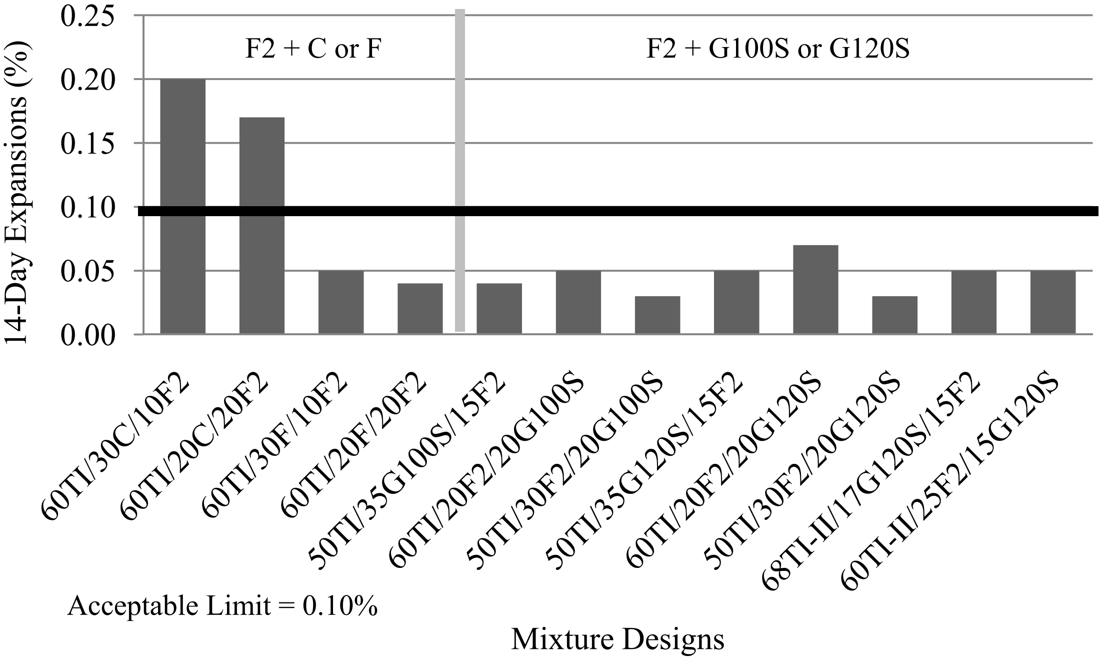

**Figure 10. ASTM C1567 ASR expansion for mixtures containing Class F2 fly ash blended with Class C or F fly ash or Grade 100 or 120 GGBFS**

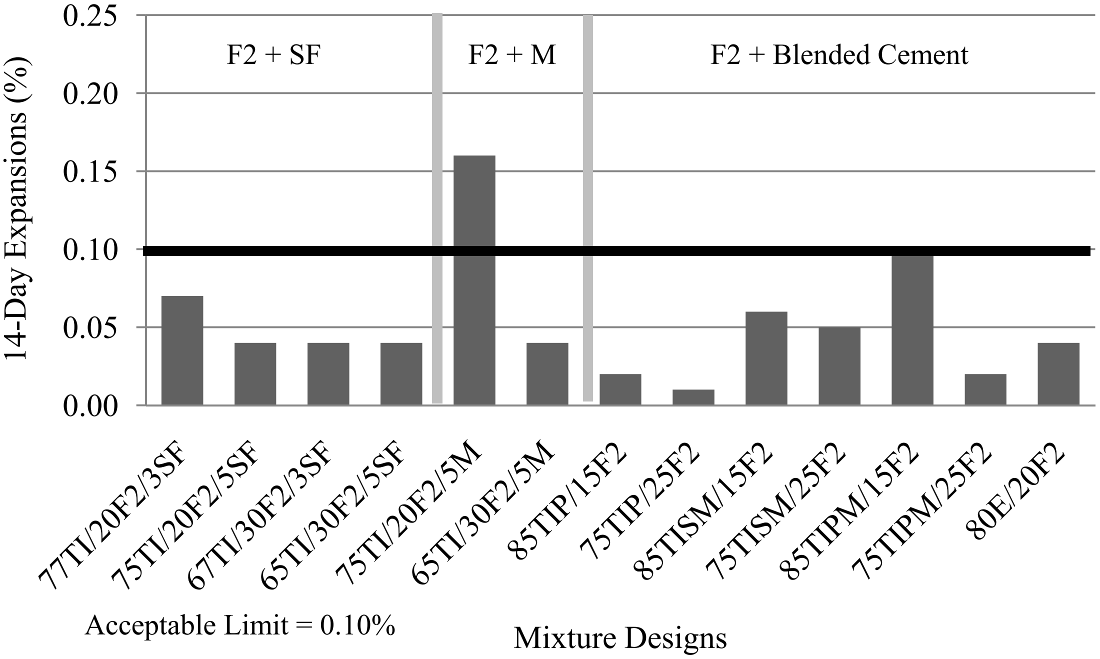

**Figure 11. ASTM C1567 ASR expansion for mixtures containing Class F2 fly ash blended with silica fume, metakaolin, or blended cement**

*Grade 100 GGBFS*

The mortar mixtures containing Grade 100 GGBFS showed almost the same pattern as the mixtures containing Class F or F2 fly ash. The combination of 20% Class C fly ash and 20% Grade 100 GGBFS showed the maximum expansion of 0.12%. The mixture with 30% Class C fly ash and 20% Grade 100 GGBFS had a low expansion of only 0.04%. The average for the 19 mixtures that had expansions ≤0.10% was the lowest of any SCM at 0.033%.

Figure 12 shows the 14 day ASR expansions for mixtures containing Grade 100 GGBFS blended with Class C, F, or F2 fly ash or Grade 120 GGBFS. Figure 13 shows the 14 day expansions for mixtures containing Grade 100 GGBFS blended with silica fume, metakaolin, or blended cement.

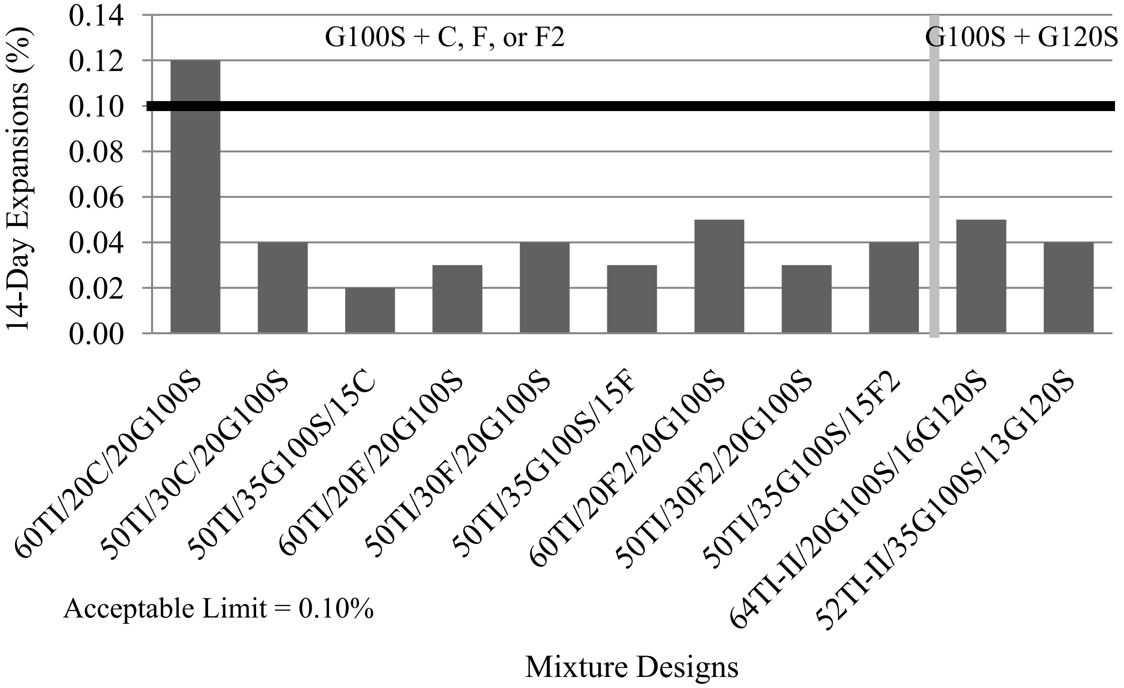

**Figure 12. ASTM C1567 ASR expansion for mixtures containing Grade 100 GGBFS blended with Class C, F, or F2 fly ash or 120 GGBFS**

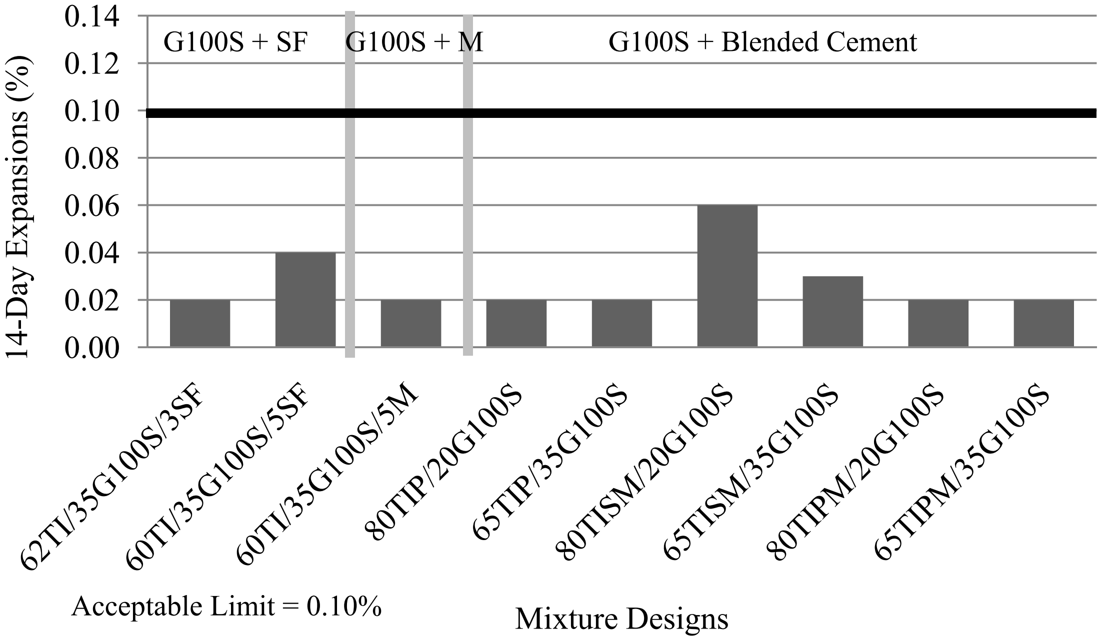

**Figure 13. ASTM C1567 ASR expansion for mixtures containing Grade 100 GGBFS blended with silica fume, metakaolin, or blended cement**

*Grade 120 GGBFS*

Grade 120 GGBFS showed a similar pattern as both Class F and F2 fly ash and Grade 100 GGBFS. The only expansions >0.10% were in the mixtures containing Class C fly ash. The Grade 120 GGBFS has a higher activity or reactivity rate than the Grade 100 GGBFS. This higher activity leads to increased alkali content in the concrete pore water solution, which caused a generally higher ASR expansion than the mixtures with Grade 100 GGBFS. Mixtures containing Grade 120 GGBFS with an ASR expansion ≤0.10% had an average expansion of 0.041%. The mixtures with Class C fly ash, again, showed the trend that higher replacement levels of Class C fly ash perform better with the 20% replacement having less expansion than the 15% replacement.

Figure 14 shows the 14 day ASR expansions for mixtures containing Grade 120 GGBFS blended with Class C, F, or F2 fly ash. Figure 15 shows the 14 day ASR expansions for mixtures containing Grade 120 GGBFS blended with Grade 100 GGBFS, silica fume, or metakaolin, while Figure 16 shows the 14 day ASR expansions for mixtures containing Grade 120 GGBFS mixed with blended cements.

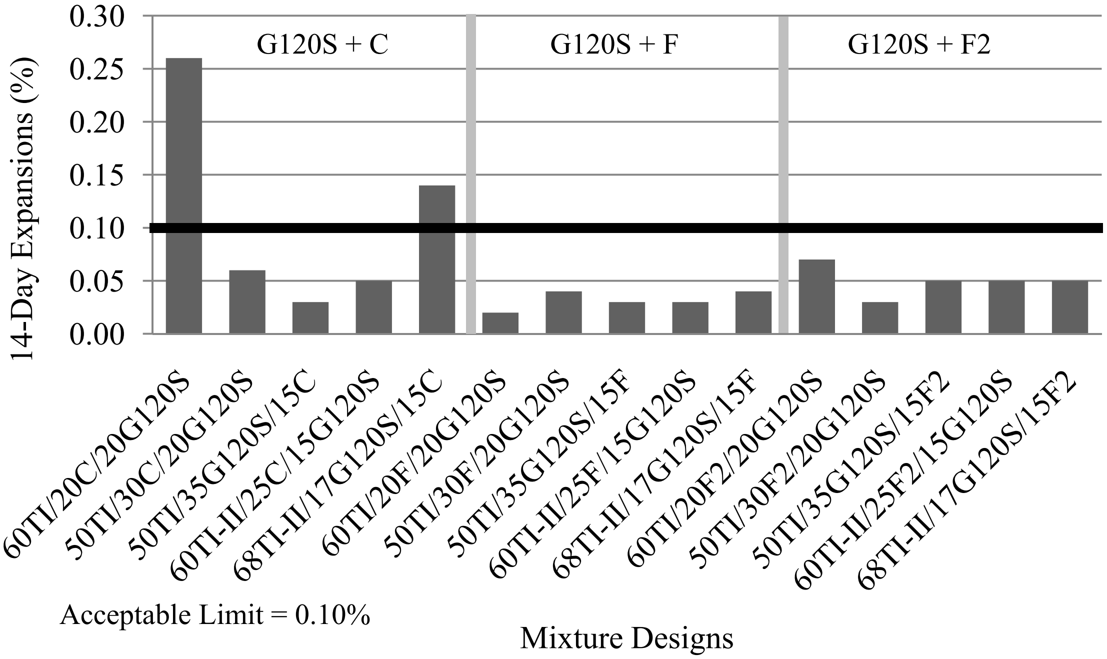

**Figure 14. ASTM C1567 ASR expansion for mixtures containing Grade 120 GGBFS blended with Class C, F or F2 fly ash**

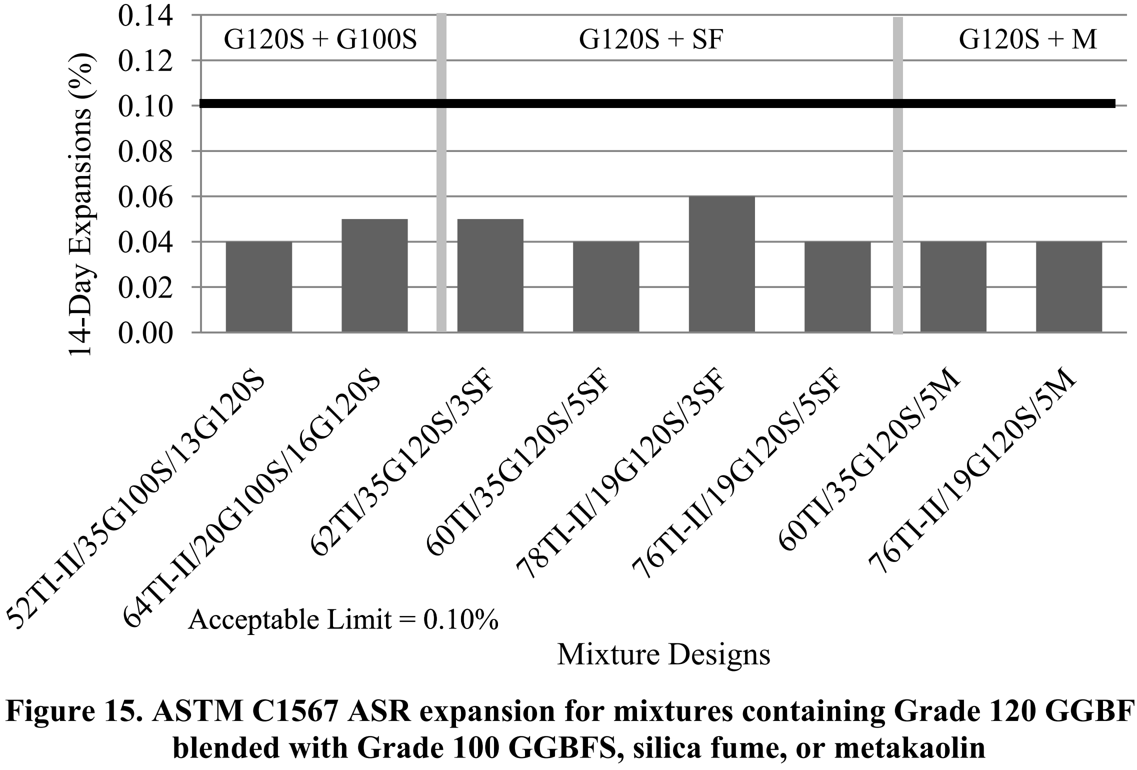

**Figure 15. ASTM C1567 ASR expansion for mixtures containing Grade 120 GGBFS blended with Grade 100 GGBFS, silica fume, or metakaolin**

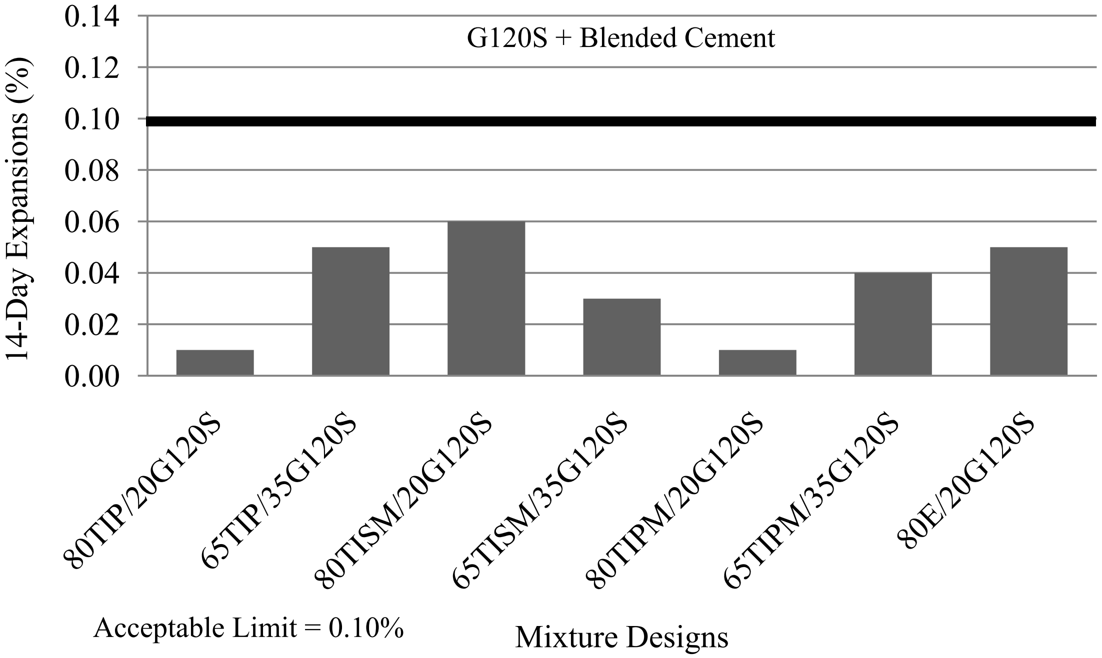

**Figure 16. ASTM C1567 expansion for mixtures containing Grade 120 GGBFS and blended cement**

*Silica Fume*

The study mixtures contained either 3 or 5% silica fume. Of the 27 mixtures tested that contained silica fume, only 3 had expansions >0.10%. All 3 of these mixtures contained Class C fly ash. The only other mixture with an expansion greater than 0.08% also contained Class C fly ash. Two trends were identified for mixtures that contained silica fume. First, mixtures with 5% silica fume replacement had lower ASR expansions than mixtures with 3% replacement. Second, mixtures containing silica fume and fly ash, for the same SCM combination, had lower ASR expansions with increased fly ash replacement levels. The only mixture containing Class C fly ash with an acceptable expansion of 0.09% satisfied both trends with 5% silica fume and the highest fly ash replacement of 30%.

Figure 17 shows the 14 day ASR expansions for mixtures containing silica fume blended with Class C, F, or F2 fly ash. Figure 18 shows the 14-day ASR expansions for the mixtures containing silica fume blended with Grade 100 or 120 GGBFS or metakaolin, while Figure 19 shows the 14 day ASR expansions of silica fume mixed with blended cements.

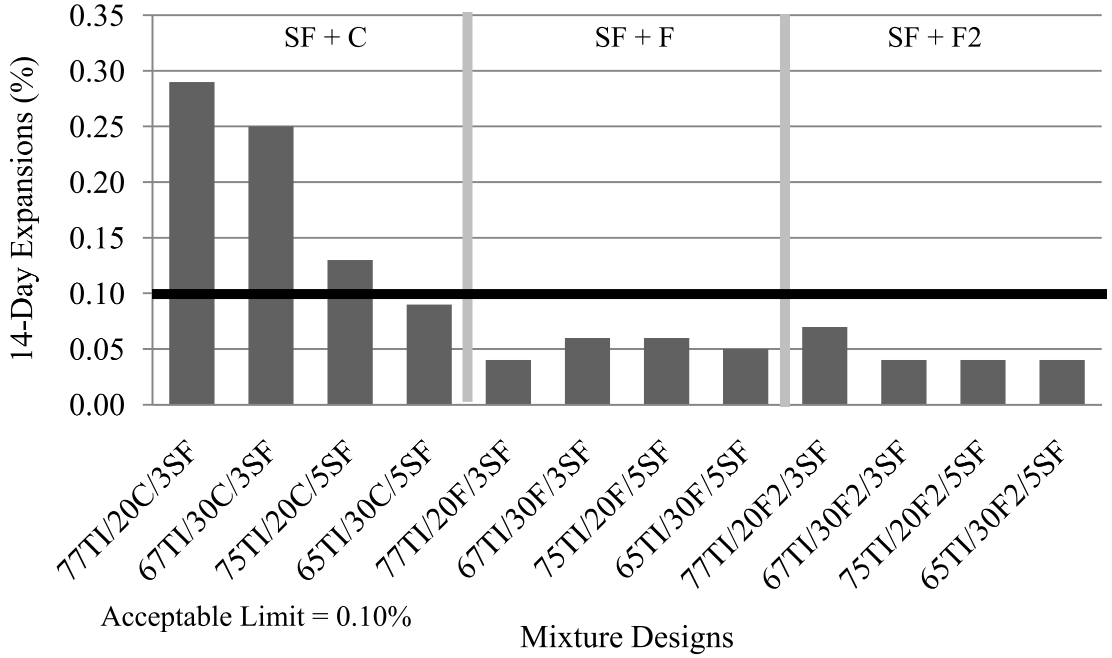

**Figure 17. ASTM C1567 ASR expansion for mixtures containing silica fume blended with Class C, F, or F2 fly ash**

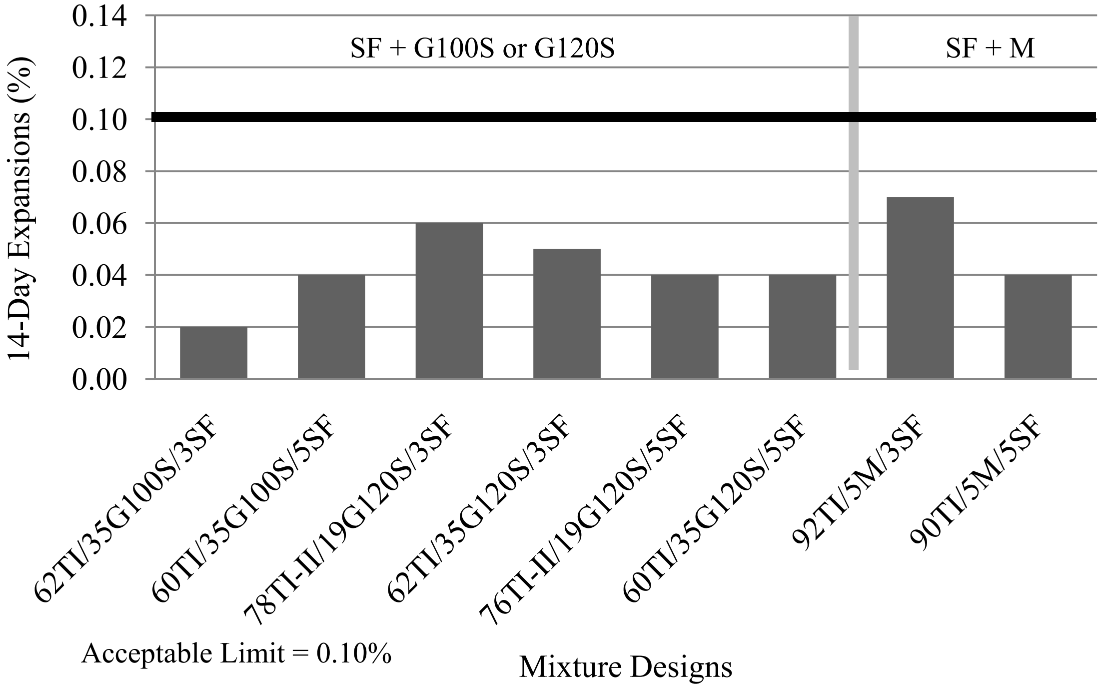

**Figure 18. ASTM C1567 ASR expansion for mixtures containing silica fume blended with Grade 100 or 120 GGBFS or metakaolin**

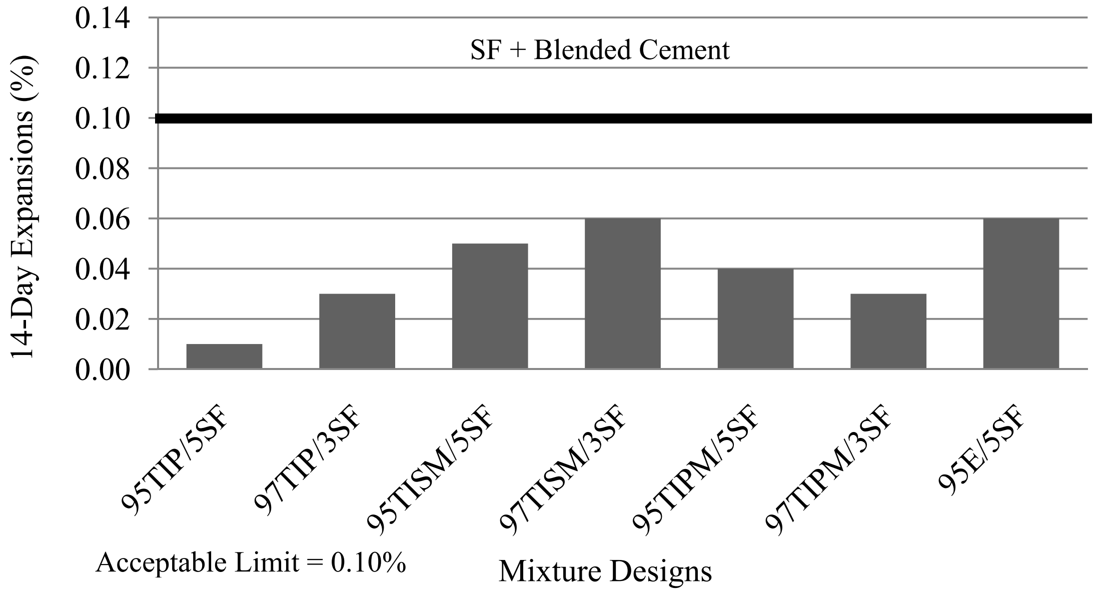

**Figure 19. ASTM C1567 ASR expansion for mixtures containing silica fume and blended cement**

*Metakaolin*

Metakaolin was used at 5% cement replacement. Once again, the mixtures containing Class C fly ash had expansions >0.10%. Two other mixtures also had expansions >0.10%. One of these mixtures included 20% Class F2 ash with an expansion of 0.16%. The higher CaO and alkali content of the Class F2 fly ash are probable causes for this higher expansion. The CaO content and a relatively low replacement level could have caused a slight pessimum effect. The mixture with limestone blended cement also had an expansion of 0.16%. The additional limestone in the cement reduces the total alkali content of the concrete but does not increase the C-S-H content. With only 5% metakaolin, the metakaolin cement replacement level was not high enough to reduce the expansion below the 0.10% limit. Figure 20 shows the 14 day ASR expansion for mixtures containing metakaolin.

*Type IP Cement*

The study Type IP cement is a blend of 25% Class F fly ash (not the same fly ash as the other ashes in this study) and 75% Type I portland cement. If the Type IP cement is broken into its cementitious constituents and compared with similar ternary mixture designs, there is no significant difference in expansions. All ternary blends with Type IP cement had an expansion ≤0.10%. The 1 mixture with an expansion of 0.10% contained 15% Class C fly ash. Figure 21 shows the 14 day ASR expansions for mixtures containing Type IP cement.

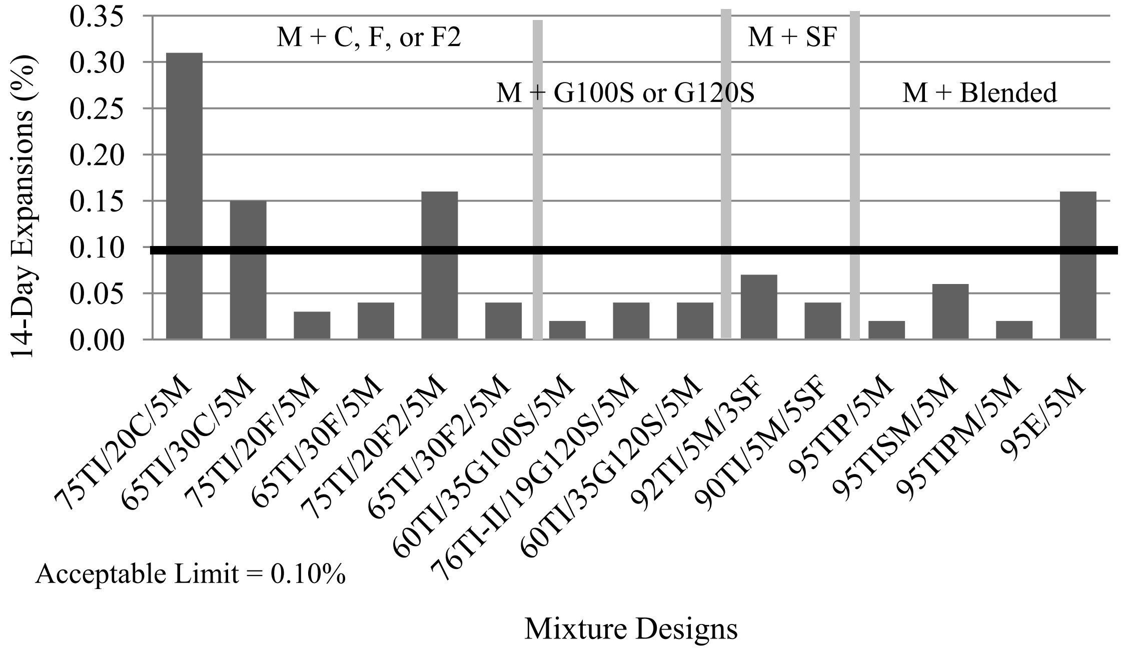

**Figure 20. ASTM C1567 ASR expansion for mixtures containing metakaolin**

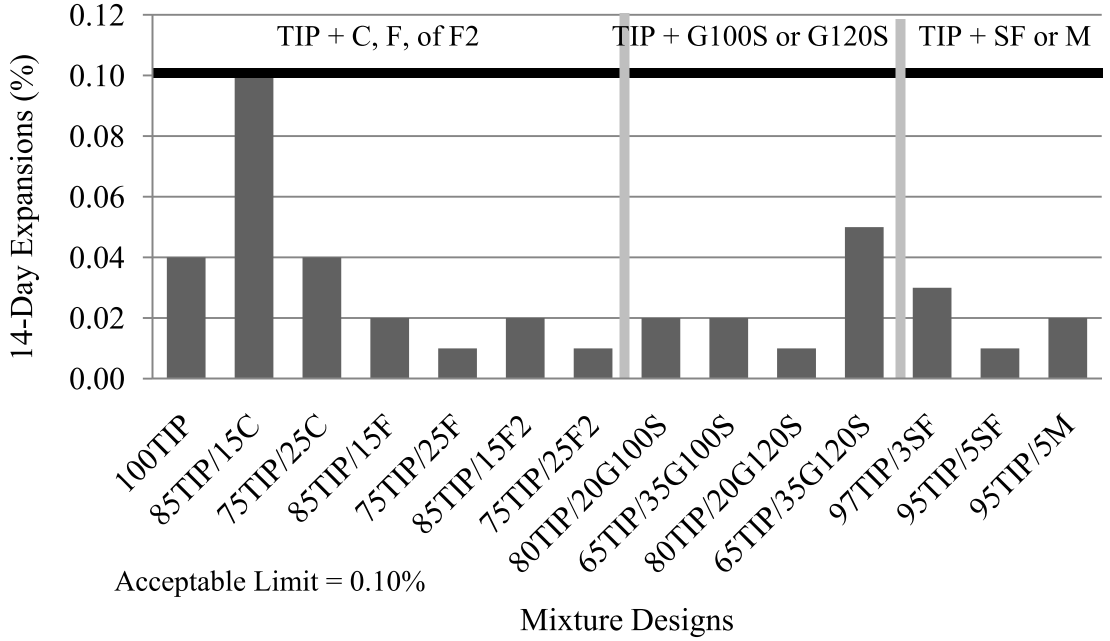

**Figure 21. ASTM C1567 ASR expansion for mixtures containing Type IP cement**

*Type IS(20) Cement*

The study Type IS(20) cement is a blend of 20% Grade 100 GGBFS and 80% Type I portland cement. The 20% Grade 100 GGBFS in the Type IS(20) cement was not adequate in reducing ASR expansion when used by itself with an expansion of 0.17%, but when blended with a third constituent, all mixtures had an expansion ≤0.10%. Lower expansions were seen when Type IS(20) was blended with GGBFS than when blended with fly ash. When comparing a Type IS(20) and silica fume blend with a non-blended Type I cement, GGBFS, and silica fume, the 14 day ASR expansions are very similar. An example of this can be seen in the mixture with 95% Type IS(20) blended with 5% silica fume, which had an ASR expansion of 0.05% and a very similar SCM ratio mixture of 76% Type I-II, 19% Grade 120 GGBFS, and 5% silica fume, which had an ASR expansion of 0.04%. The pre-blending of the Type IS(20) does not appear to have a significant effect on the ASR resistance of the SCMs. Figure 22 shows the 14 day ASR expansions for mixtures containing Type IS(20) cement.

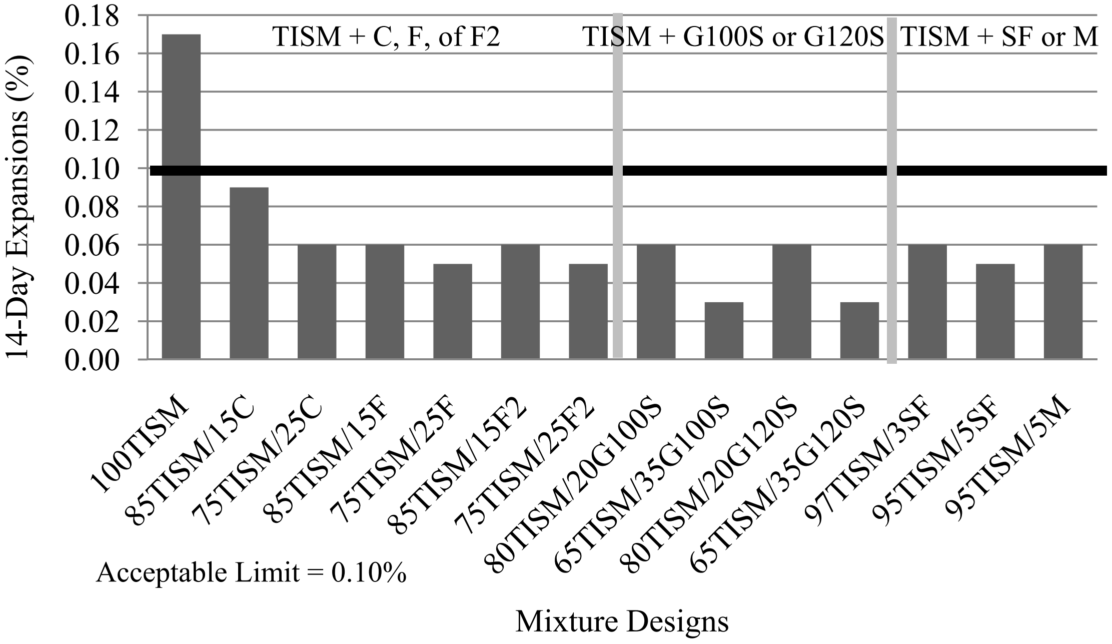

**Figure 22. ASTM C1567 ASR expansion for mixtures containing Type IS(20) cement**

*Type IP(6) Cement*

The silica fume cement replacement level in the Type IP(6) cement is 5.95%, which is higher than the silica fume replacements tested. The 100% Type IP(6) cement had an expansion of 0.11%. With an additional 3% silica fume cement replacement level, the ASR expansion dropped to 0.03%. The ternary blend with 5% silica fume had an expansion of 0.04%. The reduction between the 3 and 5% replacement is not significant. All ternary blends with Type IP(6) cement had an expansion ≤0.10%. The 2 mixtures with expansions of 0.09 and 0.10% had 15% replacement of Class F2 and C fly ash, respectively. Using the ASTM C1567 test method, silica fume content above 9% appear to provide ASR mitigation. Figure 23 shows the 14 day ASR expansions for mixtures containing Type IP(6) cement.

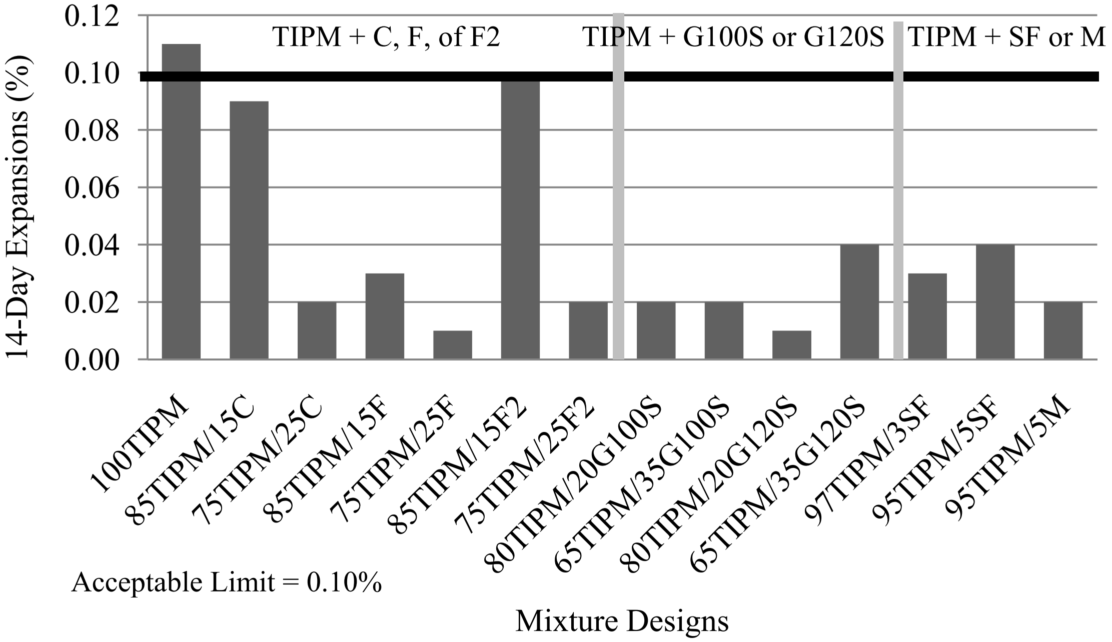

**Figure 23. ASTM C1567 ASR expansion for mixtures containing Type IP(6) cement**

*Limestone Blended Cement*

The limestone blended cement has 10% limestone, which does not chemically react, but aids in the formation of cementitious properties. When used alone or blended with Class C fly ash or metakaolin, expansions >0.10% were seen. However, low replacements (20%) of either Class F fly ash or Grade 120 GGBFS, along with high replacement (5%) of silica fume, did reduce expansion to a level below the ASR limit. Figure 24 shows the 14 day ASR expansions for mixtures containing limestone blended cement.

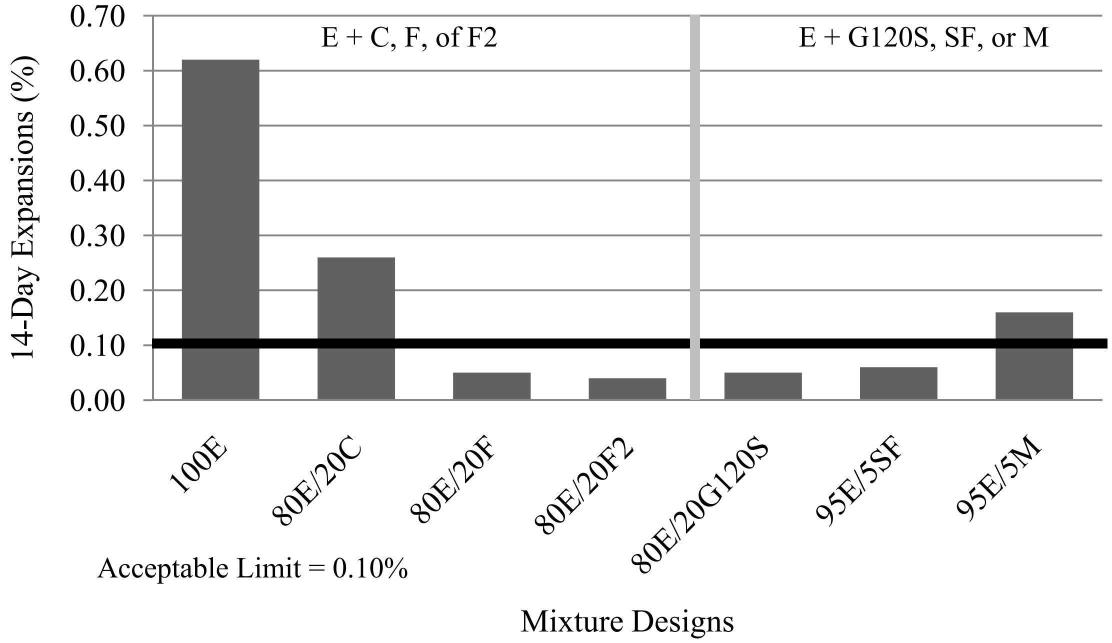

**Figure 24. ASTM C1567 expansion for mixtures containing limestone blended cement**

### Fitting Existing Standard Specifications

Several methods of predicting ternary combinations have been implemented in specifications in recent years (CSA, 2000; Caltrans, 2009). These equations are based on small samples of ternary data or interpretations of binary data to ternary or quaternary predictions. This section discusses the findings of the study to existing equations.

*Canadian Standards Association CSA A23.2-27A*

CSA Standard Specifications for mitigate ASR have been in place for more than a decade. The CSA method is based on using binary blends, but ternary blends may be used with no consideration for interaction between SCMs.

Mixtures that contained Class C fly ash had weak correlations between ASTM C1567 and the CSA standard. This weakness comes from the assumed required quantity of Class C fly ash to make a binary mixture able to mitigate ASR. A concrete having 45% replacement would likely fail the additional tests required and would not be approved for use.

Class F fly ash and GGBFS performed very well as expected and had a strong correlation. However, there were 6 mixtures with Class F or F2 fly ash, blended with Grade 100 or 120 GGBFS, that passed ASTM C1567 but did not satisfy the CSA specification. These mixture designs had a total SCM replacement from 32 to 40% and performed with a maximum expansion of 0.07%.

There were 6 mixtures tested that contained portland cement and GGBFS. These 6 mixtures were either Type I-II cement blended with Grade 100 and 120 GGBFS or Type IS(20) cement blended with Grade 100 or 120 GGBFS. All 6 mixtures failed the CSA specification but had a maximum expansion of 0.06%. The 2 mixtures with a total equivalent SCM replacement of 48% did have lower expansions than the 2 mixtures with total equivalent SCM replacements of 36%.

The mixtures containing silica fume had a good correlation. The mixtures that passed CSA but not ASTM C1567 all included Class C fly ash. The required CSA replacement level of silica fume is based on the total equivalent alkali content of the concrete. All the mixtures tested had an average alkali content of 0.92%, so the average minimum replacement level of silica fume was 2.76%. The minimum silica fume replacement level used in this study was 3%, so all mixtures containing silica fume would be expected to pass the standard based on the silica fume content alone.

Metakaolin was assigned a minimum replacement level of 10% for this study. This value proved appropriate as the same trends appeared as with many other combinations. Figure 25 graphically shows the expansions of all the ternary mixture designs tested in this study. The light gray shows the number of mixtures for a given expansion that had a calculated value ≥1.0 and, therefore, satisfied the CSA standard specification. In total, of the 117 mixtures tested in this study, 35 failed the CSA standard. Of these 35 mixtures, 22 passed ASTM C1567 with expansions ≤0.10%.

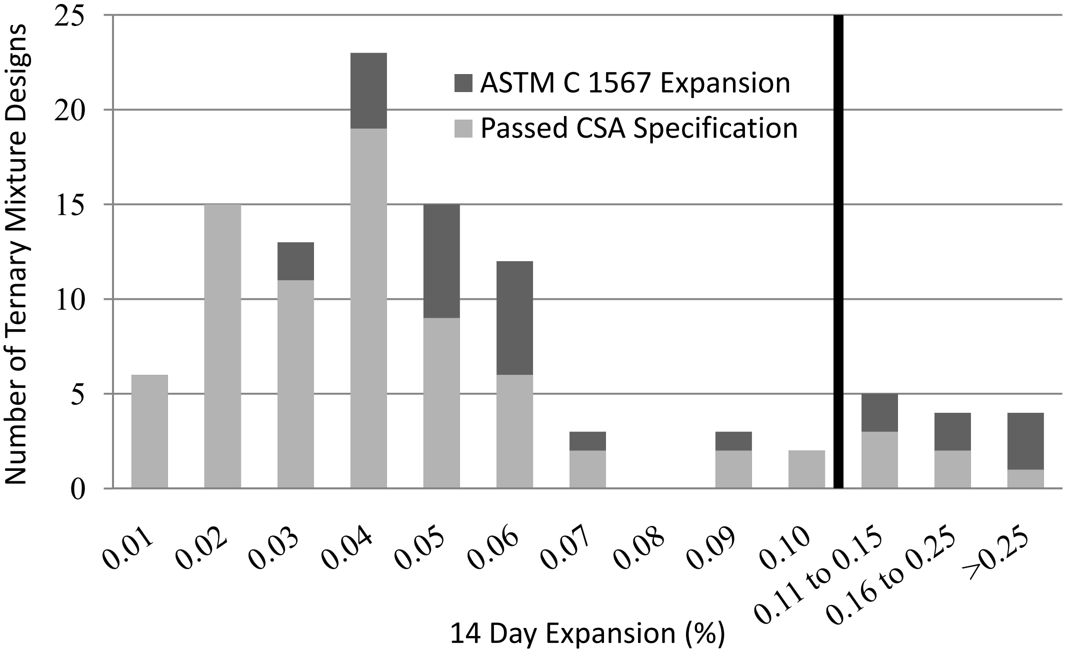

**Figure 25. Number of mixtures for a given expansion that passed CSA standard specification requirements**

There were 6 mixtures that failed ASTM C1567 but passed the CSA standard. All 6 of these mixtures contained Class C fly ash. Due to the extra testing requirements to get a Class C fly ash approved for use, the reliability of the standard is upheld. The assumption that there is no interaction between SCMs is not supported by this study's findings. There seems to be significant interaction when using ternary blends, as compared to binary blends.

*California Department of Transportation Section 90*

The California Department of Transportation (Caltrans) 2006 Standard Specifications Section 90, *Portland Cement Concrete*, was significantly altered for the 2009 standard. The 2006 standard begins by a classification system for each structure that gives a range or a minimum amount of cementitious material required. Table 28 is a replication of the table provided in the 2006 Section 90, which specifies cementitious material content requirements for specific project types.

The cementitious minima from Table 28 must contain no less than 75% cement and the remaining cementitious material must fulfill one of the following requirements: 1) for admixtures with CaO contents ≤2% (Class F fly ash), a minimum replacement level of 15% by weight of the total amount of cementitious material to be used, 2) for CaO contents between 2 and 10% (Class F fly ash), a minimum replacement level of 25% is required, 3) for silica fume, a minimum replacement level of 10% is required. The final restriction is the total amount of SCM replacement cannot exceed 35% by weight of total amount of cementitious material in the mixture. The 2006 standards also required the use of low alkali cement and did not allow GGBFS to be used.

**Table 28. 2006 Caltrans Standard Specifications Section 90 cementitious material requirements**

| Use | Cementitious Material Content Pounds/CY |
|---|---|
| Concrete designated by compressive strength: | |
| Deck slabs and slab spans of bridges | 675 min., 800 max. |
| Roof sections of exposed top box culverts | 675 min., 800 max. |
| Other portions of structures | 590 min., 800 max. |
| Concrete not designated by compressive strength: | |
| Deck slabs and slab spans of bridges | 675 min. |
| Roof sections of exposed top box culverts | 675 min. |
| Prestressed members | 675 min. |
| Seal courses | 675 min. |
| Other portion of structures | 590 min. |
| Concrete for precast members | 590 min., 925 max. |

The 2009 Standard Specification kept the same minimum/maximum cementitious material contents and still requires blended or binary mixtures, but now allows different types of SCMs to be used. The minimum cement replacement levels and how the mixture deigns are formulated have also been updated.

The 2009 standard allows raw or calcined natural pozzolans including metakaolin, Grades 100 and 120 GGBFS, and ultrafine fly ash (UFFA) to be used. The 2009 standard also allows for the blending of fly ash from different sources, as long as the combination has consistent properties and conforms to AASHTO M 295 Class F fly ash. Fly ashes with CaO content up to 15% are also now allowed.

A minimum cement replacement level for SCMs in binary mixtures was established. The minimum cement replacement level of GGBFS is 50%, which eliminated the 2006 standard provision of a maximum SCM cement replacement of 35%. Silica fume, metakaolin, and UFFA have a minimum replacement level of 12%. All fly ashes with CaO content up to 10% are grouped together with a required 25% cement replacement. Fly ashes with CaO contents from 10 to 15% have a minimum replacement level of 30%.

Formulating a mixture design is now a three-step process: 1) Determine the minimum and maximum cementitious requirement, 2) Satisfy the SCM equation (2), and 3) Satisfy the cementitious equation (3).

To satisfy the SCM equation, at least the minimum SCM cement replacement level is required. To satisfy the cementitious equation, at least the minimum required replacement level of the SCM is to be used. If more than the minimum cement replacement level is used, both equations are satisfied.

A practical binary mixture design example proves the repetitive nature of the equations. If the design problem was to determine the cementitious materials for a deck slab not designated by compressive strength and using the minimum FA fly ash replacement level. The minimum cementitious content for the element is 675 lbs/cy and the minimum replacement level for the fly ash is 25%. The SCM equation (2) becomes:

$$\frac{0 + 12 \times 25\% \times 675\ \text{lbs/cy} + 0 + 0}{675\ \text{lbs/cy}} = 3.0 \geq 3.0 \tag{4}$$

The cementitious equation (3) is also applied:

$$675\ \text{lbs/cy} - 25\% \times 675\ \text{lbs/cy} = 0 \geq 0 \tag{5}$$

If the contractor wanted to reduce costs and use 30% FA fly ash and 70% portland cement, the SCM equation becomes:

$$\frac{0 + 12 \times (30\% \times 675\ \text{lbs/cy}) + 0 + 0}{675\ \text{lbs/cy}} = 3.6 \geq 3 \qquad (6)$$

When applying the mixture design to the cementitious equation, the minimum sum of SCMs that satisfies the SCM equation (MSCM) is 25% of the minimum cementitious content. The cementitious equation becomes:

$$675\ \text{lbs/cy} - 25\% \times 675\ \text{lbs/cy} - 70\% \times 675 = 33.7 \geq 0 \qquad (7)$$

As long as the SCM equation is satisfied, the cementitious equation will be satisfied. Therefore, the following discussion on the correlation of ASTM C1567 and the Caltrans standards will focus on the application of the SCM equation.

When the SCM equation is applied to the control mixtures of pure portland cement, blended cements, and binary mixtures, only the 100% Type IP mixture passed. The 100% Type IP also passed ATM C 1567 requirements. The 35% Grade 100 GGBFS blended with 65% Type I cement passed ASTM C1567, but the 35% Grade 120 GGBFS blended with 65% Type I cement did not pass ASTM C1567. All GGBFSs are grouped together in the SCM equation; therefore, it is appropriate that a 35% slag replacement level did not pass the SCM equation.

Study mixtures containing Class C fly ash did have some success with expansions ≤0.10%, but overall, it is not recommended to use Class C fly ash to mitigate ASR. When applying the SCM equation, no mitigation capability was applied to the Class C fly ash and none of the mixtures containing Class C fly ash passed the SCM equation. Three mixtures containing Class F fly ash did not pass the SCM equation but did pass ASTM C1567. All 3 mixtures had lower replacement levels. For example, mixtures with only 17% Grade 120 GGBFS and 15% Class F fly ash with a calculated value of 2.82, theoretically, should not have mitigated ASR. When tested, this mixture had an expansion of 0.04%, which is well below the allowable expansion of 0.10%.

The mixture designs with both Grade 100 and 120 GGBFS or Type IS(20) cement blended with Grade 100 or 120 GGBFS have a total or equivalent SCM replacement level of 36 or 48%. All 6 mixture designs have less than 50% replacement and therefore failed the SCM equation. However, the highest ASTM C1567 ASR expansion for the 6 mixtures was 0.06%, well below the allowable expansion. Having such a high minimum replacement level for GGBFS is not unreasonable and may be financially beneficial, but lower replacement levels of GGBFS are successful at mitigating ASR.

The mitigating capabilities of silica fume are underestimated in the SCM equation. Of the 22 tested mixture designs that contain silica fume and passed ASTM C1567, only 11 passed the SCM equation. The extremely high minimum replacement level of 12% is the cause of the poor correlation. If the minimum replacement level was lowered to a more appropriate 5 to 7%, a much stronger correlation would exist. Using silica fume as the main ASR mitigation method is still potentially dangerous, as silica fume is known to only delay ASR. However, recent studies have shown that by combining silica fume in a ternary blend, it may mitigate instead of just delay ASR expansion.

Figure 26 graphically shows the expansions of all the ternary mixture designs tested in this study. The light gray shows the number of mixtures for a given expansion that had a calculated value ≥3.0, therefore satisfying the Caltrans standard specification. In total, of the 117 mixtures tested in this study, 66 failed the SCM equation, whereas only 24 failed ASTM C1567. However, all of the mixtures that failed ASTM C1567 also failed the SCM equation. The majority of the 42 mixtures that passed ASTM C1567 but failed the SCM equation contained either silica fume or a blend containing GGBFS. The Caltrans equations are very conservative, but they do provide mixture designs that are capable of mitigating ASR.

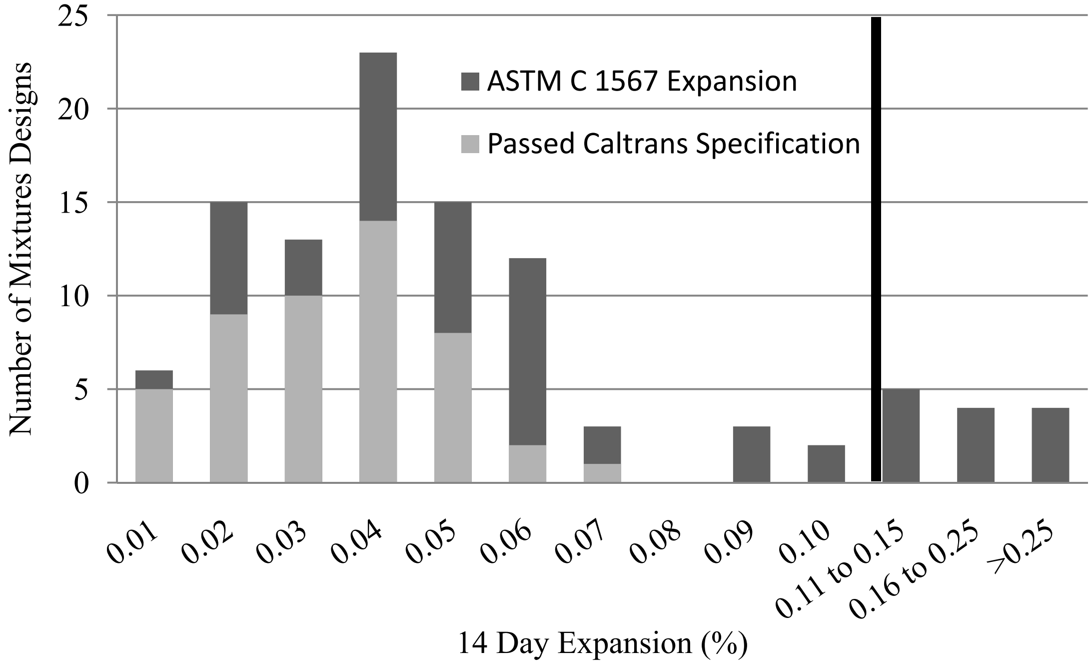

**Figure 26. Number of mixtures for a given expansion that passed Caltrans standard specification Section 90 requirements**

*Federal Aviation Administration*

The Federal Aviation Administration (FAA) requires GGBFS to be used at 25 to 55% replacement in combination with Class F fly ash used 10 to 20%. Of the 117 mixture designs tested, 16 were combinations of GGBFS and Class F or F2 fly ash and four were combinations of GGBFS and Type IP cement. Only five of the 20 met the replacement range requirements. All 20 study mixtures that contained GGBFS blended with Class F or F2 fly ash passed ASTM C1567 requirements. The only mixture with an expansion over 0.05% was the mixture with Class F2 fly ash and Grade 120 GGBFS, which had an expansion of 0.07%. The FAA guidelines are sound and simple requirements, but may not provide mitigation at the lower end of the recommendations (10% Class F fly ash or 25% GGBFS).

## SCM Combination Overview

Many ternary blends performed well even in the extremely harsh testing environment. Table 29 through Table 31 place the SCM combinations into groups by how well they generally performed. There were combinations that had an additional mixture design, which almost passed a given standard. These combinations have an asterisk (*) beside their values. These borderline values fell in the range of 0.10 to 0.13% for ASTM C1567, 0.94 to 1.00 for CSA, and 2.82 to 3.00 for Caltrans.

**Table 29. SCM combinations that mitigated ASR and their performance against standard specifications**

| | Number of Mixture Designs | | | |
|---|---|---|---|---|
| **Combination** | **Tested** | **Passed ASTM** | **Passed CSA** | **Passed Caltrans** |
| **Class F fly ash + Class F2 fly ash** | 2 | 2 | 2 | 2 |
| **Class F fly ash + Grade 100 GGBFS** | 3 | 3 | 3 | 3 |
| **Class F fly ash + Grade 120 GGBFS** | 5 | 5 | 4* | 4* |
| **Class F fly ash + Silica Fume** | 4 | 4 | 4 | 4 |
| **Class F fly ash + Metakaolin** | 2 | 2 | 2 | 2 |
| **Class F fly ash + Blended Cement** | 7 | 7 | 5* | 5* |
| **Class F2 fly ash + Grade 100 GGBFS** | 3 | 3 | 2* | 3 |
| **Class F2 fly ash + Grade 120 GGBFS** | 5 | 5 | 3* | 4 |
| **Class F2 fly ash + Silica Fume** | 4 | 4 | 4 | 3 |
| **Class F2 fly ash + Blended Cement** | 7 | 7 | 5 | 4 |
| **Grade 100 GGBFS + Grade 120 GGBFS** | 2 | 2 | 0* | 0* |
| **Grade 100 GGBFS + Silica Fume** | 2 | 2 | 2 | 1* |
| **Grade 100 GGBFS + Metakaolin** | 1 | 1 | 1 | 1 |
| **Grade 100 GGBFS + Blended Cement** | 6 | 6 | 4* | 3* |
| **Grade 120 GGBFS + Silica Fume** | 4 | 4 | 4 | 1* |
| **Grade 120 GGBFS + Metakaolin** | 2 | 2 | 1 | 1 |
| **Grade 120 GGBFS + Blended Cement** | 7 | 7 | 4* | 3* |
| **Silica Fume + Metakaolin** | 2 | 2 | 2 | 0 |
| **Silica Fume + Blended Cement** | 7 | 7 | 7 | 2 |
| **Metakaolin + Blended Cement** | 4 | 3 | 1 | 0 |

* One test mixture was borderline to passing (ASTM C1567 0.10 to 0.13%, CSA 0.94 to 1.00, Caltrans 2.82 to 3.00)

Table 30. SCM combinations that have the potential to mitigate ASR and their performance against standard specifications

| | Number of Mixture Designs | | | |
|---|---|---|---|---|
| **Combination** | **Tested** | **Passed ASTM** | **Passed CSA** | **Passed Caltrans** |
| **Class C fly ash + Grade 100 GGBFS** | 3 | 2 | 2 | 0 |
| **Class C fly ash + Grade 120 GGBFS** | 5 | 3 | 2 | 0 |
| **Class C fly ash + Blended Cement** | 7 | 6 | 4 | 0 |
| **Class F2 fly ash + Metakaolin** | 2 | 1 | 2 | 2 |

**Table 31. SCM combinations that did not mitigate ASR and their performance against standard specifications**

| | Number of Mixture Designs | | | |
|---|---|---|---|---|
| **Combination** | **Tested** | **Passed ASTM** | **Passed CSA** | **Passed Caltrans** |
| **Class C fly ash + Class F fly ash** | 1 | 0* | 1 | 0 |
| **Class C fly ash + Class F2 fly ash** | 2 | 0 | 1* | 0 |
| **Class C fly ash + Silica Fume** | 4 | 1* | 4 | 0 |
| **Class C fly ash + Metakaolin** | 2 | 0 | 2 | 0 |
| **Controls** | 12 | 3* | 2 | 1 |

* One test mixture was borderline to passing (ASTM C1567 0.10 to 0.13%, CSA 0.94 to 1.00, Caltrans 2.82 to 3.00)

Table 29 lists the SCM combinations that performed well and would be recommended for ternary mixture designs. Of the 20 combinations that would be recommended to mitigate ASR, 79 mixture designs were tested, but only 59 designs passed the CSA specification and 46 passed the Caltrans specifications. These specifications are limiting in the number of mixture designs they allow. If the standards would make even a 6% allowance for ternary blends (mixtures with an asterisk), an additional seven mixtures would pass both the CSA A23.2-27A and Caltrans Section 90 specifications.

Table 30 lists combinations that require additional testing before being recommended. These combinations had mixed results when tested according to ASTM C1567. Some of the mixtures that failed ASTM C1567 with ASR expansions >0.10% may perform adequately with moderately-reactive aggregates, instead of the highly-reactive aggregates used in this study. Class C fly ash did have the ability to mitigate ASR when blended with GGBFS or blended cements, but proper replacement levels would require project specific testing.

Table 31 lists mixtures that are generally not recommended for mitigating ASR. Apart from the control mixtures, all combinations contain Class C fly ash. When Class C fly ash is blended with Class F or F2 fly ash, silica fume, or metakaolin, at the replacement levels tested, their mitigation capabilities are insufficient.

### ASR Conclusion

This study tested 105 ternary blends in an extremely harsh testing environment. Many of the ternary blends proved successful at mitigating ASR. The results allowed trends and concerns with SCMs to be addressed, while the robustness of industry standard specifications was tested. The following conclusions were determined.

- Ternary combinations of pozzolans in this study have the potential to mitigate ASR in concrete containing highly-reactive aggregates. However, the mass combinations of cementitious materials are different for each pozzolan.
- Ternary blends combining ASTM C618 Class F fly ash, ASTM C989 GGBFS, ASTM C1240 silica fume, and ASTM C618 Class N metakaolin produce ASR-resistant concrete at lower replacement levels than required in the CSA A23 and Caltrans Section 90 standard specifications.
- ASTM C618 Class C fly ash with cement replacement levels of 30% combined with other pozzolans may provide ASR mitigation. High total SCM cement replacement levels (~50%) containing 30% ASTM C618 Class C fly ash blended with 20% ASTM C989 GGBFS may provide adequate mitigating capabilities. However, ASTM C618 Class C fly ash requires additional testing before being used to mitigate ASR.
- CSA A23.2-27A and Caltrans Section 90 base their standard specification on the assumption that SCMs act independently to mitigate alkali-silica expansion when used in a ternary blend. This assumption is not supported, as many mixtures did not have sufficient SCM replacement to meet the specifications but had acceptable expansions according to the ASTM C1567 procedure.
- ASTM C1240 silica fume can be used in ternary blends to mitigate ASR at cement replacement levels of 3 to 7%. However, the use of ASTM C1240 silica fume in binary mixtures is not recommended for exposed applications.

Table 32 shows three recommended SCM combinations and their recommended cementitious combination ranges. This table of reliable combinations can be used for preliminary mixture design for ternary blends requiring ASR mitigating capabilities.

This research provides information and direction to transportation agencies to construct new requirements for ternary blends that do not rely on the assumption that SCM interaction does not exist. Future research on the increased concrete durability due to SCM interaction is recommended.

**Table 32. Recommended ternary mixture designs**

| Cement | SCM 1 | Cementitious Mass (%) | SCM 2 | Cementitious Mass (%) | Total SCM Mass (%) |
|---|---|---|---|---|---|
| Portland | Class F | 15 - 30 | GGBFS | 20 - 35 | ≥ 50 |
| Blended | --- | --- | Class F | 15 - 30 | ≥ 50 |
| Blended | --- | --- | GGBFS | 20 – 35 | ≥ 50 |

Portland refers ASTM C150 portland cements
Blended refers to ASTM C595 Type IP (20) or Type IS (25) blended cements
Class F refers to ASTM C618 Class F fly ash
GGBFS refers to ASTM C989 Grade 100 or Grade 120 GGBFS
Total SCM Mass includes percentage of supplementary cementitious mass in blended cement

## CONCRETE FRESH STATE PROPERTIES

### Experimental Methods for Concrete Fresh State Properties

ASTM C231 was followed to calculate the entrained air in the concrete (ASTM). To measure the workability of the concrete, the slump test was used following ASTM C143 (ASTM). Two different setting time tests were run in all the mixtures, a mortar setting time described in ASTM C191 (ASTM), and a concrete setting time described in ASTM C403 (ASTM). Finally, bleeding was measured following the procedure described in ASTM C232 (ASTM).

### Results for Concrete Fresh State Properties

*Mortar Setting Time*

Setting time tests were run for both the mortar and concrete mixtures following ASTM C191 and ASTM C403, respectively. Table 33 presents the results for binary and control mixtures; Table 34 summarizes the results for Type IP mixture designs; Table 35 summarizes the results for Type ISM mixture designs; Table 36 presents the data for mixtures with two types of fly ash; Table 37 presents the data for mixtures that have slag; and, Table 38 presents the setting time data for mixtures with fly ash and either metakaolin or silica fume.

These setting times, determined by the Vicat Needle testing procedure (ASTM C191), are measures of the effect of the cementitious combinations in the stiffening characteristics related to early age hydration and water loss.

**Table 33.Mortar setting time for binary and control mixtures**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **100TI** | 137 | 221 |
| **80TI/20C** | 233 | 410 |
| **80TI/20F** | 195 | 304 |
| **80TI/20F2** | 232 | 342 |

**Table 34. Mortar setting time for Type IP cement mixtures**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **100TIP** | 187 | 280 |
| **85TIP/15C** | 246 | 355 |
| **75TIP/25C** | 307 | 408 |
| **85TIP/15F** | 187 | 241 |
| **85TIP/15F2** | 216 | 309 |
| **65TIP/35G120S** | 194 | 304 |
| **97TIP/3SF** | 169 | 244 |
| **95TIP/5M** | 169 | 246 |

**Table 35. Mortar setting time for Type ISM cement mixtures**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **100TISM** | 169 | 248 |
| **75TISM/25C** | 250 | 386 |
| **75TISM/25F2** | 226 | 339 |
| **65TISM/35G120S** | 175 | 283 |
| **97TISM/3SF** | 186 | 271 |

**Table 36. Mortar setting time for ternary mixtures with fly ash only**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **60TI/30F2/10C** | 327 | 475 |
| **60TI/20C/20F** | 286 | 525 |
| **60TI/20C/20F2** | 387 | 621 |
| **60TI/30C/10F** | 389 | 623 |
| **60TI/30C/10F2** | 339 | 584 |
| **60TI/20F/20F2** | 249 | 394 |
| **60TI/30F/10F2** | 234 | 360 |

**Table 37. Mortar setting time for mixtures with GGBFS**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **65TI/35G120S** | 171 | 274 |
| **50TI/35G120S/15F** | 190 | 327 |
| **60TI/20F/20G120S** | 205 | 326 |
| **50TI/30F/20G120S** | 250 | 383 |
| **60TI/20F2/20G120S** | 212 | 338 |
| **50TI/35G120S/15F2** | 138 | 246 |
| **62TI/35G120S/3SF** | 215 | 335 |
| **60TI/35G120S/5M** | 182 | 287 |

**Table 38. Mortar setting time for other ternary mixtures**

| Mixture Design | Mortar Initial Set (min) | Mortar Final Set (min) |
|---|---|---|
| **75TI/20F/5M** | 189 | 282 |
| **65TI/30F/5SF** | 164 | 270 |
| **65TI/30F/5M** | 193 | 322 |
| **75TI/20F2/5SF** | 188 | 310 |
| **75TI/20F2/5M** | 189 | 282 |
| **67TI/30F2/3SF** | 235 | 356 |
| **65TI/30F2/5M** | 249 | 362 |

### *Concrete Setting Time*

Table 39 presents the results for binary and the control mixture; Table 40 summarizes the results for Type IP mixture designs; Table 41 summarizes the results for Type ISM mixture designs;

Table 42 presents the data for mixtures with two types of fly ash; Table 43presents the data for mixtures that have slag; and Table 44 presents the setting time data for mixtures with fly ash and either metakaolin or silica fume.

Concrete setting times, determined according ASTM C403, are used to estimate the finishing operations windows, sawing and grinding operations, and texturing operations.

**Table 39. Concrete setting time for binary and control mixtures**

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **100TII** | 193 | 328 |
| **80TII/20C** | 329 | 445 |
| **80TII/20F** | 269 | 342 |
| **80TII/20F2** | 235 | 327 |

**Table 40. Concrete setting time for Type IP cement mixtures**

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **100TIP** | 268 | 362 |
| **85TIP/15C** | 374 | 497 |
| **75TIP/25C** | 497 | 543 |
| **85TIP/15F** | 363 | 491 |
| **85TIP/15F2** | 314 | 454 |
| **65TIP/35G120S** | 147 | 251 |
| **97TIP/3SF** | 287 | 383 |
| **95TIP/5M** | 225 | 313 |

**Table 41. Concrete setting time for Type ISM cement mixtures**

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **100TISM** | 284 | 369 |
| **75TISM/25C** | 451 | 589 |
| **75TISM/25F2** | 349 | 504 |
| **65TISM/35G120S** | 204 | 380 |
| **97TISM/3SF** | 249 | 341 |

Table 42. Concrete setting time for ternary mixtures with fly ash only

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **60TII/30F2/10C** | 667 | 797 |
| **60TII/20C/20F** | 521 | 651 |
| **60TII/20C/20F2** | 240 | 315 |
| **60TII/30C/10F** | 442 | 604 |
| **60TII/30C/10F2** | 237 | 330 |
| **60TII/20F/20F2** | 174 | 317 |
| **60TII/30F/10F2** | 483 | 603 |

Table 43. Concrete setting time for mixtures with GGBFS

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **65TII/35G120S** | 396 | 548 |
| **50TII/35G120S/15F** | 494 | 647 |
| **60TII/20F/20G120S** | 436 | 579 |
| **50TII/30F/20G120S** | 543 | 697 |
| **60TII/20F2/20G120S** | 283 | 407 |
| **50TII/35G120S/15F2** | 399 | 561 |
| **62TII/35G120S/3SF** | 349 | 466 |
| **60TII/35G120S/5M** | 321 | 455 |

Table 44. Concrete setting time for other ternary mixtures

| Mixture Design | Concrete Initial Set (min) | Concrete Final Set (min) |
|---|---|---|
| **75TII/20F/5M** | 304 | 409 |
| **65TII/30F/5SF** | 474 | 534 |
| **65TII/30F/5M** | 462 | 604 |
| **75TII/20F2/5SF** | 275 | 379 |
| **75TII/20F2/5M** | 296 | 406 |
| **67TII/30F2/3SF** | 322 | 433 |
| **65TII/30F2/5M** | 323 | 447 |

### *Paste Content*

The volume of paste was calculated taking into account the volume of cementitious materials, water and air. The results are summarized in Table 45 through Table 50. The paste content is a parameter related to shrinkage, cracking, finishing effort, and placement.

### *Bleeding*

Bleeding was measured for all the mixture designs. Table 45 presents the results for binary and the control mixture; Table 46 summarizes the results for Type IP mixture designs; Table 47 summarizes the results for Type ISM mixture designs; Table 48 presents the data for mixtures with two types of fly ash; Table 49 presents the data for mixtures that have GGBFS; and Table 50 presents the setting time data for mixtures with fly ash and either metakaolin or silica fume.

**Table 45. Fresh concrete properties for binary and control mixtures**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **100TII** | 33.21 | 8.0 | 3.50 | 1.09 |
| **80TII/20C** | 33.62 | 8.0 | 2.25 | 0.25 |
| **80TII/20F** | 32.45 | 6.0 | 3.50 | 1.90 |
| **80TII/20F2** | 30.30 | 3.3 | 2.00 | 3.25 |

**Table 46. Fresh concrete properties for Type IP cement mixtures**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **100TIP** | 30.44 | 4.0 | 3.75 | 1.57 |
| **85TIP/15C** | 31.61 | 5.2 | 2.25 | 1.97 |
| **75TIP/25C** | 31.60 | 4.9 | 3.75 | 6.49 |
| **85TIP/15F** | 31.31 | 4.5 | 2.00 | 1.04 |
| **85TIP/15F2** | 32.00 | 5.5 | 2.25 | 1.20 |
| **65TIP/35G120S** | 31.72 | 5.5 | 4.00 | 6.02 |
| **97TIP/3SF** | 31.89 | 5.8 | 4.00 | 0.48 |
| **95TIP/5M** | 31.30 | 5.0 | 2.00 | 0.24 |

**Table 47. Fresh concrete properties for Type ISM cement mixtures**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **100TISM** | 33.19 | 7.0 | 6.50 | 5.99 |
| **75TISM/25C** | 33.55 | 7.0 | 7.75 | 1.88 |
| **75TISM/25F2** | 31.53 | 3.8 | 5.25 | 3.55 |
| **65TISM/35G120S** | 34.11 | 8.3 | 2.75 | 2.26 |
| **97TISM/3SF** | 33.67 | 7.5 | 2.00 | 0.55 |

**Table 48. Fresh concrete properties for ternary mixtures with fly ash only**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **60TII/30F2/10C** | 34.38 | 8.0 | 9.75 | 3.18 |
| **60TII/20C/20F** | 33.80 | 7.5 | 5.25 | 7.20 |
| **60TII/20C/20F2** | 31.88 | 4.9 | 5.50 | 1.94 |
| **60TII/30C/10F** | 34.16 | 8.0 | 2.25 | 0.32 |
| **60TII/30C/10F2** | 32.74 | 6.0 | 8.00 | 7.44 |
| **60TII/20F/20F2** | 32.03 | 4.5 | 2.75 | 6.42 |
| **60TII/30F/10F2** | 34.07 | 7.3 | 8.75 | 11.62 |

**Table 49. Fresh concrete properties for mixtures with GGBFS**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **65TII/35G120S** | 31.99 | 6.0 | 6.25 | 4.08 |
| **50TII/35G120S/15F** | 34.32 | 8.5 | 8.50 | 2.48 |
| **60TII/20F/20G120S** | 33.33 | 7.0 | 6.00 | 1.82 |
| **50TII/30F/20G120S** | 34.01 | 7.5 | 7.50 | 0.53 |
| **60TII/20F2/20G120S** | 31.30 | 4.5 | 3.00 | 5.64 |
| **50TII/35G120S/15F2** | 32.68 | 6.5 | 8.25 | 4.53 |
| **62TII/35G120S/3SF** | 33.94 | 8.5 | 6.25 | 0.41 |
| **60TII/35G120S/5M** | 33.40 | 8.0 | 6.75 | 1.30 |

**Table 50. Fresh concrete properties for other ternary mixtures**

| Mixture Design | Volume of Paste (% of total Volume) | Entrained Air (% of total Volume) | Slump (in.) | Bleeding (% of volume of water) |
|---|---|---|---|---|
| **75TII/20F/5M** | 34.39 | 8.5 | 4.75 | 0.90 |
| **65TII/30F/5SF** | 33.83 | 7.1 | 3.75 | 1.13 |
| **65TII/30F/5M** | 35.11 | 9.0 | 6.75 | 0.30 |
| **75TII/20F2/5SF** | 30.85 | 3.5 | 3.50 | 0.58 |
| **75TII/20F2/5M** | 31.26 | 4.2 | 2.75 | 2.00 |
| **67TII/30F2/3SF** | 31.10 | 3.5 | 3.25 | 2.37 |
| **65TII/30F2/5M** | 32.91 | 6.0 | 5.75 | 2.19 |

## Discussion of Concrete Fresh State Properties

### *Setting Time*

Different mixture designs will both stiffen and develop strength at different rates. The setting time test, both for concrete and for mortar, give information that helps quantify the first hours of stiffening of the mixtures. This information can be use to choose the appropriate mixture design for a project and provides information for the construction operations.

### *Relationship Between Mortar and Concrete Setting Time*

In this research program, ternary cementitious combinations were tested using both Type I cement and Type II cement as base cementitious material. The Type I cement was tested using mortar specimens and using the Vicat Needle test according to ASTM C191. The Type II cement was tested using concrete samples and following the penetration method according to ASTM C403.

The mortar setting time testing procedure described in the standards uses a sample with “normal consistency.” The mortar setting time test does not indicate the setting time of the concrete that will be placed in a project; it gives a setting time and water demand value that is used in standards to compare cementitious combinations.

The concrete penetration resistance test standard allows for the actual mixture design that will be placed in a job site to be tested. This provides data on the setting time of the concrete to be placed. However, it is critical to understand that environmental conditions, such as temperature and humidity, and admixtures have an effect on the setting time values.

In summary, the mortar test is used to compare different cementitious materials and the concrete setting time provides data on concrete mixture design.

Figure 27 through Figure 30 show the comparison between the two tests for initial and final set for the mixtures that had the same mass percentage of cementitious components.

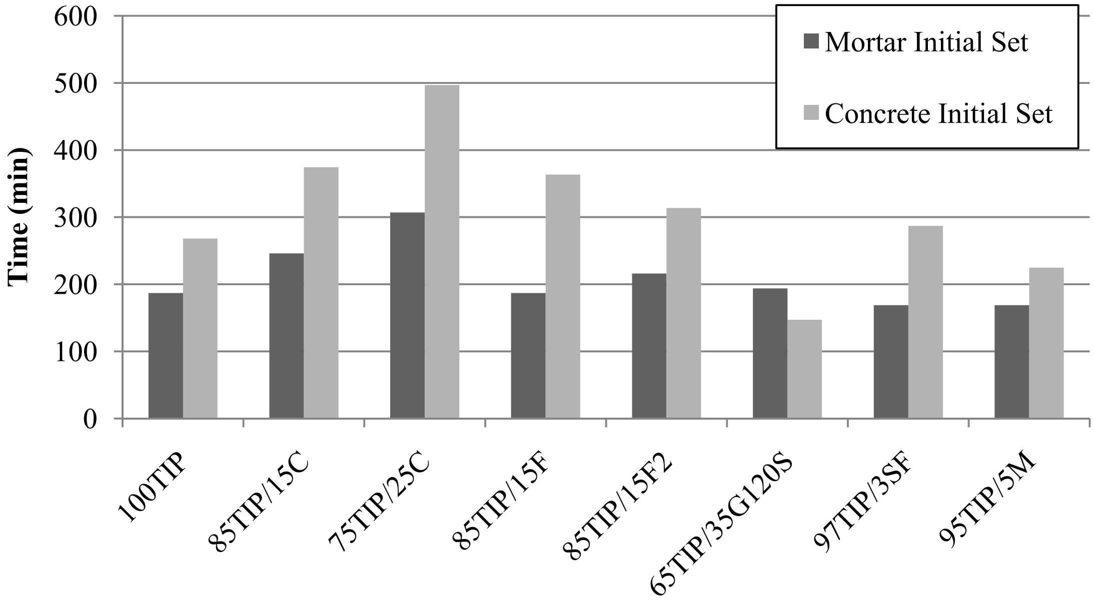

Figure 27. Initial set for Type IP cement mixtures

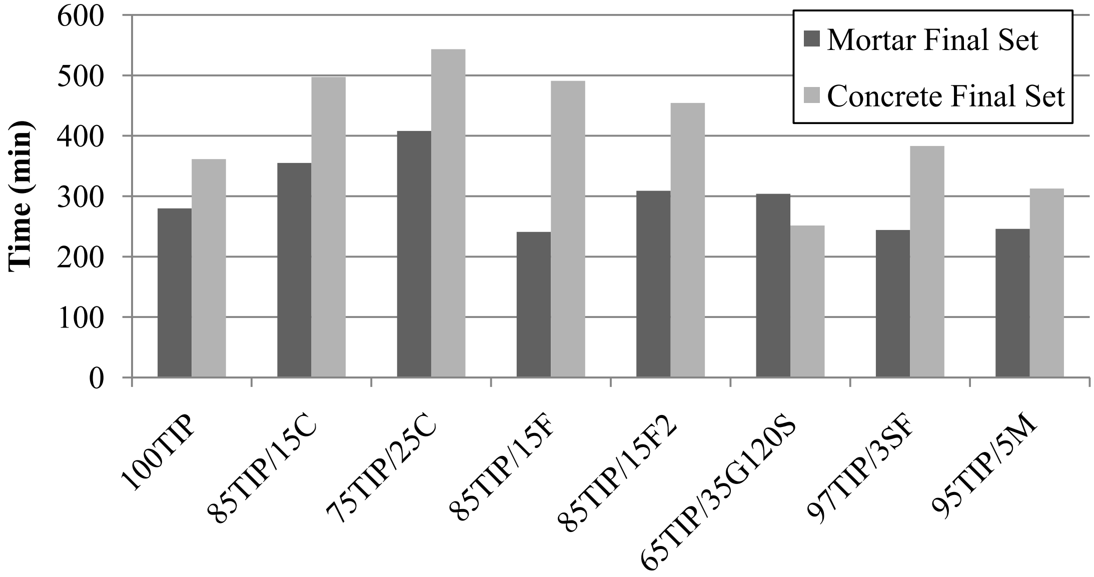

Figure 28. Final set for Type IP cement mixtures

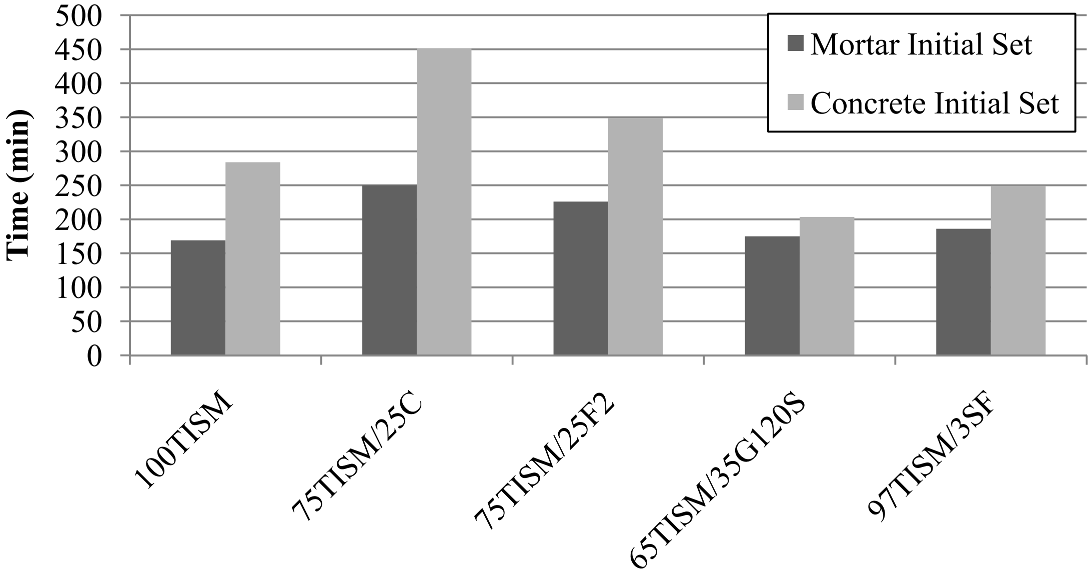

Figure 29. Initial set for Type ISM cement mixtures

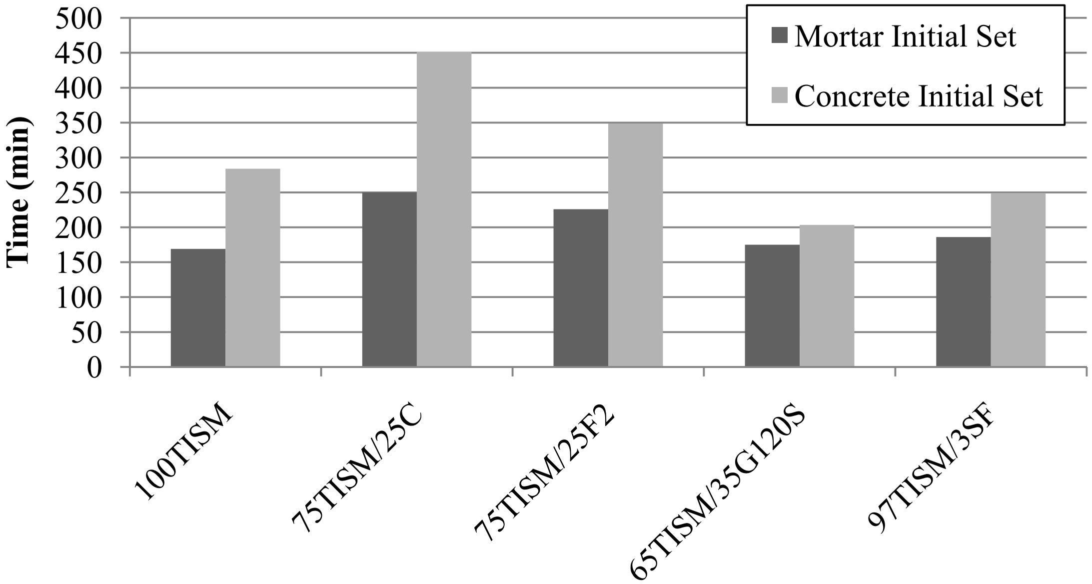

Figure 30. Final set for Type ISM cement mixtures

Figure 27 through Figure 30 show there is no well-defined relationship between mortar and concrete setting time. While the concrete setting times are typically greater than mortar setting times, the two different tests are not correlated directly, because they measure different properties. In addition, the mortar and concrete mixtures were designed with different water to cementitious materials ratios. The lack of admixtures in the mortar specimens and the use of admixtures in the concrete specimens also affect the setting time information. In summary, the samples were different and the tests are different; therefore, no relationship between the tests should be assumed from these data.

### *General Aspects that Affect Setting Time*

Before going into the specific mixtures, this section will provide an overview of some of the factors that impact setting time.

Gypsum is added to portland cements and blended portland-pozzolan cements to control aluminate reactions and their impact on the setting time of concrete. The sulfur oxides provided by the gypsum and the sulfur oxides in the clinker substantially influence the setting time. Typically the industry uses a measurement of equivalent $SO_3$ to indicate the amount of sulfur oxides in cements. Usually, there is between 2.5% to 3.0% of $SO_3$ in portland cement.

Sulfates retard the stiffening in concrete. The addition of pozzolanic materials to portland cement or blended portland-pozzolan cements changes the content of $SO_3$ and $C_3A$, thereby changing the balance between these compounds in the system and so affecting setting time and early stiffening.

In the first few days of placing concrete, most of the strength is developed by the portland cement, and not by the pozzolans. Therefore, the total portland cement content in the mixture also affects the setting time value. More portland cement in the mixture will decrease the setting time for that particular mixture for a given w/cm value.

Lubrication of the particles also has an important role in setting time. If a cementitious component or another material in the mixture adsorbs water and does not let the water lubricate the other particles, the setting time may decrease.

Table 51 through Table 56 present the values for the total portland cement content for the mixtures, as well as the $SO_3$ content with respect to the portland cement content for both concrete and mortar mixtures. The TIP and TISM mixtures have the same values for mortar and concrete specimens, because the same materials and ratios were kept for concrete and mortar.

Fly ashes and GGBFS blended in a binary mixture with portland cement slow down the reactions that generate early strength gain in concrete. Silica fume and metakaolin blended in binary mixtures with portland cement accelerate the early strength gain of concrete. The behavior of blended portland-pozzolan cements is different. Even though blended cements have pozzolans in them, the gypsum content is adjusted to compensate for the effects that pozzolans have in the mixture.

**Table 51. Portland cement and sulfate content of binary, TIP, and TISM mortar mixtures**

| Mixture Design | Portland Cement (%) | $SO_3$ (%) | $SO_3$ / PC (%) |
|---|---|---|---|
| **100TI** | 100 | 2.63 | 2.63 |
| **80TI/20C** | 80 | 2.64 | 3.31 |
| **80TI/20F** | 80 | 2.24 | 2.80 |
| **80TI/20F2** | 80 | 2.26 | 2.83 |
| **100TIP** | 75 | 2.74 | 3.65 |
| **85TIP/15C** | 64 | 2.73 | 4.29 |
| **75TIP/25C** | 56 | 2.73 | 4.85 |
| **85TIP/15F** | 64 | 2.43 | 3.81 |
| **85TIP/15F2** | 64 | 2.45 | 3.84 |
| **65TIP/35G120S** | 49 | 2.74 | 5.63 |
| **97TIP/3SF** | 73 | 2.66 | 3.66 |
| **95TIP/5M** | 71 | 2.60 | 3.65 |
| **100TISM** | 80 | 2.85 | 3.56 |
| **75TISM/25C** | 60 | 2.81 | 4.69 |
| **75TISM/25F2** | 60 | 2.34 | 3.90 |
| **65TISM/35G120S** | 52 | 2.82 | 5.41 |
| **97TISM/3SF** | 78 | 2.77 | 3.57 |

**Table 52. Portland cement and sulfate content of ternary mortar mixtures**

| Mixture Design | Portland Cement (%) | $SO_3$ (%) | $SO_3$ / PC (%) |
|---|---|---|---|
| **100TI** | 100 | 2.63 | 2.63 |
| **60TI/30F2/10C** | 60 | 2.09 | 3.48 |
| **60TI/20C/20F** | 60 | 2.25 | 3.76 |
| **60TI/20C/20F2** | 60 | 2.28 | 3.80 |
| **60TI/30C/10F** | 60 | 2.46 | 4.09 |
| **60TI/30C/10F2** | 60 | 2.47 | 4.11 |
| **60TI/20F/20F2** | 60 | 1.87 | 3.12 |
| **60TI/30F/10F2** | 60 | 1.86 | 3.10 |
| **65TI/35G120S** | 65 | 2.67 | 4.11 |
| **50TI/35G120S/15F** | 50 | 2.38 | 4.76 |
| **60TI/20F/20G120S** | 60 | 2.26 | 3.77 |
| **50TI/30F/20G120S** | 50 | 2.07 | 4.14 |
| **60TI/20F2/20G120S** | 60 | 2.29 | 3.81 |
| **50TI/35G120S/15F2** | 50 | 2.40 | 4.80 |
| **62TI/35G120S/3SF** | 62 | 2.60 | 4.19 |
| **60TI/35G120S/5M** | 60 | 2.54 | 4.24 |
| **75TI/20F/5M** | 75 | 2.11 | 2.81 |
| **65TI/30F/5SF** | 65 | 1.92 | 2.95 |
| **65TI/30F/5M** | 65 | 1.91 | 2.95 |
| **75TI/20F2/5SF** | 75 | 2.14 | 2.85 |
| **75TI/20F2/5M** | 75 | 2.13 | 2.84 |
| **67TI/30F2/3SF** | 67 | 2.01 | 2.99 |
| **65TI/30F2/5M** | 65 | 1.95 | 3.00 |

**Table 53. Portland cement and sulfate content of binary, TIP, and TISM concrete mixtures**

| Mixture Design | Portland Cement (%) | $SO_3$ (%) | $SO_3$ / PC (%) |
|---|---|---|---|
| **100TII** | 100 | 2.70 | 2.70 |
| **80TII/20C** | 80 | 2.70 | 3.38 |
| **80TII/20F** | 80 | 2.30 | 2.87 |
| **80TII/20F2** | 80 | 2.32 | 2.90 |
| **100TIP** | 75 | 2.74 | 3.65 |
| **85TIP/15C** | 64 | 2.73 | 4.29 |
| **75TIP/25C** | 56 | 2.73 | 4.85 |
| **85TIP/15F** | 64 | 2.43 | 3.81 |
| **85TIP/15F2** | 64 | 2.45 | 3.84 |
| **65TIP/35G120S** | 49 | 2.74 | 5.63 |
| **97TIP/3SF** | 73 | 2.66 | 3.66 |
| **95TIP/5M** | 71 | 2.60 | 3.65 |
| **100TISM** | 80 | 2.85 | 3.56 |
| **75TISM/25C** | 60 | 2.81 | 4.69 |
| **75TISM/25F2** | 60 | 2.34 | 3.90 |
| **65TISM/35G120S** | 52 | 2.82 | 5.41 |
| **97TISM/3SF** | 78 | 2.77 | 3.57 |

**Table 54. Portland cement and sulfate content of ternary concrete mixtures**

| Mixture Design | Portland Cement (%) | $SO_3$ (%) | $SO_3$ / PC (%) |
|---|---|---|---|
| **100TII** | 100 | 2.70 | 2.70 |
| **60TII/30F2/10C** | 60 | 2.13 | 3.55 |
| **60TII/20C/20F** | 60 | 2.30 | 3.83 |
| **60TII/20C/20F2** | 60 | 2.32 | 3.87 |
| **60TII/30C/10F** | 60 | 2.50 | 4.16 |
| **60TII/30C/10F2** | 60 | 2.51 | 4.18 |
| **60TII/20F/20F2** | 60 | 1.92 | 3.19 |
| **60TII/30F/10F2** | 60 | 1.90 | 3.17 |
| **65TII/35G120S** | 65 | 2.72 | 4.18 |
| **50TII/35G120S/15F** | 50 | 2.41 | 4.83 |
| **60TII/20F/20G120S** | 60 | 2.31 | 3.84 |
| **50TII/30F/20G120S** | 50 | 2.10 | 4.21 |
| **60TII/20F2/20G120S** | 60 | 2.33 | 3.88 |
| **50TII/35G120S/15F2** | 50 | 2.43 | 4.87 |
| **62TII/35G120S/3SF** | 62 | 2.64 | 4.26 |
| **60TII/35G120S/5M** | 60 | 2.58 | 4.31 |
| **75TII/20F/5M** | 75 | 2.16 | 2.88 |
| **65TII/30F/5SF** | 65 | 1.97 | 3.02 |
| **65TII/30F/5M** | 65 | 1.96 | 3.02 |
| **75TII/20F2/5SF** | 75 | 2.19 | 2.92 |
| **75TII/20F2/5M** | 75 | 2.19 | 2.91 |
| **67TII/30F2/3SF** | 67 | 2.05 | 3.06 |
| **65TII/30F2/5M** | 65 | 2.00 | 3.07 |

The increase or decrease of time to set has to be analyzed from a control reference point. Table 55 through Table 58 present a comparative analysis of the setting time data that will help understand the effect of the pozzolans in the mixtures.

**Table 55. Comparative analysis of setting time for binary, TIP, and TISM mortar mixtures**

| Mixture Design | Change of Initial Set (min) | Change of Final Set (min) |
|---|---|---|
| **100TI** | 0 | 0 |
| **80TI/20C** | 96 | 189 |
| **80TI/20F** | 58 | 83 |
| **80TI/20F2** | 95 | 121 |
| **100TIP** | 0 | 0 |
| **85TIP/15C** | 59 | 75 |
| **75TIP/25C** | 120 | 128 |
| **85TIP/15F** | 0 | -39 |
| **85TIP/15F2** | 29 | 29 |
| **65TIP/35G120S** | 7 | 24 |
| **97TIP/3SF** | -18 | -36 |
| **95TIP/5M** | -18 | -34 |
| **100TISM** | 0 | 0 |
| **75TISM/25C** | 81 | 138 |
| **75TISM/25F2** | 57 | 91 |
| **65TISM/35G120S** | 6 | 35 |
| **97TISM/3SF** | 17 | 23 |

**Table 56. Comparative analysis of setting time for Ternary mortar mixtures**

| Mixture Design | Change of Initial Set (min) | Change of Final Set (min) |
|---|---|---|
| **100TI** | 0 | 0 |
| **60TI/30F2/10C** | 190 | 254 |
| **60TI/20C/20F** | 149 | 304 |
| **60TI/20C/20F2** | 250 | 400 |
| **60TI/30C/10F** | 252 | 402 |
| **60TI/30C/10F2** | 202 | 363 |
| **60TI/20F/20F2** | 112 | 173 |
| **60TI/30F/10F2** | 97 | 139 |
| **65TI/35G120S** | 0 | 0 |
| **50TI/35G120S/15F** | 19 | 53 |
| **60TI/20F/20G120S** | 34 | 52 |
| **50TI/30F/20G120S** | 79 | 109 |
| **60TI/20F2/20G120S** | 41 | 64 |
| **50TI/35G120S/15F2** | -33 | -28 |
| **62TI/35G120S/3SF** | 44 | 61 |
| **60TI/35G120S/5M** | 11 | 13 |
| **100TI** | 0 | 0 |
| **75TI/20F/5M** | 52 | 61 |
| **65TI/30F/5SF** | 27 | 49 |
| **65TI/30F/5M** | 56 | 101 |
| **75TI/20F2/5SF** | 51 | 89 |
| **75TI/20F2/5M** | 52 | 61 |
| **67TI/30F2/3SF** | 98 | 135 |
| **65TI/30F2/5M** | 112 | 141 |

**Table 57. Comparative analysis of setting time for binary, TIP, and TISM concrete mixtures**

| Mixture Design | Change of Initial Set (min) | Change of Final Set (min) |
|---|---|---|
| **100TII** | 0 | 0 |
| **80TII/20C** | 136 | 116 |
| **80TII/20F** | 76 | 14 |
| **80TII/20F2** | 42 | -1 |
| **100TIP** | 0 | 0 |
| **85TIP/15C** | 106 | 136 |
| **75TIP/25C** | 229 | 182 |
| **85TIP/15F** | 95 | 130 |
| **85TIP/15F2** | 45 | 93 |
| **65TIP/35G120S** | -121 | -110 |
| **97TIP/3SF** | 19 | 22 |
| **95TIP/5M** | -43 | -49 |
| **100TISM** | 0 | 0 |
| **75TISM/25C** | 167 | 220 |
| **75TISM/25F2** | 65 | 135 |
| **65TISM/35G120S** | -80 | 11 |
| **97TISM/3SF** | -35 | -29 |

**Table 58. Comparative analysis of setting time for ternary concrete mixtures**

| Mixture Design | Change of Initial Set (min) | Change of Final Set (min) |
|---|---|---|
| **100TII** | 0 | 0 |
| **60TII/30F2/10C** | 474 | 468 |
| **60TII/20C/20F** | 328 | 323 |
| **60TII/20C/20F2** | 47 | -13 |
| **60TII/30C/10F** | 249 | 275 |
| **60TII/30C/10F2** | 44 | 2 |
| **60TII/20F/20F2** | -19 | -11 |
| **60TII/30F/10F2** | 290 | 275 |
| **65TII/35G120S** | 0 | 0 |
| **50TII/35G120S/15F** | 97 | 99 |
| **60TII/20F/20G120S** | 40 | 31 |
| **50TII/30F/20G120S** | 147 | 149 |
| **60TII/20F2/20G120S** | -113 | -141 |
| **50TII/35G120S/15F2** | 3 | 13 |
| **62TII/35G120S/3SF** | -48 | -82 |
| **60TII/35G120S/5M** | -76 | -93 |
| **100TII** | 0 | 0 |
| **75TII/20F/5M** | 111 | 81 |
| **65TII/30F/5SF** | 281 | 206 |
| **65TII/30F/5M** | 269 | 275 |
| **75TII/20F2/5SF** | 82 | 51 |
| **75TII/20F2/5M** | 103 | 77 |
| **67TII/30F2/3SF** | 129 | 104 |
| **65TII/30F2/5M** | 130 | 119 |

### *Mortar Setting Time*

The setting time of mortars is used to compare the setting time of cementitious combinations. In these research binary mixtures with Type I portland cement, and binary mixtures with blended portland-pozzolan cements are considered controls, and ternary mixtures were compared to these controls.

The Class C fly ash designated C in this report increased the setting time of mortars 189 minutes for the final set and 96 minutes for the initial set when replacing 20% of Type I portland cement in a binary mixture. The increase in time is greater than the increases caused by the F and F2 fly ashes, because of the high content of oxides of sulfur in the C fly ash (2.70% compared to 0.68% for the F ash and 0.80% for the F2 ash). The information in Table 51 shows that the ratio of oxides of sulfur to the total amount of portland cement increased from 2.63% to 3.31% when C fly ash is added in the mixture. These oversulfonated mixtures exhibited delayed setting.

The mixture of C fly ash with TIP and TISM blended portland-pozzolan cements also increased the setting time with respect to the control by 128 minutes and 138 minutes for final set, respectively, when the fly ash replaced 25% of the blended cements. The two numbers are close to each other because the blended portland-pozzolan cements are modified by adding gypsum to optimize the setting time of the finished blended cements.

When C fly ash is mixed in ternary mixtures with Class F fly ashes, the final setting time increases up to 402 minutes compared to the 100% Type I control. This is the largest increase in setting time. The increase in setting time is caused by several factors. First, fly ash has limited cementitious properties at early ages. Second, these ternary mixtures have 40% less portland cement, which provides less hydration reaction product to cause the stiffening needed for setting. Finally, the soluble sulfates are not optimized to efficiently set the cementitious material. C fly ash had high setting time values reaching up to 623 minutes for final set when mixed with Class F fly ashes.

The Class F fly ash designated F in this report increased the setting time with respect to the control by 83 minutes for the final set and 58 minutes for the initial set, when a binary mixture with 20% ash was tested. The F fly ash had a smaller retarding effect than the C and the F2 ashes used in this study. The ratio of oxides of sulfur to the total portland cement supports this information in Table 51. The mixture with C ash has a ratio of 3.31%, while the F2 ash is 2.83% and F is the lowest at 2.80%.

The combination of the F fly ash with TIP blended portland-pozzolan cement did not have a significant effect on setting time compared to the control. The final set was actually reduced by 39 minutes and the initial set did not change. These values are small enough that environmental changes explain the fluctuation. Also, the amount of fly ash used was 15% of the total cementitious material, which is a small amount.

The combination of F fly ash with the C fly ash and the F2 fly ash significantly increased the setting time of mortars. The cementitious combinations of the C ash with the F ash showed an increase in final set of up to 402 minutes compared to the 100% Type I portland cement control. When the two Class F ashes were used, the increase was not as large, but it was still significant. When a large amount of fly ash is used, the setting time will increase due to the low cementitious properties of fly ash at early ages. The setting time will be increased, because when a large amount of fly ash is used, a significant percentage of portland cement is subtracted from the cementitious combination. As presented in Table 56, the increase on final set was 173 minutes and 139 minutes with respect to the control for the two mixture designs with both Class F fly ashes.

Ternary mixtures with GGBFS and F fly ash were tested and up to 50% of portland cement was replaced by pozzolans. GGBFS has cementitious properties and does not delay the setting time as much as the fly ashes. When the F fly ash was used with GGBFS, the delay in setting time compared to a control with 65% Type I cement and 35% GGBFS ranged from 52 minutes to 109 minutes for the final set. Increasing the fly ash amount from 15% to 20% of the total cementitious materials did not have an effect on the setting time of the mortars. However, when 30% of the total cementitious materials were replaced with the F fly ash, the final setting time increased to 109 minutes with respect to the control.

Ternary mixtures with F fly ash and silica fume or metakaolin were also tested using the mortar setting time method. With respect to the control mixture of 100% Type I portland cement, the mixture's initial and final set increased. However, when comparing the ternary mixtures with the binary mixture of 80% Type I portland cement and 20% Class F fly ash, the mixture's setting time did not change significantly. There is some indication that the silica fume and the metakaolin accelerated the mixture and compensated for the decrease in the amount of portland cement. However, the change in setting time is small and it is not definitive; therefore, more research should be conducted. Silica fume and metakaolin require calcium hydroxide and water to react and give strength to the mixture. Since hydration of the cement has only just started, there is not a significant amount of calcium hydroxide in the mixture; therefore, these pozzolans do not contribute to the stiffening by reaction. However, they do adsorb water, taking away some of the mobility from the mixture and impacting the stiffening.

The Class F fly ash designated F2 in this report increased the setting time of the binary mortar mixture with Type I cement. The 20% replacement of portland cement with the F2 fly ash increased the final setting time of the mixture 121 minutes and increased the initial set 95 minutes. The ratio of oxides of sulfur to the total portland cement explains why the F2 fly ash had a lower impact in the setting time than the C ash. The C ash has a ratio of 3.31%, while the F2 ash has a ratio of 2.83%, and the Class F is the lowest with ratio of 2.80% as shown in Table 51.

The mixture with the F2 fly ash and TIP blended portland-pozzolan cement had a small effect in setting time when 15% of the total cementitious material was used, increasing the final setting time 29 minutes. The mixture with Class F2 and TISM had a larger amount of fly ash (25% of the total cementitious material) and increased the final setting time 91 minutes. A small amount (15%) replacing a portland cement or a portland-pozzolan blended cement did not have a significant effect in setting time, because of the small amount being used, the low cementitious properties at early ages of the fly ash, and the small percentage of sulfates that the Class F fly ashes are introducing in the cementitious mixtures.

The combination of the F2 fly ash with the C ash and the F ash significantly increased the setting time of mortars. The cementitious combination of the C ash with the F2 ash showed an increase in final set of up to 402 minutes, compared to the 100% Type I portland cement control. When the two Class F ashes were used, the increase was not as large, but it was still significant. As presented in Table 56, the increase on final set was 173 minutes and 139 minutes with respect to the control for the two mixture designs with both Class F fly ashes. Using two different fly ashes to replace 40% of the cementitious materials slows down the reaction, because fly ash has limited cementitious properties at early ages, and a large amount of portland cement is subtracted from the mixture.

Combining the F2 fly ash with GGBFS and Type I portland cement did not have a significant effect on setting time. 60TI/20F2/20G120S mixture final setting time increased 64minutes and the 50TI/35G120S/15F2 mixture decreased 28 minutes. These changes in setting time are not significant considering the final setting time for the control mixture was 274 minutes. The cementitious properties in slag cements and the fact that only a small percentage of the F2 ash was used explain why environmental factors would have a larger effect on setting time.

Ternary mixtures containing the F2 fly ash, Type I cement, and metakaolin or silica fume presented similar results to those observed with the F fly ash. The data presented in Table 33 and Table 38 shows there is not a significant change in setting time between the 80TI/20F2 mixture design and the ternary mixtures with Class F2 fly ash, even though the amount of portland cement was reduced. However, from these data, it cannot be generalized that silica fume and metakaolin will decrease the setting time.

Ground granulated blast furnace slag was used in three binary and seven ternary mixtures of mortar. Comparing the 65TI/35G120S mixture to the 100% Type I portland cement mixture, there was a slight increase in the setting time of the mortar, 34 minutes for initial set and 53 minutes for final set. This increase in setting time is predictable because the GGBFS has less cementitious properties than a Type I portland cement.

GGBFS was also used with TIP and TISM blended portland-pozzolan cements. In both cases the increase of setting time was small. Table 55 presents a comparison between the setting time for the controls and the binary mixtures in which 35% of the total cementitious materials were replaced with Grade 120 slag. The table shows an increase in time of final set with respect to the controls of 24 minutes for the TIP mixture and 35 minutes for the TISM mixture. Because the portland-pozzolan blended cements setting time are optimized when they are blended, the slag cement affects it in a similar way to portland cement.

Ternary mixtures of GGBFS, Type I portland cement, and fly ashes were also tested. When small amounts of the F fly ash were used (15% and 20% of the total cementitious materials), the final set increased 53 and 52 minutes, respectively. However, when the amount of the F fly ash was increased to 30% of the total cementitious materials, the final set was increased 109 minutes. The F fly ash did not show a significant increase in setting time when it was used at 20% of the total cementitious materials; however, it did have a delaying effect when at 30% of the total cementitious materials. Similarly, the F2 fly ash was used in small amounts (15% and 20% of the total cementitious materials) and did not generate a significant change in setting time, as shown in Table 56. GGBFS was also used in ternary mixtures of mortar with Type I portland cement and silica fume or metakaolin. Even though there was a small reduction in the total amount of portland cement, the increase in setting time was not significant due to the silica fume and metakaolin in the mixture.

Metakaolin was used in six mixture designs. For the ternary mixture with GGBFS and Type I portland cement, the addition of metakaolin actually increased the final setting time by 13 minutes with respect to the control. The binary mixture of TIP blended portland-pozzolan cement and metakaolin decreased the final setting time 34 minutes with respect to the control. Neither of these numbers are very significant. Metakaolin will not affect the strength gain in the first hours, because it will not have time to react. In these cases, the reduction in mobility that metakaolin will generate, when it takes water from the mixture, was less important than the effect of reducing the total amount of portland cement in the mixture.

Ternary mixtures with metakaolin, Type I portland cement, and fly ashes were also tested. The total amount of portland cement was decreased with respect to the binary mixtures of Type I portland cement and fly ashes. However, the addition of metakaolin mitigated this drop in cement content and the setting time of the specimens did not change significantly.

The changes in setting time are relatively small compared to the actual setting time of the mixtures. In further research, more emphasis should be given on the behavior of metakaolin with these particular mixture designs.

Silica fume was used in six mixture designs. The binary mixture of TIP blended portland-pozzolan cement and silica fume decreased the final setting time 34 minutes. Similarly, the final setting time of the ternary mixtures with Type I portland cement and fly ashes was decreased when silica fume was included in the mixture. The total amount of portland cement was decreased with respect to the binary mixtures of Type I portland cement and fly ashes. However, the addition of silica fume mitigated this drop in cement content and the setting time of the specimens did not change significantly. Similar to metakaolin, silica fume will take water away from the mixture and lower the mobility of the mortar, slightly impacting the setting time.

On the contrary, when used with a TISM portland-pozzolan cement and with a ternary mixture that also had Type I portland cement and GGBFS, the final setting time increased. For a 3% replacement of the TISM cement, the final setting time increased 23minutes and for a 62TI/35G120S/3SF, the final setting time increased 61 minutes.

The changes in setting time are relatively small compared to the actual setting time of the mixtures. In further research, more emphasis should be put on the behavior of silica fume with these particular mixture designs. From this data, it does not appear to be an important factor in the setting time of the mixtures.

*Concrete Setting Time*

The setting time of concrete test is one technique to assess a concrete mixture design. In this research, binary mixtures with Type I portland cement, binary mixtures with blended portland-pozzolan cements, and ternary mixtures were studied.

The Class C fly ash designated C in this report increased the setting time of concrete 116 minutes for the final set and 136 minutes for the initial set when replacing 20% of Type II portland cement in a binary mixture. The increase in time is greater than the increases caused by the F ash and the F2 fly ash. Table 53 shows that the ratio of oxides of sulfur and the total amount of portland cement increased from 2.70% to 3.38% when the fly ash is added to the mixture.

The mixture of C fly ash with TIP and TISM blended portland-pozzolan cements also increased the setting time with respect to the control by 182 minutes and 220 minutes for final set, respectively, when the fly ash replaced 25% of the blended cements. These increases are higher than the corresponding increases for the Class F fly ashes as seen in Table 57. When the C fly ash is mixed in ternary mixtures with the F2 fly ash, the setting time shows an interaction problem, probably between the F2 ash and the admixtures used in the study.

Table 57 shows the change in setting time for ternary mixtures comparing them with the 100% Type II portland cement control. The data for the mixtures containing the C fly ash and the F2 fly ash is scattered and does not show any trend that is directly related to the supplementary cementitious materials.

Table 57 also shows an increase of up to 323 minutes for final setting time in ternary mixtures containing the C ash and the F fly ash. The decrease of portland cement content in the mixture, as well as an increase in oxides of sulfur due to the use of a significant amount of fly ash, explain the delay in the final setting time of the concrete mixture.

The Class F fly ash, designated F in this report, increased the setting time with respect to the control 14 minutes for the final set and 76 minutes for the initial set when a binary mixture with 20% ash was tested. The F fly ash had a smaller retarding effect than the C fly ash.

The combination of the F fly ash with TIP blended portland-pozzolan cement increased the final setting time of the mixture 130 minutes. The total amount of portland cement was reduced; therefore, the setting time increased. The use of Class F fly ash in the concrete mixtures has a larger impact in the concrete mixtures.

When Class F fly ash is mixed in ternary mixtures with Class F2 fly ash, the setting time shows an interaction problem, probably between the Class F2 fly ash and the admixtures used in this study. Table 57 shows the change in setting time for ternary mixtures comparing them with the 100% Type II portland cement control. The data for the mixtures containing Class F and Class F2 fly ash is scattered and does not show any logic that is directly related to the mineral admixtures. More research should be done to discover if more ternary mixtures present a similar incompatibility issue.

Table 57 also shows an increase of up to 323 minutes for final setting time in ternary mixtures containing the C ash and the F ash. The decrease of portland cement content in the mixture explains the delay in the final setting time of the concrete mixture.

Ternary mixtures with GGBFS and the F fly ash were tested and up to 50% of the Type II portland cement was replaced by pozzolans. The F fly ash was used with GGBFS and the delay in setting time compared to a control with 65% Type II cement and 35% GGBFS ranged from 31 minutes to 149 minutes for the final set. Increasing the fly ash amount from 15% to 20% of the total cementitious materials had an inverse effect and actually decreased the setting time from 647 to 579, which was not a significant decrease and was caused by environmental factors.

However, when 30% of the total cementitious materials were replaced with the F fly ash, the final setting time increased to 697 minutes. The reduction in portland cement and the low cementitious properties of the F ash at early ages causes the delay in setting time.

Ternary mixtures with the F fly ash and silica fume or metakaolin were also tested using the mortar setting time standard. With respect to the control mixture of 100% Type II portland cement, the mixture's initial and final set increased. Also, when comparing the ternary mixtures with the binary mixture of 80% Type II portland cement and 20% F fly ash, the mixtures setting time increased. Silica fume and metakaolin do not seem to have a big influence on the setting time of the mixture, because in the first hours silica fume and metakaolin do not impact the strength, only the mobility of the mixture.

The Class F fly ash designated F2 in this report has a compatibility issue with the admixtures used in this study. The data obtained is scattered, especially when the fly ash was used in ternary mixtures with other fly ashes or in ternary mixtures with GGBFS.

GGBFS was used in three binary and seven ternary mixtures of concrete. Comparing the 65TI/35G120S mixture with respect to the 100% Type II portland cement mixture, there was a slight increase in the setting time of the mortar, 203 minutes for initial set and 220 minutes for final set. This increase in setting time is predictable, because the GGBFS has less cementitious properties than a Type II portland cement, and the oxides of sulfur increase with the addition of the slag.

GGBFS was also used with TIP and TISM blended portland-pozzolan cements. In the case of the TIP blended portland-pozzolan cement, the GGBFS accelerated the setting time with respect to the control 100% TIP. The slag has cementitious properties and will reduce the setting time in this particular case. The TISM blended portland-pozzolan cement has 20% Grade 100 slag in it, which is less reactive than the Grade 120 slag. This caused a small difference in the setting time when the two were used together: the initial setting time was 80 minutes faster but the final setting time was 11 minutes longer.

The ternary mixtures of GGBFS, Type II portland cement, and fly ashes were also tested. Increasing the F fly ash amount from 15% to 20% of the total cementitious materials had an inverse effect and actually decreased the setting time from 647 to 579 minutes, which was not a significant decrease and was probably caused by environmental factors. However, when 30% of the total cementitious materials were replaced by the F fly ash, the final setting time increased to 697 minutes. The F fly ash has very limited cementitious properties at early ages, and a high replacement of portland cement will delay the setting time.

GGBFS was also used in ternary mixtures of concrete with Type II portland cement and silica fume or metakaolin. Both silica fume and metakaolin showed a reduction in the initial and final setting time of the concrete specimens. Table 58 presents the decrease in setting time with respect to the control caused by metakaolin and silica fume. These reductions are caused because silica fume and metakaolin stiffen the mixture. However, the reductions were not significant.

Metakaolin was used in six mixture designs. For the ternary mixture with GGBFS and Type II portland cement, the addition of metakaolin decreased the final setting time by 93 minutes with respect to the control. The binary mixture of TIP blended portland-pozzolan cement and metakaolin decreased the final setting time 49 minutes with respect to the control.

Ternary mixtures with metakaolin, Type II portland cement, and fly ashes were tested The total amount of portland cement decreased with respect to the binary mixtures of Type II portland cement and fly ash. The addition of metakaolin did not seem to have an evident effect in the setting time of the mixtures. The final setting time increased up to 604 minutes.

The changes in setting time are relatively small compared to the actual setting time of the mixtures. In further research, more emphasis should be put on the behavior of metakaolin with these particular mixture designs. Metakaolin does not engage in the strength gain reaction at the first hours, because the reaction needs calcium hydroxide, which is not generated until later in the process of setting. Stiffening does occur because metakaolin is a calcined clay and will take water from the mixture and reduce its mobility. From this data, it does not appear to be an important factor in the setting time of the mixtures.

Silica fume was used in six mixture designs. The binary mixture of TIP blended portland-pozzolan cement and silica fume increased the final setting time 22 minutes. Similarly, the final setting time of the ternary mixtures with Type II portland cement and fly ash was not evidently affected by the addition of silica fume.

Lastly, when silica fume was used with TISM portland-pozzolan cement and with a ternary mixture with Type II portland cement and GGBFS, the final setting time decreased. For a 3% replacement of the TISM cement, the final setting time decreased 29 minutes and for a 62TI/35G120S/3SF, the final setting time decreased 82 minutes.

The changes in setting time are relatively small compared to the actual setting time of the mixtures. In further research, more emphasis should be put on the behavior of silica fume with these particular mixture designs. Silica fume reduces the mobility of the concrete in the first hours by attracting water to its large surface area. However, in the first hours, silica fume does not take part in the strengthening reaction. From these data, silica fume does not appear to have an important impact on the setting time of the concrete mixtures.

### *Bleeding*

Bleeding is the process by which free water comes to the surface of the concrete due to the settlement of solid materials within the concrete mixture.

The environment where the concrete is placed will affect the bleeding requirements of the mixtures. In dry environments, a higher bleeding potential is required; inversely; in a humid environment ,a low bleeding potential is desired. The information and guidelines given, herein, will help determine which supplementary cementitious materials will best aid in improving a concrete mixture that has the best bleeding characteristics.

### *General Aspects that Affect Bleeding*

Bleeding can be affected by many factors, primarily the amount of fine powder in the mixture. The total water content in the concrete samples was held constant for all the mixture designs. However, the actual volume of paste did change, because of the variability of air content, unit weight of cementitious materials, and the different dosages of the admixtures used.

The flow and the air entrainment of the fresh concrete are also parameters that influence bleeding of fresh concrete. A high slump generally promotes bleeding in concrete. Air entrainment of concrete reduces bleeding rates because the entrained air bubbles make it more difficult for free water to escape.

### *Effect of Pozzolans on Bleeding*

The use of pozzolans has an effect on every aspect of the concrete properties, including bleeding. The parameter used to assess it in this report is the ratio of potential bleed water to the total water in the mixture.

Class C fly ash designated C in this study contains forms of calcium that are readily soluble in water. This characteristic makes the C fly ash reduce the bleeding potential of mixtures. In addition, fly ashes tend to reduce the bleeding, because they take more water from the mixture during the first hours than portland cement. For example, in the control mixtures, it lowered the bleeding potential from 1.09% of the total water for the 100% Type II portland cement to 0.25% of the total water when 20% of the Type II portland cement was replaced with C fly ash. In addition the bleeding potential of the binary mixture of TISM cement with 25% C fly ash decreased to 1.88% from the control value of 5.99%.

There is a strong effect when too much of the C fly ash is used. The best example is observed in the binary mixtures with TIP blended portland-pozzolan cement. As stated in the materials section, a Class C fly ash is blended in the TIP; therefore, when 15% of the TIP cement is replaced by the C fly ash, a large amount of Class C ash is in the mixture. The first three entries in Table 46 show how when the C ash is increased, the bleeding potential also increases from 1.57% of the total water for a 100% TIP mixture to 1.97% of the total water for 15% replacement and 6.49% of the total water for 25% replacement of the total cementitious materials.

On the other hand, with TISM blended portland-pozzolan cement, the effect of the C fly ash is reversed. The bleeding is reduced from 5.99% of the total water for the control to 1.88% of the total water.

In ternary mixtures of concrete with two different fly ashes and Type II portland cement, the percentage of C fly ash (with respect to the total amount of cementitious materials) needed to reduce the bleeding potential was 30%. The mixture 60TII/30C/10F had a 0.32% bleeding potential compared to the mixture 60TII/20C/20F, which had a 7.20% bleeding potential.

The Class F fly ash designated F in this report generally decreased the bleeding potential of the mixtures because of its fineness.

Even though, for the majority of the mixture designs, the F fly ash reduced the bleeding potential, in the binary control mixture with 80% Type II portland cement and 20% of the F fly ash, a slight increase in bleeding potential was observed. The 100% Type II cement had a bleeding potential of 1.09% and the binary mixture increased to 1.90%. When the fly ash was used with TIP blended portland-pozzolan cement, the bleeding potential was reduced from 1.57% to 1.04%.

When the F fly ash was mixed with other fly ashes, the bleeding potential was high for three out of the four mixtures tested. The exception was the ternary mixture 60TII/30C/10F, where the C fly ash reduced the bleeding potential. The F fly ash with the F2 showed high bleeding potentials. The main reason is an incompatibility problem with the F2 fly ash and the admixtures used in the research. Table 48 summarizes the results for the ternary mixtures with two fly ashes. Table 49 shows the bleeding potential measured for ternary mixture of concrete with Type II portland cement, Grade 120 slag, and the F fly ash. The use of fly ash reduced the bleeding potential from 4.08% to 0.53%, even with an increase of slump of 1.25 inches. The interaction between these mineral admixtures and the Type II cement create a mixture with a low bleeding potential.

Ternary mixtures with F fly ash and silica fume or metakaolin had low bleeding potentials. The silica fume and the metakaolin limited the bleeding potential and, therefore, the three mix designs have low potentials that range from 0.30% to 1.13%. It was noted that metakaolin was more efficient in reducing bleeding potential than silica fume. Silica fume's very low fineness and very high surface has a large water requirement that reduces bleeding. Metakaolin also is very fine.

The Class F fly ash designated F2 in this report presented a compatibility problem with the admixtures used in this research. Therefore, the numbers obtained do not reflect an accurate value that should be discussed herein.

GGBFS by itself with Type II portland cement increased the bleeding potential with respect to the control. The 65TII/35G120S mixture had a bleeding potential of 4.08% compared to 1.09% for the 100% Type II cement. Slag cements take longer to set than normal portland cement and have about the same fineness as portland cement. When added to the mixture, GGBFS particles take longer to dissolve and, during this time, the water is free to escape the concrete mixture.

The blended portland-pozzolan cements behaved different from each other. The TIP bleeding potential increased when 35% of it was replaced by GGBFS from 1.57% of the total water to 6.02% of the total water. The TISM bleeding potential dropped from 5.99% of the total water to

2.26% of the total water when 35% of the TISM was replaced with slag. GGBFS can reduce the bleeding potential if used in the right amounts.

In ternary mixtures, slag had low bleeding potentials when mixed with the F fly ash. The bleeding potential dropped to 0.53% for the mixture 50TII/30F/20G120S. The F2 ash had a compatibility problem and did not behave adequately. Lastly, metakaolin and silica fume reduced the bleeding potential down to 1.30% and 0.41%, respectively, as showed in Table 49.

Metakaolin was very efficient in lowering the bleeding potential of mixtures. The clay properties of this pozzolan and the fineness of it help it grab water and keep it in the mixture.

In the binary mixture with TIP blended portland-pozzolan cement, the bleeding potential was lowered from 1.57% of the total water for the 100% TIP mixture to 0.24% of the total water for the binary. In addition, when used in ternary mixtures, it behaved the same way. The mixture 60TII/35G120S/5M had a bleeding potential of 1.30%, much lower than 4.08%,of the total water, which 65TII/35G120S had. Also, the ternary mixtures with fly ash lowered their bleeding potential below 1% as shown in Table 50.

In the binary mixture with TIP blended portland-pozzolan cement, the bleeding potential was lowered from 1.57% of the total water for the 100% TIP mixture to 0.48% of the total water for the binary. Also for the TISM blended portland-pozzolan cement, the bleeding potential was lowered from 5.99% to 0.55% of the total water.

In addition, when used in ternary mixtures, it behaved similarly. The mixture 60TII/35G120S/3SF had a bleeding potential of 0.41%, much lower than 4.08%, which 65TII/35G120S had. Finally, the ternary mixtures with fly ash lowered their bleeding potential to 1.13% of the total water.

## Further Work on Fresh Properties

As stated in the introduction, further research needs to be done on the fresh characteristics of ternary mixtures of concrete, focusing on particular variables, some of which are detailed below.

- The setting time tests for mortar and concrete can’t be correlated because they are two different test procedures. Furthermore, the mortar setting time uses a “normal consistency” mortar, which means that the water to cementitious materials ratio varies.
- The $SO_3$ component in blended cement is optimized to adjust the setting time due to the effect of the pozzolans. If ternary mixtures were also optimized for setting time and blended, the setting time would be standard for the ternary mixtures and finishing operations would be standard for ternary portland-pozzolan blended cements.
- The C fly ash increased the setting time of the majority of the mixtures where it was used. The low cementitious properties at early ages and the high content of oxides of sulfur delayed the setting time of the mixtures where it was used. This fly ash also had a mitigating effect on the bleeding potential. The calcium hydroxide and the fineness of the

fly ash forced some of the water to stay in mixtures, reducing the bleeding potential. There was a level of replacement of the C ash that created the inverse effect, when too much Class C fly ash was used in the mixture design, the bleeding increased significantly.

- The F fly ash used in the study increased the setting time of the mixtures. The increase was not as significant as the one observed for the C fly ash, especially when the replacement was less than 20%. The lower content of sulfur oxides in the F fly ash explains why this ash did not have a greater effect on setting time. The F ash also mitigates bleeding, because of its fineness. Even though it was not as effective as the C ash, there wasn't a pessimum level observed with this fly ash.
- The F2 fly ash used had a compatibility problem with the admixtures used in the study. More research should be done to understand why this incompatibility problem occurs and how to avoid it. However, we have learned from this experience that trial batching should be done before doing a full-scale project. The Vicat needle test with mortar could be used to flag incompatibility problems with cementitious materials and admixtures.
- Using two different types of fly ash to replace 60% of the portland cement will increase the setting time of the mixture up to 400 minutes for the final set and will definitely slow down the strength gain of the mixture. Fly ash cementitious properties are very limited at early ages. Also, the C ash introduced a significant amount of sulfates into the mixture. The decrease in portland cement, in addition to these two parameters, increase the setting time of the ternary cementitious mixtures significantly.
- The setting time of mixtures with GGBFS was not changed dramatically compared to the controls. The cementitious properties of GGBFS used the sulfur oxides that the slag added to the mixture; therefore, there wasn't much excess $SO_3$ added to the portland cement. Bleeding was increased when GGBFS was used. The size of the particles of slag cement does not force water to stay in the concrete mixtures. Furthermore, the longer time it takes to dissolve the particles gives a longer time for water to escape the concrete mixture.
- In the first hours after the mixing, metakaolin does not appear to have a significant effect in setting time, probably because there is not enough calcium hydroxide for this pozzolan to start reacting. Metakaolin's inherit nature as a calcine clay, as well as the shape and size of its particles, help it attach itself to water from the mixture. This process reduces the mobility of the mixture and greatly reduces the bleeding potential.
- Silica fume also does not show a significant impact on setting time, because it does not start reacting. The really high fineness of silica fume and very large specific surface area, make silica fume take a significant amount of water from the mixture. Bleeding potential, as well as the mobility of the mixture, are greatly reduced as a result.

In summary, the fresh properties of ternary mixtures of concrete are important because they affect how we will construct the future infrastructure. Blended ternary portland-pozzolan cements, which can be optimized for setting time and strength, should be used. Depending on the project and the site, different ternary mixtures should be chosen to obtain the most desirable bleeding potential for those specific conditions.

## CONCRETE COMPRESSIVE STRENGTH

### Compressive Strength Methods

Following ASTM C39, Standards Test Method for Compressive Strength of Cylinder Concrete Specimens, 4 in. cylinders were cast and tested for each concrete mixture design. All specimens were cured at 100% relative humidity and 70±3 degrees F until tested.

### Concrete Compressive Strength Results

The 7 day and 28 day strengths can be found in Table 59 to Table 65. The strength development, 28/7 day $F_c$ ratio is also given in the strength tables. $F_c$ ratios that are either greater than 1.67 or less than 1.25 are undesirable and are shaded gray and in boldface type in the following tables. Graphs of compressive strength vs. time were plotted to show the strength development of various ternary mixtures and are presented in the Appendix.

**Table 59. Compressive strength results for mixtures with 100% cement**

| | Compressive Strength (psi) | | |
|---|---|---|---|
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** |
| **100TI** | 5360 | 6350 | **1.19** |
| **100TIP** | 3980 | 5340 | 1.34 |
| **100TISM** | 3100 | 5220 | **1.68** |
| **100E** | 4930 | 5880 | **1.19** |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 60. Compressive strength results for mixtures with Class C fly ash**

| | Compressive Strength (psi) | | |
|---|---|---|---|
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** |
| **80TI/20C** | 4530 | 6010 | 1.33 |
| **60TI/20C/20F** | 4910 | 6910 | 1.41 |
| **60TI/20C/20F2** | 2940 | 4770 | 1.62 |
| **60TI/30C/10F** | 4510 | 6540 | 1.45 |
| **60TI/30C/10F2** | 5130 | 7290 | 1.42 |
| **85TIP/15C** | 4370 | 6070 | 1.39 |
| **75TIP/25C** | 3370 | 5020 | 1.49 |
| **75TISM/25C** | 2710 | 4510 | 1.66 |
| **80E/20C** | 4730 | 5970 | 1.26 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 61. Compressive strength results for mixtures with Class F fly ash**

| | Compressive Strength (psi) | | |
|---|---|---|---|
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** |
| **80TI/20F** | 5380 | 7260 | 1.35 |
| **60TI/20C/20F** | 4910 | 6910 | 1.41 |
| **60TI/30C/10F** | 4510 | 6540 | 1.45 |
| **60TI/20F/20F2** | 3080 | 4622 | 1.50 |
| **75TI/20F/5SF** | 7080 | 9900 | 1.40 |
| **77TI/20F/3SF** | 5640 | 8230 | 1.46 |
| **60TI/20F/20G120S** | 5580 | 8040 | 1.44 |
| **75TI/20F/5M** | 6680 | 8550 | 1.28 |
| **60TI/30F/10F2** | 3740 | 6130 | 1.64 |
| **65TI/30F/5SF** | 5170 | 7950 | 1.54 |
| **67TI/30F/3SF** | 4680 | 7480 | 1.60 |
| **50TI/30F/20G120S** | 4960 | 7370 | 1.49 |
| **65TI/30F/5M** | 4150 | 5330 | 1.28 |
| **50TI/35G120S/15F** | 5200 | 7700 | 1.48 |
| **85TIP/15F** | 4630 | 5750 | 1.24 |
| **75TIP/25F** | 2800 | 3700 | 1.32 |
| **80E/20F** | 4930 | 6150 | 1.25 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 62. Compressive strength results for mixtures with Class F2 fly ash**

| | Compressive Strength (psi) | | |
|---|---|---|---|
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** |
| **80TI/20F2** | 5320 | 6720 | 1.26 |
| **60TI/20C/20F2** | 2940 | 4770 | 1.62 |
| **60TI/20F/20F2** | 3080 | 4620 | 1.50 |
| **75TI/20F2/5SF** | 4140 | 5950 | 1.44 |
| **77TI/20F2/3SF** | 4670 | 7320 | 1.57 |
| **60TI/20F2/20G120S** | 3290 | 6520 | **1.98** |
| **75TI/20F2/5M** | 4370 | 7440 | **1.70** |
| **60TI/30C/10F2** | 5130 | 7290 | 1.42 |
| **65TI/30F2/5SF** | 4800 | 8110 | **1.69** |
| **67TI/30F2/3SF** | 3920 | 7390 | **1.89** |
| **65TI/30F2/5M** | 2820 | 4550 | 1.61 |
| **50TI/35G120S/15F2** | 5160 | 7220 | 1.40 |
| **85TIP/15F2** | 5050 | XX | Missing Data |
| **75TIP/25F2** | 2990 | 4330 | 1.45 |
| **75TISM/25F2** | XX | 5070 | Missing Data |
| **80E/20F2** | 4070 | 5230 | 1.29 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 63. Compressive strength results for mixtures with Grade 120 slag**

| | Compressive Strength (psi) | | |
|---|---|---|---|
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** |
| **65TI/35G120S** | 5570 | 7960 | 1.43 |
| **60TI/20F/20G120S** | 5580 | 8040 | 1.44 |
| **50TI/30F/20G120S** | 4960 | 7370 | 1.49 |
| **50TI/35G120S/15F** | 5200 | 7700 | 1.48 |
| **60TI/20F2/20G120S** | 3290 | 6520 | **1.98** |
| **50TI/35G120S/15F2** | 5160 | 7220 | 1.40 |
| **62TI/35G120S/3SF** | 4900 | 6470 | 1.32 |
| **60TI/35G120S/5M** | 5090 | 6790 | 1.33 |
| **65TIP/35G120S** | 4700 | XX | Missing Data |
| **50TIP/50G120S** | 3080 | 5740 | **1.87** |
| **65TISM/35G120S** | 2170 | 5180 | **2.38** |
| **80E/20G120S** | 5150 | 6580 | 1.28 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 64. Compressive strength results for mixtures with silica fume**

| Mixture ID | Compressive Strength (psi)<br>7 Day | 28 Day | $F_c$ |
|---|---|---|---|
| **75TI/20F/5SF** | 7083 | 9895 | 1.40 |
| **77TI/20F/3SF** | 5640 | 8230 | 1.46 |
| **65TI/30F/5SF** | 5170 | 7950 | 1.54 |
| **67TI/30F/3SF** | 4680 | 7480 | 1.60 |
| **75TI/20F2/5SF** | 4140 | 5950 | 1.44 |
| **77TI/20F2/3SF** | 4670 | 7320 | 1.57 |
| **65TI/30F2/5SF** | 4800 | 8110 | **1.69** |
| **67TI/30F2/3SF** | 3920 | 7390 | **1.89** |
| **62TI/35G120S/3SF** | 4900 | 6470 | 1.32 |
| **97TIP/3SF** | 5740 | 9790 | **1.70** |
| **97TISM/3SF** | 4490 | 7320 | 1.63 |
| **95E/5SF** | 4860 | 6900 | 1.42 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

**Table 65. Compressive strength results for mixtures with metakaolin**

| Mixture ID | Compressive Strength (psi)<br>7 Day | 28 Day | $F_c$ |
|---|---|---|---|
| **75TI/20F/5M** | 6680 | 8550 | 1.28 |
| **65TI/30F/5M** | 4150 | 5330 | 1.28 |
| **75TI/20F2/5M** | 4370 | 7440 | **1.70** |
| **65TI/30F2/5M** | 2820 | 4550 | 1.61 |
| **60TI/35G120S/5M** | 5090 | 6790 | 1.33 |
| **95TIP/5M** | 6170 | 9470 | 1.53 |
| **95E/5M** | 6770 | 8170 | 1.21 |

Mixture designs with $F_c$ that are undesirable are **shaded and in boldface type**.

## Concrete Compressive Strength Discussion

### *100% Cement*

All of the 100 % cement control mixtures had $F_c$ ratios out of the range of acceptable values except for Type IP cement. Both the Type I cement and the limestone blended cements had $F_c$ values of 1.19, which is lower than the desired range. The Type ISM had a $F_c$ value of 1.68, which exceeds the desirable range. The Type ISM cement had the lowest 28-day compressive strength at 5,220 psi and the Type I had the highest compressive strength at 6,350 psi.

*Class C Fly Ash*

Mixtures containing Class C fly ash had $F_c$ ratios ranging from 1.26 to 1.66. Therefore, all the mixtures containing Class C fly ash had $F_c$ ratios within the range of acceptable values. The mixture with the lowest 28 day compressive strength was the 75TISM/25C mixture with only 4,500 psi. The 60TI/30C//10F2 mixture had the highest compressive strength of 7,290 psi at 28 days.

*Class F Fly Ash*

Mixtures containing Class F fly ash had $F_c$ ratios ranging from 1.25 to 1.64. Therefore, all of the mixtures containing Class F fly ash had $F_c$ ratios within the range of acceptable values. Two mixture designs had 28 day strengths under 5,000 psi: 60TI/20F/20F2 and 75TIP/25F with compressive strength values of 4,620 and 3,700 psi, respectively. The only mixture with a 28 day compressive strength over 9,000 psi was 75TI/20F/5SF with a compressive strength of 9,900 psi.

*Class F2 Fly Ash*

Four mixtures containing Class F2 fly ash did not have acceptable $F_c$ ratios. These mixture designs were 60TI/20F2/20G120S, 75TI/20F2/5M, 65TI/30F2/5SF, and 67TI/30F2/3SF. All four mixtures had $F_c$ ratios greater than the acceptable value of 1.67. The 60TI/20C/20F2, 60TI/20F/20F2, and 65TI/30F2/5M mixtures had compressive strengths less than 5,000 psi at 28 days. The only mixture design with a compressive strength over 8,000 psi was the 65TI/30F2/5SF mixture at 8,110 psi.

*Grade 120 Slag*

Three of the ternary mixtures containing Grade 120 slag did not have acceptable $F_c$ ratios. These mixtures were 60TI/20F2/20G120S, 50TIP/50G120S, and 65TISM/35G120S with $F_c$ ratios of 1.98, 1.87, and 2.38, respectively. The 65TISM/35G120S mixture had the lowest 28 day compressive strength at 5,180 psi, while 60TI/20F/20G120S had the highest 28 day compressive strength at 8,040 psi.

*Silica Fume*

Three of the ternary mixtures containing silica fume did not have acceptable $F_c$ ratios. These mixtures were 65TI/30F2/5SF, 67TI/35G120S/3SSF, and 97TIP/3SF with $F_c$ ratios of 1.69, 1.89, and 1.70, respectively. Overall strength development by 28 days is higher with mixtures containing silica fume. Of the 12 mixture designs containing silica fume, 9 of them had compressive strengths >7,000 psi by 28 days.

*Metakaolin*

All of the mixtures containing metakaolin had acceptable $F_c$ ratios except for 75TI/20F2/5M. It had a $F_c$ ratio of 1.70, which is greater than the allowable 1.67. The lowest 28 day strength occurred with the 65TI/39F2/5M mixture, having only 4,550 psi. The highest strength was the 95TIP/5M mixture with a compressive strength of 9,470 psi by 28 days.

### Concrete Compressive Strength Conclusions

Most of the ternary blends tested had $F_c$ ratios between 1.25 and 1.67, which is the ideal range. High replacement levels of SCMs can delay strength gain, so early age strengths are generally lower than a 100% portland cement mixture. However, by 28 days, many of the binary and ternary mixture combinations had higher compressive strengths than the pure portland cement control mixture.

## RAPID FREEZE-THAW

### Freeze-Thaw Methods

Following ASTM C666 method A, 28 mixture designs have completed the 300 cycles with relative dynamic modulus of elasticity greater than 60%. Due to capacity restrictions, the remaining mixture design specimens are stored in a -20°F freezer until space in the freeze-thaw machine is available.

### Freeze-Thaw Results

Table 66 contains the weight loss of each specimen, as well as an averaged weight loss for the set of specimens. Table 67 contains the durability factor for the individual specimens and their average. Finally, Table 68 contains the entrained air content measured 5 minutes after discharge, number of freeze-thaw cycles specimens subjected to, and the minimum relative dynamic modulus of elasticity of each mixture design.

**Table 66. Weight loss of specimens**

| | Weight Loss (lbs) | | | | |
|---|---|---|---|---|---|
| **Mixture ID** | **Specimen 1** | **Specimen 2** | **Specimen 3** | **Specimen 4** | **Average** |
| **60TI/20F2/20G120S** | 0.02 | 0.01 | 0.03 | | 0.02 |
| **75TI/20F2/5M** | -1.18 | 0.01 | 0.01 | | -0.38 |
| **60TI/30C/10F** | 0.18 | 0.26 | 0.29 | | 0.24 |
| **60TI/30C/10F2** | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 |
| **50TI/30F/20G120S** | 0.02 | 0.05 | 0.01 | | 0.03 |
| **65TI/30F/5M** | 0.01 | 0.02 | 0.00 | 0.01 | 0.01 |
| **65TI/30F2/5SF** | 0.23 | 0.18 | 0.25 | | 0.22 |
| **67TI/30F2/3SF** | 0.05 | 0.04 | 0.03 | | 0.04 |
| **50TI/35G120S/15F** | 0.06 | 0.07 | | | 0.07 |
| **50TI/35G120S/15F2** | 0.05 | 0.02 | 0.01 | | 0.03 |
| **85TIP/15C** | 0.08 | 0.09 | | | 0.09 |
| **85TIP/15F** | 0.09 | 0.09 | | | 0.09 |
| **85TIP/15F2** | 0.13 | 0.12 | 0.10 | | 0.12 |
| **97TIP/3SF** | 0.08 | 0.05 | 0.06 | | 0.06 |
| **75TIP/25C** | 0.30 | 0.29 | 0.32 | | 0.30 |
| **65TIP/35G120S** | 0.09 | 0.08 | 0.08 | | 0.08 |
| **75TIP/25F2** | 0.10 | 0.11 | 0.10 | | 0.10 |
| **75TIP/25F** | 0.15 | 0.16 | | | 0.16 |
| **65TI/35G120S** | 0.01 | 0.01 | 0.00 | | 0.01 |
| **100TIP** | 0.12 | 0.13 | 0.11 | | 0.12 |
| **100TISM** | 0.05 | 0.08 | 0.10 | | 0.08 |
| **60TI/30F2/10C** | 0.08 | 0.09 | | | 0.09 |
| **50TIP/50G120S** | 0.07 | 0.10 | 0.06 | | 0.08 |
| **100E** | 0.27 | 0.29 | 0.26 | | 0.27 |
| **80E/20S** | 0.27 | 0.29 | 0.29 | | 0.28 |
| **80E/20F** | 0.29 | 0.31 | 0.31 | | 0.30 |
| **95E/5M** | 0.01 | 0.00 | 0.02 | | 0.01 |

**Table 67. Durability factor of specimens**

| | Durability Factor | | | | |
|---|---|---|---|---|---|
| **Mixture ID** | **Specimen 1** | **Specimen 2** | **Specimen 3** | **Specimen 4** | **Average** |
| **60TI/20F2/20G120S** | 131 | 100 | 112 | | 114 |
| **75TI/20F2/5M** | 112 | 112 | 100 | | 108 |
| **60TI/30C/10F** | 97 | 97 | 101 | | 98 |
| **60TI/30C/10F2** | 96 | 100 | 100 | 100 | 99 |
| **50TI/30F/20G120S** | 121 | 90 | 90 | | 100 |
| **65TI/30F/5M** | 135 | 100 | 93 | 93 | 105 |
| **65TI/30F2/5SF** | 97 | 97 | 97 | | 97 |
| **67TI/30F2/3SF** | 96 | 96 | 96 | | 96 |
| **50TI/35G120S/15F** | 104 | 104 | | | 104 |
| **50TI/35G120S/15F2** | 100 | 100 | 90 | | 97 |
| **85TIP/15C** | 100 | 100 | | | 100 |
| **85TIP/15F** | 100 | 97 | | | 98 |
| **85TIP/15F2** | 102 | 105 | 105 | | 104 |
| **97TIP/3SF** | 105 | 105 | 102 | | 104 |
| **75TIP/25C** | 97 | 97 | 97 | | 97 |
| **65TIP/35G120S** | 105 | 102 | 102 | | 103 |
| **75TIP/25F2** | 118 | 87 | 102 | | 102 |
| **75TIP/25F** | 113 | 113 | | | 113 |
| **65TI/35G120S** | 100 | 104 | 100 | | 101 |
| **100TIP** | 106 | 84 | 99 | | 96 |
| **100TISM** | 105 | 77 | 77 | | 87 |
| **60TI/30F2/10C** | 100 | 100 | | | 100 |
| **50TIP/50G120S** | 104 | 100 | 137 | | 114 |
| **100E** | 97 | 97 | 97 | | 97 |
| **80E/20S** | 107 | 112 | 95 | | 105 |
| **80E/20F** | 94 | 97 | 97 | | 96 |
| **95E/5M** | 105 | 105 | 109 | | 106 |

**Table 68. Other characteristics of freeze-thaw specimens**

| Mixture ID | Air Content (%) | Freeze-Thaw Cycles | Min. Dynamic Modulus of Elasticity |
|---|---|---|---|
| **60TI/20F2/20G120S** | 4.6 | 300 | 100 |
| **75TI/20F2/5M** | 4.1 | 300 | 100 |
| **60TI/30C/10F** | 5.9 | 309 | 100 |
| **60TI/30C/10F2** | 5.1 | 300 | 96 |
| **50TI/30F/20G120S** | 6.5 | 300 | 90 |
| **65TI/30F/5M** | 7.2 | 300 | 93 |
| **65TI/30F2/5SF** | 3.8 | 309 | 100 |
| **67TI/30F2/3SF** |  | 300 | 96 |
| **50TI/35G120S/15F** | 3.8 | 300 | 104 |
| **50TI/35G120S/15F2** | 9.5 | 300 | 90 |
| **85TIP/15C** |  | 300 | 100 |
| **85TIP/15F** |  | 300 | 97 |
| **85TIP/15F2** |  | 300 | 96 |
| **97TIP/3SF** |  | 316 | 97 |
| **75TIP/25C** |  | 309 | 100 |
| **65TIP/35G120S** |  | 316 | 97 |
| **75TIP/25F2** |  | 316 | 82 |
| **75TIP/25F** | 7.8 | 300 | 113 |
| **65TI/35G120S** | 7.9 | 300 | 100 |
| **100TIP** |  | 304 | 85 |
| **100TISM** |  |  |  |
| **60TI/30F2/10C** |  | 300 | 100 |
| **50TIP/50G120S** | 8.5 | 300 | 100 |
| **100E** | 7.35 | 309 | 100 |
| **80E/20S** | 7.1 | 304 | 96 |
| **80E/20F** | 3.85 | 309 | 96 |
| **95E/5M** | 6.5 | 300 | 100 |

### Freeze-Thaw Discussion

All 28 mixtures had an air content of at least 4%, and an average durability factor greater than 80, which is the satisfactory limit for freeze-thaw testing. Durability factors greater than 100 are achieved by the specimens gaining strength throughout the 300 freeze-thaw cycles. The only mixture with an average durability factor under 90% was the 100TISM, also known as a Type IS(20) cement, with an average durability factor of 87%. Figure 31 shows the durability factor vs. the entrained air percent. At this time, no definite correlations can be made between the durability factor and the entrained air content.

All binary and ternary mixtures tested that used a Type I cement had dynamic moduli between 80 and 120. Most of the dynamic modulus readings fall within the range of 100±5. The mixtures that contain blended cement had a slightly wider dynamic moduli range of 75 to 130. However, many of the readings still fell within the range of 100±5. From cycle 35 through 76, the mixture 100TIP had a steady dynamic modulus of 77. This mixture is the only mixture with a dynamic modulus less than 80 at any point during the test; however, after 300 cylces, the dynamic modulus was 85.

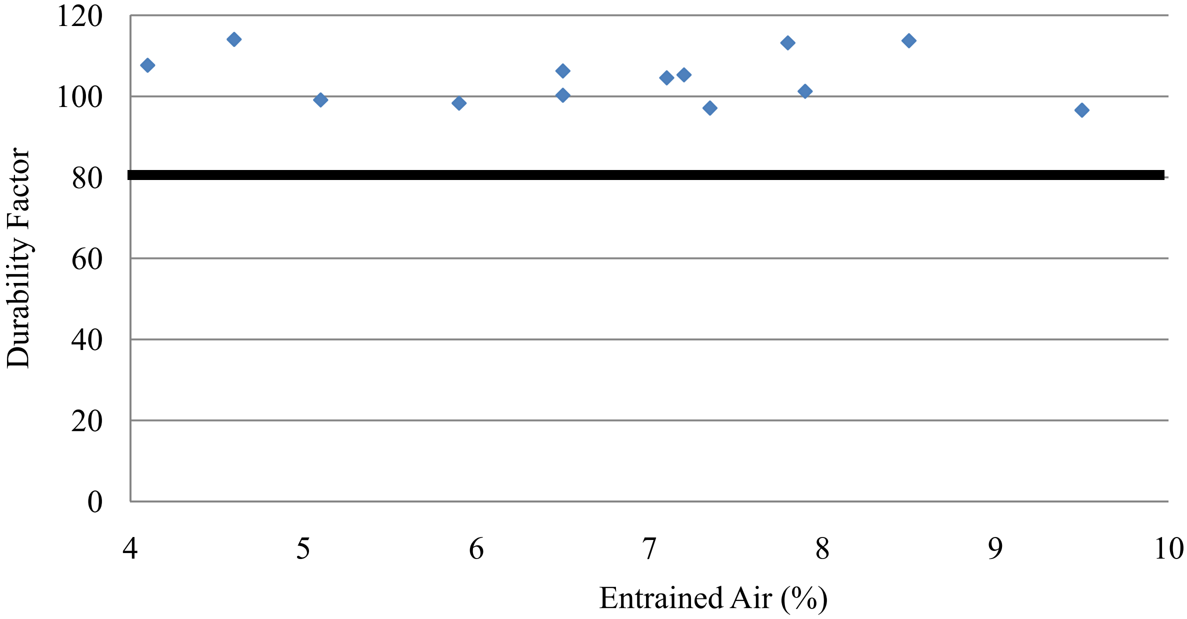

Figure 31. Durability factor association for entrained air volumes

### Freeze-Thaw Conclusion

With an entrained air volume greater than 4%, all tested mixture designs provided sufficient freeze-thaw durability. Some of the mixture design test specimens were able to gain strength through the freeze-thaw cycles and had a durability factor of greater than 100 after 300 cycles.

## CHLORIDE ION RESISTANCE AND RESISTIVITY

### Analytical Development

It is essential to determine the resistivity from the AASHTO T277 data to compare with the results from the Wenner technique. The Wenner testing device and AASHTO T277 are related by Ohm’s law. The AASHTO T277 test can be modeled as an electrical circuit consisting of a power source, steady voltage drop, and a resistor. The resistor in this system is the 5.1 cm (2 in.) thick by 10 cm (2 in.) diameter concrete specimen. The basic equation for electrical resistivity in a solid is equation (8) and is calculated by rearranging the Ohm’s law.

$$\rho = R \times \frac{Area}{Thickness} \tag{8}$$

Then, substituting the resistance (R) into equation (8), the resistivity (ρ) of the specimen can be determined using equation (9). The units of resistivity are typically expressed as kΩ*cm (kΩ*in). The T277 test has a constant voltage drop (60V) across the resistor, a known coulomb value and time interval, and the dimensions of the specimen are also known, so resistivity can be directly calculated. In this way, the data from the AASHTO T277 method can be theoretically compared to data obtained using the Wenner method.

$$\rho = \frac{V \times Area}{I \times Thickness} \tag{9}$$

The Wenner technique uses a series of four probes attached to a power source. The spacing of the probes is constant (a=5.1 cm or 2 in.), and a known current is passed between the two outer probes and the resulting voltage drop across the two inner probes is measured. Diagrams of this are shown in Figure 32 and Figure 33. The equation for determining the resistivity of a solid using the Wenner device is given by equation (10), where *a* is the distance between probes.

$$\rho = 2 \times \pi \times a \times \frac{V}{I} \tag{10}$$

It is important to understand that this current is not one dimensional: it is three dimensional. When resistivity is measured on a round cylinder using the Wenner meter, the current is restrained within the concrete and interference is caused by the concrete and air interface. To account for this interference, the data needs to be converted into an equivalent semi-infinite slab resistivity, where there are no curvature effects. This is accomplished with a geometric correction factor (K). Resistivity readings from a semi-infinite flat slab better represent the resistivity of the material; whereas, the resistivity from the curved cylinder has interference from the edge of the cylinder. The values obtained by using the Wenner device should be divided by the proper correction factor, as in equation (11), by K= 2.7 for 5.1 cm (2 in.) probe spacing and 10 cm by 20 cm (4 in. x 8 in.) cylinder. The geometric correction factor is applied the same to all 10 cm by 20 cm (4 in. x 8 in.) cylinders used in this test.

$$\rho_{real} = \rho_{measured}/K \tag{11}$$

To account for heating of the specimens during AASHTO T277 testing, the joule effect was considered. The equation developed is equation (12), where $Q_o$ is the total corrected charge, $Q_{c,6h}$ is the measured charge obtained from AASHTO T277 corrected for specimen diameter, β=1245, and δT is the temperature rise during testing (in kelvin). This equation is to be used with the AASHTO T277 test and the results of this test are not equal for all mixtures. For mixtures with higher permeability (higher coulomb, lower resistivity), larger heating variations occur during testing as compared with low permeability mixtures. This is due to larger currents passing through the interconnected voids. In all cases, larger temperature variations produce larger joule effect adjustments.

$$Q_o = e^{[\ln(Q_{c'6h}) + \beta(1/\delta T - 1/273)]} \tag{12}$$

By comparing values determined from the same concrete mixture using the AASHTO T277 method with equation (8) and the Wenner technique with equation (10), a relationship may be determined. However, these relationships must be normalized to a uniform ambient condition. With the application of both the geometric correction and the adjustment for the joule effect, the results can be analytically combined as an evaluation tool for concrete. The results can be completed quickly and with less effort using the Wenner technique to determine the chloride ion ingress into concrete. The testing using the Wenner technique takes about 30 minutes to complete, as compared to more than 24 hours for the AASHTO T277 method.

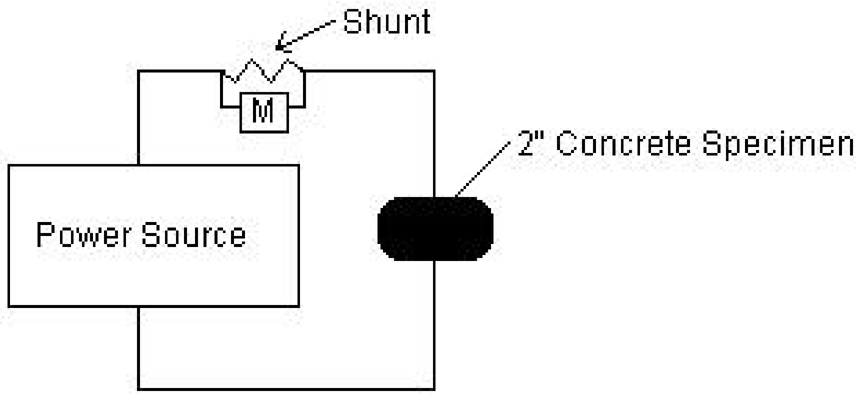

**Figure 32. AASHTO T277 testing apparatus**

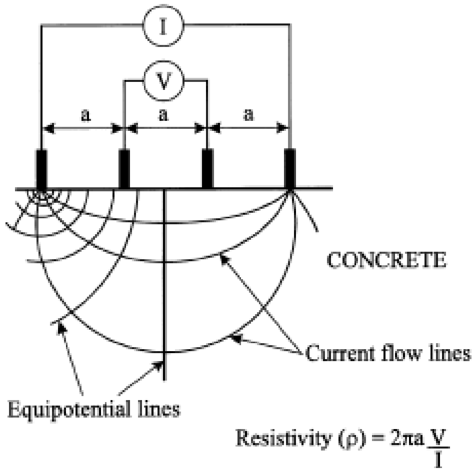

**Figure 33. Wenner meter methods**

### *ASTM C1202*

In accordance with ASTM C1202, concrete cylinders were prepared from concrete mixtures with various amounts of pozzolanic materials. These cylinders were wet cured in a curing tank with lime for 14 days before being removed for dry curing. They were tested on the 98th day after they were cast. These cylinders, after being wet cured, were sliced using either a lapidary saw or modified tile saw into 2 in. thick by 4 in. diameter specimens. Once sliced, they were allowed to dry. When dry, epoxy was applied to the outside diameter of the slice. The specimens were allowed to dry for at least 1 week before testing. The testing procedures were done in accordance with ASTM C1202 using a commercially available instrument manufactured for use with the ASTM C1202 testing method. The specimens were wet cured for 14 days to allow the cement and pozzolans to react and to simulate the curing duration that may be applied on structures in the field. Once removed, they were exposed to laboratory temperatures until the day they were tested.

This was a complete testing set up with a power source, testing cells, and all the software needed to collect and compile the data. The software included a data logger that collected the current and temperature of the cells, variability to be able to test the specimens at different voltages and different times, and a report generating system.

The results obtained by using this testing method are in coulombs (Amp*sec), which is an integration of the current, applied over the testing time. This coulomb value is then reduced according to ASTM C1202 to an equivalent result that would be obtained using a specimen diameter of 3.75 in. The values in ASTM C1202 were established using 3.75 in. diameter specimens, so, to compare experimental results with the standard in ASTM C1202, this correction should be applied.

### *Wenner Resistivity Florida Department of Transportation Method FM 5-578*

The testing method FM 5-578 requires three 4.0 in. by 8.0 in. specimens meeting ASTM C470 requirements. All specimens should be moist cured in a moist room (without lime) until the day of testing. 24 hours after being cast, the cylinder molds are removed and 4 marks are placed at 0, 90, 180, and 270 degrees around the circumference of the top of the cylinder. The cylinders are then placed back in the curing room until the time of testing, at which time the cylinders are removed.

The Wenner resistivity probe, with 1.5 in. probe spacing, is then placed with its handle parallel to the center of the cylinder, at approximately half the height of the cylinder. The operator then waits 3 to 5 seconds for a stable reading, and then rotates the cylinder to take readings below the 0, 90, 180, and 270 degree marks. These readings are to be done twice per cylinder. Once this is completed, the operator moves on to the next cylinder. When readings have been collected for all three specimens, the readings are averaged to obtain the average resistivity for the mixture.

Resistivity readings were done in accordance with the Florida Department of Transportation (FDOT) testing method (FM 5-578) with the exception of the probe spacing, number of cylinders cast, and resistivity characterization for permeability. The data in this report were tested using a probe spacing of 2 in., instead of 1.5 as recommended by FDOT; and the number of cylinders cast for testing varied from 2 to 6, instead of 3, as recommended. The probe spacing could not be changed as it came from the manufacturer with 2 in. spacing; however, the 2 in. spacing was beneficial when compared to the 1.5 in. spacing because there is less large aggregate interference with the longer spacing. Large aggregate interference occurs when the spacing is not more than 2 times the diameter of the largest aggregate size and with longer spacing there is less interference.

**Results**

Results for Wenner Resistivity and chloride ion penetration resistance, as well as conversions between test methods, are found in Table 69 and Table 70.

**Table 69. Wenner resistivity conversions to coulombs**

| Mixture | Measured Resistivity (ρ) (kΩ*cm) | Geometric K Factor | Geometric Adjusted Resistivity (GAR) (kΩ*cm) | Calculated Coulombs from GAR (Coulombs) |
|---|---|---|---|---|
| **75TI/20F/5M** | 28.7 | 2.7 | 10.6 | 1711 |
| **60TI/30F/10F2** | 8.4 | 2.7 | 3.1 | 5857 |
| **60TI/20F2/20G120S** | 42.4 | 2.7 | 15.7 | 1158 |
| **75TI/20F2/5M** | 42.6 | 2.7 | 15.8 | 1152 |
| **67TI/30F2/3SF** | 36.3 | 2.7 | 13.4 | 1352 |
| **60TI/20F/20F2** | 14.8 | 2.7 | 5.5 | 3328 |
| **100TIP** | 20.5 | 2.7 | 7.6 | 2394 |
| **60TI/30F2/10C** | 17 | 2.7 | 6.3 | 2887 |
| **75TISM/25C** | 18.7 | 2.7 | 6.9 | 2630 |
| **75TISM/25F2** | 30.6 | 2.7 | 11.3 | 1603 |
| **97TISM/3SF** | 49.3 | 2.7 | 18.2 | 997 |
| **75TI/20F/5SF** | 36.4 | 2.7 | 13.5 | 1349 |
| **100TI** | 17.9 | 2.7 | 6.6 | 2746 |
| **65TI/30F2/5SF** | 64 | 2.7 | 23.7 | 767 |
| **65TIP/35G120S** | 73.8 | 2.7 | 27.3 | 666 |
| **60TI/20F/20G120S** | 36.3 | 2.7 | 13.4 | 1354 |
| **100E** | 16.7 | 2.7 | 6.2 | 2938 |
| **80E/20G120S** | 29.8 | 2.7 | 11 | 1650 |
| **95E5SF** | 46 | 2.7 | 17 | 1068 |
| **62TI/35G120S/3SF** | 62.8 | 2.7 | 23.3 | 782 |
| **60TI/35G120S/5M** | 65.1 | 2.7 | 24.1 | 754 |
| **75TI/20F2/5SF** | 65.6 | 2.7 | 24.3 | 748 |
| **77TI/20F2/3SF** | 42.4 | 2.7 | 15.7 | 1158 |
| **65TISM/35G120S** | 39.2 | 2.7 | 14.5 | 1253 |
| **50TI/35G120S/15SF** | 47.2 | 2.7 | 17.5 | 1040 |
| **85TIP/15F** | 25.8 | 2.7 | 9.6 | 1902 |

75TI/20F/5M = 75% Type I cement, 20% Class F fly ash, 5% metakaolin

**Table 70. AASHTO T277 Conversions to resistivity**

| Mixture | Raw Average (Coulomb) | Joule Effect (Coulomb) | Calculated Resistivity (kΩ*cm) |
|---|---|---|---|
| **75TI/20F/5M** | 1621 | 1369 | 13.3 |
| **60TI/30F/10F2** | 6786 | 3871 | 4.7 |
| **60TI/20F2/20G120S** | 2316 | 1804 | 10.1 |
| **75TI/20F2/5M** | 2363 | 1877 | 9.7 |
| **67TI/30F2/3SF** | 1987 | 1611 | 11.3 |
| **60TI/20F/20F2** | 5490 | 3431 | 5.3 |
| **100TIP** | 4023 | 2715 | 6.7 |
| **60TI/30F2/10C** | 6137 | 3558 | 5.1 |
| **75TISM/25C** | 4023 | 2725 | 6.7 |
| **75TISM/25F2** | 3032 | 2173 | 8.4 |
| **97TISM/3SF** | 935 | 845 | 21.5 |
| **75TI/20F/5SF** | 1163 | 1032 | 17.6 |
| **100TI** | 4562 | 3068 | 5.9 |
| **65TI/30F2/5SF** | 1512 | 1308 | 13.9 |
| **65TIP/35G120S** | 1176 | 1040 | 17.5 |
| **60TI/20F/20G120S** | 2000 | 1709 | 10.6 |
| **100E** | 5890 | 3649 | 5 |
| **80E/20G120S** | 1970 | 1703 | 10.7 |
| **95E5SF** | 1656 | 1415 | 12.9 |
| **62TI/35G120S/3SF** | 984 | 872 | 20.9 |
| **60TI/35G120S/5M** | 698 | 627 | 29 |
| **75TI/20F2/5SF** | 1230 | 1071 | 17 |
| **77TI/20F2/3SF** | 1900 | 1555 | 11.7 |
| **65TISM/35G120S** | 1568 | 1318 | 13.8 |
| **50TI/35G120S/15SF** | 1437 | 1216 | 15 |
| **85TIP/15F** | 3634 | 2555 | 7.1 |

75TI/20F/5M = 75% Type I cement, 20% Class F fly ash, 5% metakaolin

### Discussion

*Resistivity and AASHTO T277*

*Coulomb to Coulomb*

To confirm a relationship between the AASHTO T277 test and resistivity, data was collected and compiled in Figure 34 through Figure 38. Each data point represents 8 to 48 readings with 8 readings per cylinder for resistivity and 2 to 6 specimens for ASTM C1202. For Figure 34 through Figure 37, the coulombs calculated from resistivity are on the vertical axis and experimental coulomb values from T277 are on the horizontal axis with a one to one (unity) line also shown. The important relationship to notice in these figures is not necessarily how close the data are to the best fit line, but how closely the best fit line is to unity. The closeness of the data to the line will be discussed later. The closer the line is to unity, the better the relationship is between these two methods under Ohm's law. For reference, Figure 37 shows the corrected (including temperature and geometric) and uncorrected (no correction factors applied) coulomb lines. Notice the corrected data line is much closer to the unity line than the uncorrected line. This indicates that with these corrections, the relationship through Ohm's law is valid. To understand how each of these corrections affects the data, they are plotted separately in Figure 35 and Figure 36, keeping either the joule effect adjustment or geometric correction unchanged for each plot. Figure 34 shows the effect of the joule effect adjustment as the geometric correction is unchanged. Notice that the higher coulomb mixtures are corrected the most by the joule effect adjustment. This is due to the excessive heating of the specimens caused by high permeability mixtures. Figure 35 shows the effect of the geometric correction, as the joule effect adjustment is unchanged. As can be seen, these corrections are made to account for most of the discrepancies in the coulomb relationship for Ohm's law for these two testing methods.

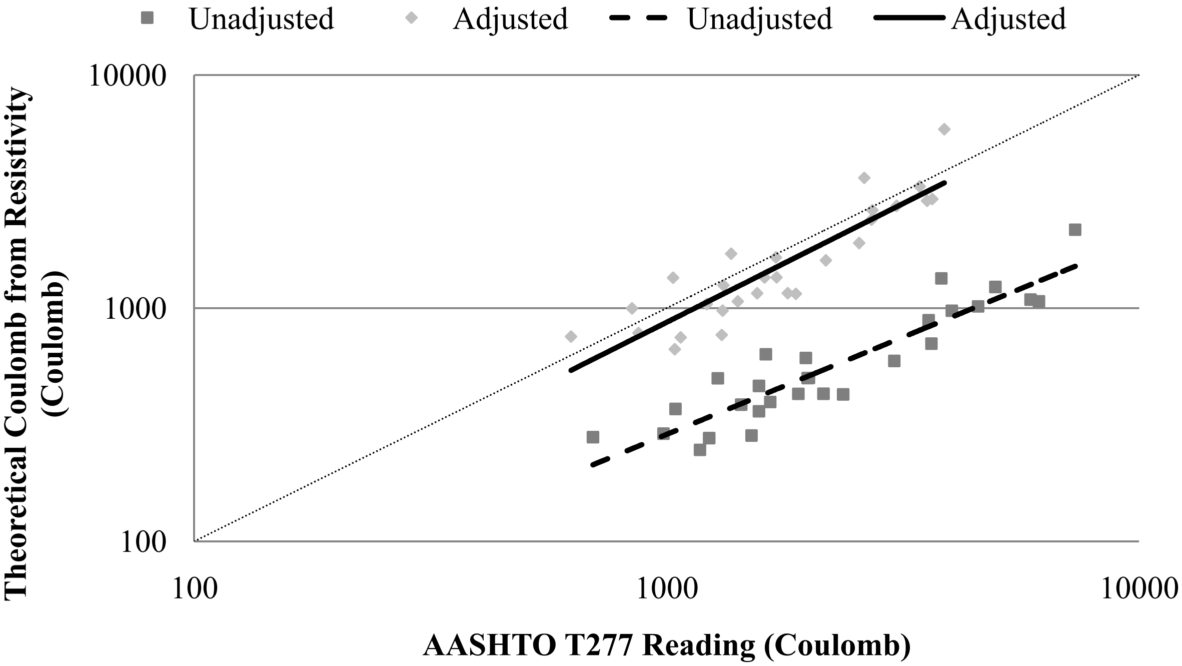

**Figure 34. Adjusted and unadjusted T277 coulomb vs. theoretical coulomb from resistivity**

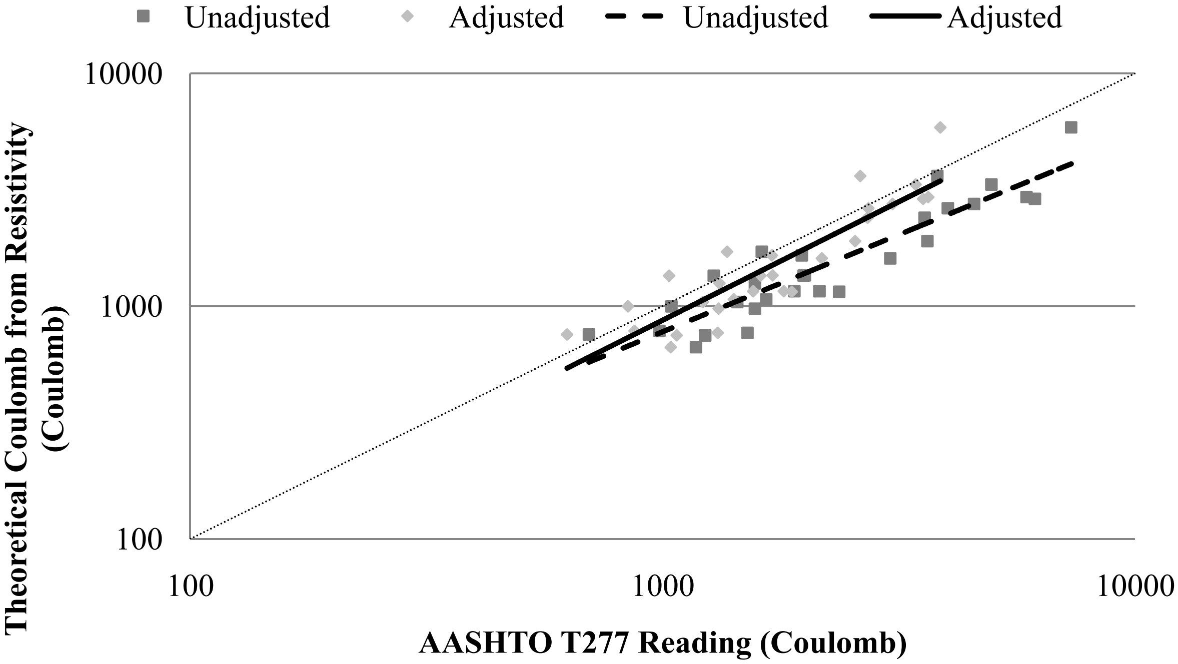

Figure 35. Joule effect adjustment – T277 coulomb vs. resistivity coulomb

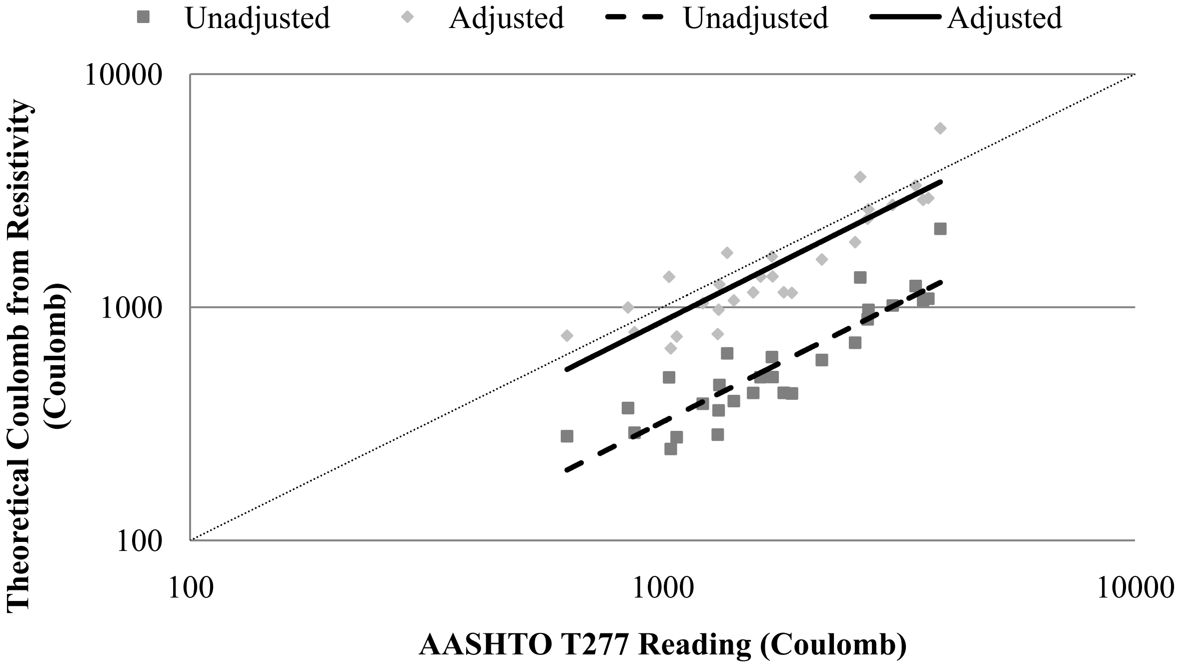

Figure 36. Geometric correction – T277 coulomb vs. resistivity coulomb

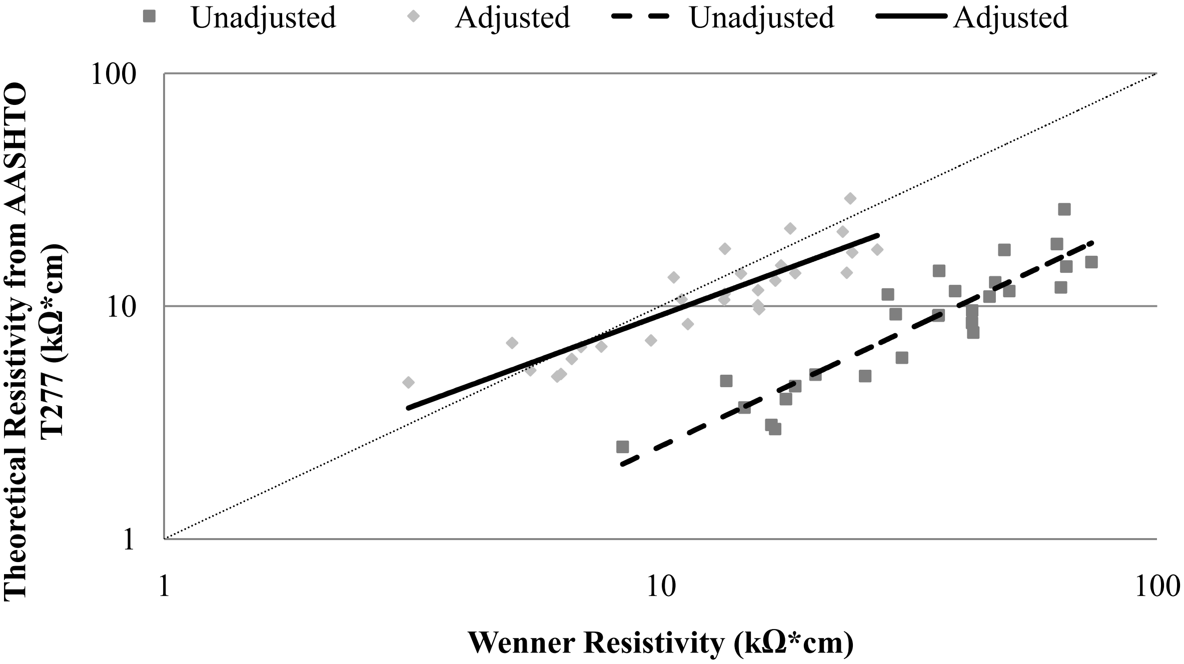

Figure 37. Adjusted and unadjusted Wenner resistivity vs. T277 resistivity (1 in.=2.54 cm)

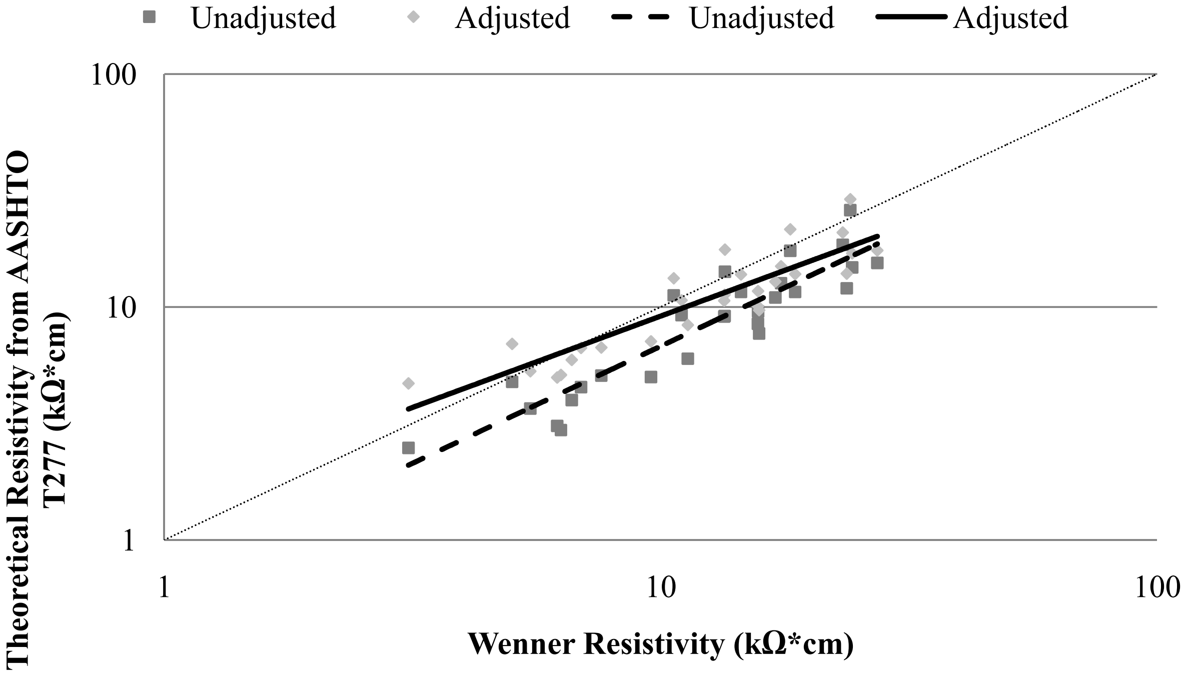

Figure 38. Joule effect adjustment – resistivity vs. AASHTO T277 resistivity (1 in.=2.54 cm)

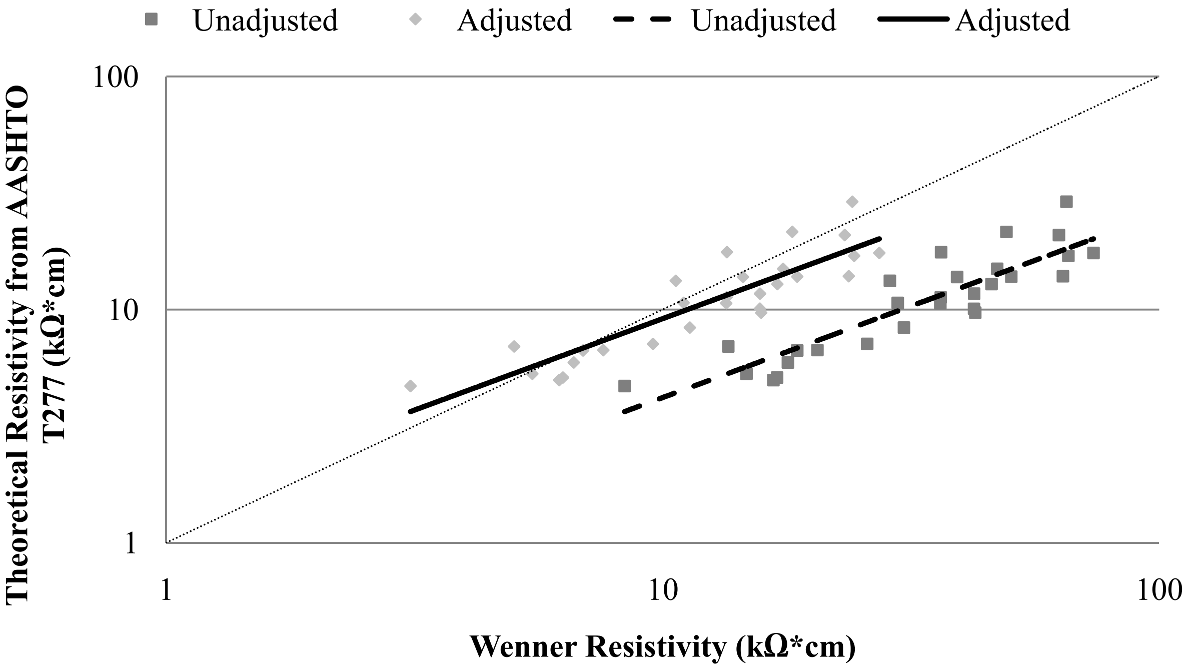

Figure 39. Geometric correction – resistivity vs. AASHTO T277 resistivity (1 in.=2.54 cm)

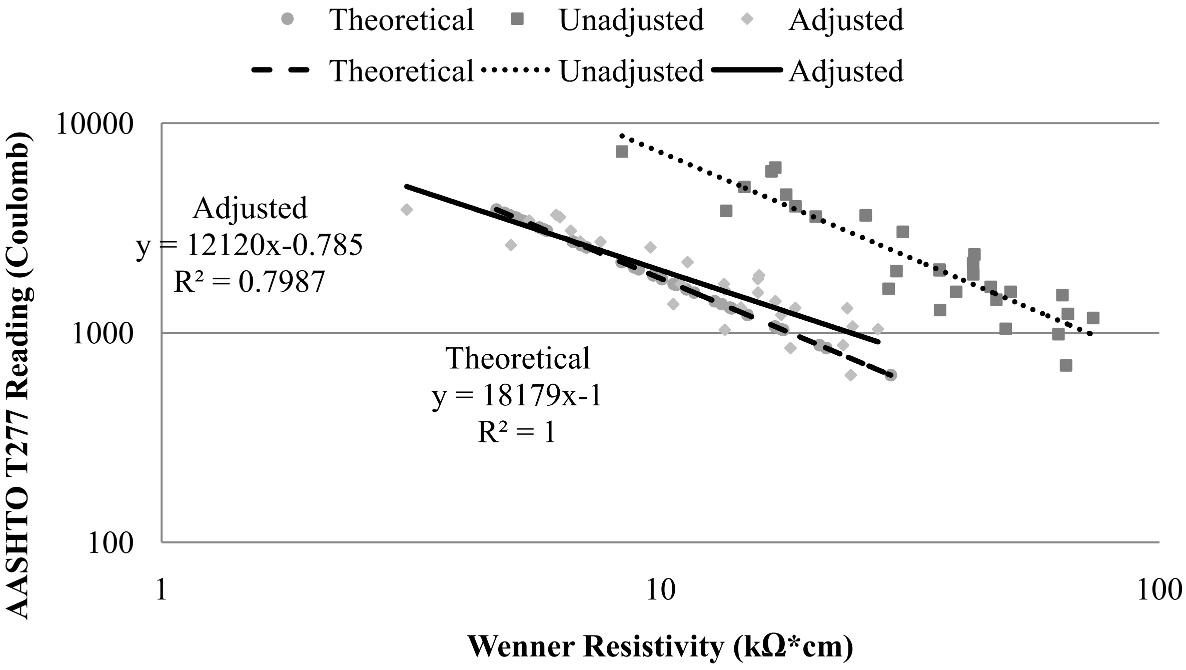

Figure 40. Resistivity vs. AASHTO T277 coulomb (1 in.=2.54 cm)

*Resistivity to Resistivity*

Looking at the data in terms of resistivity, the same trend is observed as in the coulomb comparisons. The calculated resistivity using T277 data is shown on the vertical axis and the experimentally determined resistivity is shown on the horizontal axis with a one to one line shown diagonally in Figure 41. Again, it is more important with these plots to notice the proximity of the best-fit line in relation to unity than it is for how closely the data fits the best-fit line. How the data fits the lines will be discussed in the next section. As with the coulomb comparisons, either the temperature corrected values or the geometric corrected values are kept the same for each plot to observe the effect of the correction.

*Resistivity vs. Coulomb*

Based on the previous discussion with coulomb and resistivity comparisons, it is expected that there would be a similar relationship between coulomb and resistivity. In Figure 40, a theoretical line is presented which represents coulomb values based on T277 testing in correlation with resistivity calculated from the T277 results as discussed previously. It is apparent that there is a relationship between AASHTO T277 and resistivity readings based on the fit of the trend line to the data ($R^2 = 0.799$) and the proximity of the trend line to the theoretical line. Figure 40 also contains uncorrected data for comparison.

By using the theoretical adjustments for the joule effect and the geometric correction factor, it can be seen that the adjusted predictive line in Figure 40 was much closer to the theoretical values obtained from AASHTO T277, meaning that the Ohm's law relationship is nearly valid for these two testing methods. There still exists a variance between the theoretical and adjusted values; however, this can be explained by looking at surface resistivity vs. concrete resistivity. Surface resistivity is determined by the Wenner device and only determines the resistivity a small distance into the concrete (up to a depth equal to the probe spacing). For clarification, this is not the same as the curvature correction described earlier. Concrete conductivity is determined through the AASHTO T277 test over the entire depth of the specimen. At the surface of the concrete, there may be more paste present, which may have a different resistivity than the center of the concrete, which contains relatively less paste. This accounts for the differences in the theoretical vs. empirical readings.

*Dry Curing Time Before Testing*

Resistivity results obtained from testing of concrete cylinders can vary because of drying after being wet cured. Table 71 shows the increase in resistivity readings based on letting a wet cylinder dry cure for 5 minutes, 35 minutes, and 55 minutes after being removed from water. An increase of 24% in the resistivity reading can be obtained by leaving the cylinder out for 50 minutes. This emphasized the need to standardize the testing method to compare the results obtained.

**Table 71. Drying Time Effect on Resistivity**

| Drying time (min.) | Resistivity (kΩ*cm) | Difference vs. 5 min. |
|---|---|---|
| 5 | 55.25 | 0% |
| 35 | 63.25 | 14% |
| 55 | 68.75 | 24% |

*Variation in Relationship*

To understand how closely the adjusted equation is to the theoretical equation, an investigation into the percent variation between the results of each equation was performed. Figure 41 shows the same equations and relationship as Figure 40, but with the variation limits shown in a variation triangle. To understand the variation triangle, the top of the triangle shows where there is no variation (where the two equations are equal), the first row from the top shows where the results of each equation vary by about 5%. (To the right of the vertical line, the adjusted equation overestimates the coulomb value by 5% and to the left, it underestimates by 5% from the theoretical value.) Table 72 shows the results of each equation and the variation at each point to the right of equality. This comparison is done to show how closely the theoretical trend line, determined using Ohm's law, and the experimental data trend line, determined through lab testing, are and should not be corrected on actual resistivity values. About 96% of the adjusted equation values are within 25% of the theoretical equation values within the data points of the trend line for adjusted values (3.1 [1.2] to 27.3 [10.7] kΩ*cm [kΩ*in]).

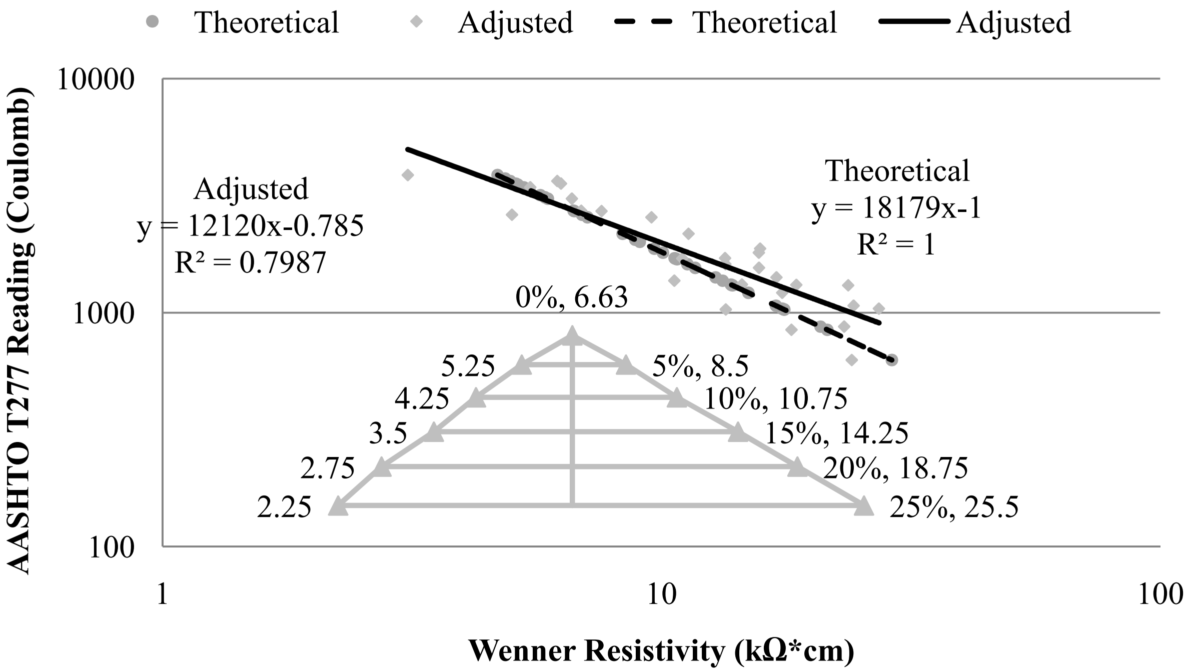

**Figure 41. Adjusted equation variation from theoretical equation (1 in.=2.54 cm)**

**Table 72. Adjusted equation variation from theoretical equation**

| Resistivity kΩ*cm (kΩ*in) | Theoretical Eq. (coulomb) | Adjusted Eq. (coulomb) | % Variation |
|---|---|---|---|
| 6.57 (2.6) | 2768 | 2768 | 0% |
| 8.5 (3.3) | 2139 | 2261 | 5% |
| 10.75 (4.2) | 1691 | 1881 | 10% |
| 14.25 (5.6) | 1276 | 1508 | 15% |
| 18.75 (7.4) | 970 | 1216 | 20% |
| 25.5 (10) | 713 | 956 | 25% |

## Resistivity Conclusion

To use chloride ion penetration as an acceptance criterion, an effective and simpler means of testing concrete than AASHTO T277 needs to be used. Through this research and research performed by others, there is a correlation between AASHTO T277 and resistivity using a Wenner four-probe device. The AASHTO T277 6 hour testing results and results obtained using a Wenner resistivity meter can be related through Ohm's law for blended and unblended cement concrete mixtures.

An excellent relationship between the two testing methods has been developed and it is considered valid based on the correlation of the data presented. This is particularly true for mixtures with higher permeability. More research should be conducted to further correlate this data with low permeability mixtures.

By using adjustments for cylinder geometry for resistivity and the joule effect during testing for T277, it is possible to obtain resistivity measurements from a 10 cm by 20 cm (4 in. by 8 in.) cylinder and compare them to theoretical resistivity data obtained by using AASHTO T277. These factors were verified through independent testing at the University of Utah. With these factors, it is possible to obtain correlations for ternary mixture, binary mixture, and unblended cement concretes.

This data supports the use of the Wenner device as a quality assurance/quality control (QA/QC) tool in concrete field-testing. Continued research into how to ensure that concrete in the field is saturated to an acceptable level (which should also be determined) should be performed, as well as environmental effects on resistivity readings in situ. Cylinders cast as QA specimens and placed in wet curing for strength testing could be used for resistivity testing. Consistent testing methods should be followed to obtain correct correlations.

Through testing, it was found that resistivity readings taken at 5 minutes as compared to those taken at 35 minutes after being removed from wet cure are about 14% lower, and compared to 55 minutes are about 24% lower. This shows that testing in a fully saturated condition is necessary and there is a need for standardization to obtain reliable correlations. Comparing the adjusted equation with the theoretical equation within the 25th percentile from Figure 40, the coefficient of variation is 0.7 and the standard deviation is 1,375 coulombs. With the adjusted equation, values are within the 25th percentile of the theoretical line, so the chloride penetration resistance can be predicted by resistivity values from the Wenner devices. The technique requires a geometric correction for the Wenner device and the consideration of the joule effect for the T277 values.

## SHRINKAGE

### Shrinkage Methods

Following ASTM C157, two 6 x 12 in. cylinders were cast for each mixture design. The specimens were wet cured for 14 days; then, air dry cured for the remainder of the test. Percent change in length for each specimen was recorded at 2, 7, 14, 21, 28, 56, 91, and about 365 days from the initial mix date. The compactor buttons used for length measurements occasionally fell off the specimens. When this occurred, the buttons were re-adhered and a new zero reading was recorded. Measurements from then on used the new zero length as the reference length and added the change in length to the average change in length of the date the new zero reading was measured.

### Shrinkage Results

Tables 73 through 79 are broken down by SCM type. The acceptable value at 28 days is taken as 500 με, which is 0.05% length change. The length measurements that exceed this value are shaded and in boldface type. Note that the shrinkage will produce negative length changes, so the values that exceed 500 με will actually be more negative than -500 με.

**Table 73. Shrinkage results for mixtures with 100% cement**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **100TI** | -22 | 1 | 7 | -256 | -344 | **-578** | | |
| **100TIP** | 17 | 25 | -12 | | | | | |
| **100TISM** | -52 | -10 | -7 | -143 | -330 | | | |
| **100E** | -32 | -25 | 15 | -167 | -221 | -470 | **-598** | |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 74. Shrinkage results for mixtures with Class C fly ash**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **80TI/20C** | -12 | 34 | 25 | -221 | | -347 | | |
| **60TI/20C/20F2** | -71 | -7 | 59 | -266 | -352 | **-568** | | |
| **60TI/30C/10F** | 12 | 20 | 7 | -231 | -239 | **-568** | | |
| **60TI/30C/10F2** | -25 | 30 | -39 | -128 | -202 | -421 | | |
| **85TIP/15C** | -52 | 37 | 10 | -182 | -202 | -443 | **-536** | **-549** |
| **75TIP/25C** | 2 | -5 | 7 | -268 | | **-560** | | |
| **60TI/20C/20F** | 5 | 30 | 1 | -221 | -236 | **-524** | | |
| **60TI/30F2/10C** | | -128 | -22 | -148 | -288 | **-573** | **-610** | **-598** |
| **80E/20C** | 64 | 44 | 57 | -140 | -209 | -453 | **-598** | **-568** |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 75. Shrinkage results for mixtures with Class F fly ash**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **80TI/20F** | 5 | 78 | 32 | -133 | | -408 | | |
| **60TI/20F/20F2** | -57 | -116 | | | | | | |
| **75TI/20F/5SF** | | -187 | -91 | -177 | -236 | -472 | **-536** | **-566** |
| **60TI/20F/20G120S** | -71 | -103 | | | | | | |
| **75TI/20F/5M** | -84 | -148 | | | | | | |
| **60TI/30C/10F** | 12 | 20 | 7 | -231 | -239 | **-568** | | |
| **60TI/30F/10F2** | 20 | 15 | 10 | -234 | -285 | **-549** | | -79 |
| **65TI/30F/5SF** | -52 | -103 | | | | | | |
| **50TI/30F/20G120S** | 30 | 69 | 69 | -130 | -273 | -468 | **-529** | **-507** |
| **65TI/30F/5M** | 27 | 59 | 71 | 138 | -130 | -345 | -411 | -416 |
| **50TI/35G120S/15F** | 27 | 57 | 76 | -133 | -379 | **-578** | **-647** | **-640** |
| **85TIP/15F** | -66 | 71 | 7 | -128 | -261 | **-561** | **-699** | **-782** |
| **60TI/20C/20F** | 5 | 30 | 1 | -221 | -236 | **-524** | | |
| **80E/20F** | 30 | 2 | 22 | -133 | -172 | -436 | **-559** | **-541** |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 76. Shrinkage results for mixtures with Class F2 fly ash**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **80TI/20F2** | 25 | 27 | -5 | -197 | | **-507** | | |
| **60TI/20C/20F2** | -71 | -7 | 59 | -266 | -352 | **-568** | | |
| **60TI/20F/20F2** | -57 | -116 | | | | | | |
| **75TI/20F2/5SF** | 42 | 69 | 62 | -79 | -155 | -381 | -468 | -463 |
| **77TI/20F2/3SF** | | | | | | | | |
| **60TI/20F2/20G120S** | 32 | 67 | 69 | -7 | -84 | -338 | -418 | -475 |
| **75TI/20F2/5M** | 47 | 25 | 62 | -121 | -189 | -438 | **-566** | **-637** |
| **60TI/30C/10F2** | -25 | 30 | -39 | -128 | -202 | -421 | | |
| **60TI/30F/10F2** | 20 | 15 | 10 | -234 | -285 | **-549** | | |
| **67TI/30F2/3SF** | 2 | -15 | 15 | -148 | -217 | -401 | -472 | **-509** |
| **65TI/30F2/5M** | -127 | -150 | 69 | -111 | -182 | -401 | -465 | **-522** |
| **50TI/35G120S/15F2** | 30 | 66 | 94 | 52 | 20 | -160 | -234 | -340 |
| **85TIP/15F2** | -170 | 32 | 27 | -76 | -113 | -300 | -416 | -435 |
| **60TI/30F2/10C** | | -128 | -22 | -148 | -288 | **-573** | **-610** | **-598** |
| **80E/20F2** | 47 | 27 | 47 | -96 | -143 | -359 | **-502** | -487 |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 77. Shrinkage results for mixtures with Grade 120 slag**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **65TI/35G120S** | | -189 | -111 | -214 | -240 | -486 | **-535** | **-557** |
| **60TI/20F2/20G120S** | 32 | 67 | 69 | -7 | -84 | -338 | -418 | -475 |
| **60TI/20F/20G120S** | -71 | -103 | | | | | | |
| **50TI/30F/20G120S** | 30 | 69 | 69 | -130 | -273 | -468 | **-529** | **-507** |
| **50TI/35G120S/15F** | 27 | 57 | 76 | -133 | -379 | **-578** | **-647** | **-640** |
| **50TI/35G120S/15F2** | 30 | 66 | 94 | 52 | 20 | -160 | -234 | -340 |
| **62TI/35G120S/3SF** | 37 | 32 | 91 | 1 | -25 | -217 | -308 | -431 |
| **60TI/35G120S/5M** | 12 | 20 | 86 | -44 | -96 | -280 | -361 | -473 |
| **65TIP/35G120S** | -34 | 25 | 66 | -86 | -98 | -194 | | |
| **80E/20G120S** | 39 | 1 | 34 | -59 | -98 | -285 | -421 | -458 |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 78. Shrinkage results for mixtures with silica fume**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **75TI/20F2/5SF** | 42 | 69 | 62 | -79 | -155 | -381 | -468 | -463 |
| **77TI/20F2/3SF** | | | | | | | | |
| **75TI/20F/5SF** | | -187 | -91 | -177 | -236 | -472 | **-536** | **-566** |
| **65TI/30F/5SF** | -52 | -103 | | | | | | |
| **67TI/30F2/3SF** | 2 | -15 | 15 | -148 | -217 | -401 | -472 | **-509** |
| **62TI/35G120S/3SF** | 37 | 32 | 91 | 1 | -25 | -217 | -308 | -431 |
| **97TIP/3SF** | | | | | | | | |
| **95E/5SF** | 15 | 54 | 22 | 74 | -39 | | | -374 |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

**Table 79. Shrinkage results for mixtures with metakaolin**

| | Specimen Strain (με) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 2** | **Day 7** | **Day 14** | **Day 21** | **Day 28** | **Day 56** | **Day 91** | **Day ~365** |
| **75TI/20F2/5M** | 47 | 25 | 62 | -121 | -189 | -438 | **-566** | **-637** |
| **75TI/20F/5M** | -84 | -148 | | | | | | |
| **65TI/30F/5M** | 27 | 59 | 71 | 138 | -130 | -345 | -411 | -416 |
| **65TI/30F2/5M** | -127 | -150 | 69 | -111 | -182 | -401 | -465 | **-522** |
| **60TI/35G120S/5M** | 12 | 20 | 86 | -44 | -96 | -280 | -361 | -473 |
| **95TIP/5M** | | | | | | | | |
| **95E/5M** | | | | | | | | |

Mixture designs with micro strain greater than 500 are **shaded and in boldface type**.

## Shrinkage Discussion

The appendix contains figures showing strain vs. time for each SCM. The bold bar on each figure marks the acceptable value of 500 με at 28 days .

### *100% Cement*

The largest strain encountered by the 100% cement mixtures was the 100% Type I cement with 344 με. The 100% Type IS(20) had a very similar expansion at 330 με. With a strain of only 221 με at 28 days, the 100% limestone blended cement has the least expansion. The strain for the 100% TIP through the 14 day reading are similar to the TIS(20) mixture and could be expected to have a similar 28 day value as well.

*Class C Fly Ash*

All mixtures containing Class C fly ash had strains less than 500 με at 28 days. By 56 days, four of the nine mixtures still had strains less than 500 με, and the other five mixtures had strains less than 600 με. The 85TIP/15C, 60TI/30F2/10C, and 80E/20C mixtures were tested at 365 days and all three still had strains less than 500 με.

*Class F Fly Ash*

All mixtures containing Class F fly ash, for which data has been collected, had strains less than 500 με at 28 days. The average strain at 28 days for these mixtures was 246 με. Of the mixtures with 365 day test data, the 85% TIP with 15% Class F fly ash had a significantly higher strain than the other mixtures, with a strain of 782με. Whereas, the mixture containing 65% Type I cement, 30% Class F fly ash, and 5% metakaolin had a strain of only 416 με at 365 days.

*Class F2 Fly Ash*

All mixtures containing Class F2 fly ash, for which data has been collected, had strains less than 500 με at 28 days. The average strain at 28 days for these mixtures was 182 με. The least strain at 28 days and 365 days was the mixture of 50% Type I cement, 35% Grade 120 GGBFS, and 15% Class F2 fly ash that had strains of 20με and -340 με, respectively.

*Grade 120 GGBFS*

All mixtures containing Grade 120 GGBFS, for which data has been collected, had strains less than 500 με at 28 days. The average strain at 28 days for these mixtures was 142 με. Six mixtures, 60TI/20F2/20G120S, 50TI/35G120S/15F2, 62TI/35G120S/3SF, 60TI/35G120S/5M, 65TIP/35G120S, and 80E/20G120S, had strains of less than 100 με at 28 days. No mixtures that were tested at 365 days had strains larger than 650 με.

*Silica Fume*

All mixtures containing silica fume, for which data has been collected, had strains less than 500 με at 28 days. The mixture designs 62TI/35G120S/3SF and 95E/5SF had the lowest 28 day strains of -25 με and -39 με, respectively. Of the mixtures with 365 day readings, the highest was the 75% Type I cement, 20% Class F fly ash, and 5% silica fume with a strain of 566 με.

*Metakaolin*

All mixtures containing metakaolin, for which data has been collected, had strains less than 500 με at 28 days. The average 28 day strain was 149 με. The mixture containing 75% Type I cement, 20% Class F2 fly ash, and 5% metakaolin had the highest 365 day strain at 637 με. The other mixtures with 365 day readings were all under 525 με.

## Shrinkage Conclusion

All mixtures that were tested for shrinkage had strains less than 500 με at 28 days and some still had strains less than 500 με at 365 days.

## SCALING

### Scaling Method

Following ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, two specimens of dimensions 10 x 10 x 4 in. were made from each concrete mixture design. After 14 days of wet curing and 14 days of dry curing, water-tight dikes were placed on the top surface of each specimen. A calcium chloride solution was poured into the dike to a depth of approximately 1/4 in. Specimens were then placed in a freezer for 16 to 18 hours. The samples were then removed, and allowed to thaw. At the end of five freeze-thaw cycles, the solution was rinsed off and the bricks were visually examined. Following visual examination, new solution was poured into the dike and the test was continued. The test ended after 50 freeze-thaw cycles.

During a visual examination, specimens were rated on a scale of 0 to 5, with 0 having no scaling and 5 having severe scaling. A photograph was also taken of each sample. Sample photographs to demonstrate the rating scale are shown in Figure 42 through Figure 47.

**Figure 42. Visual rating of 0 (no scaling)**

Figure 43. Visual rating of 1 (very slight scaling, 3 mm depth maximum, no coarse aggregate visible)

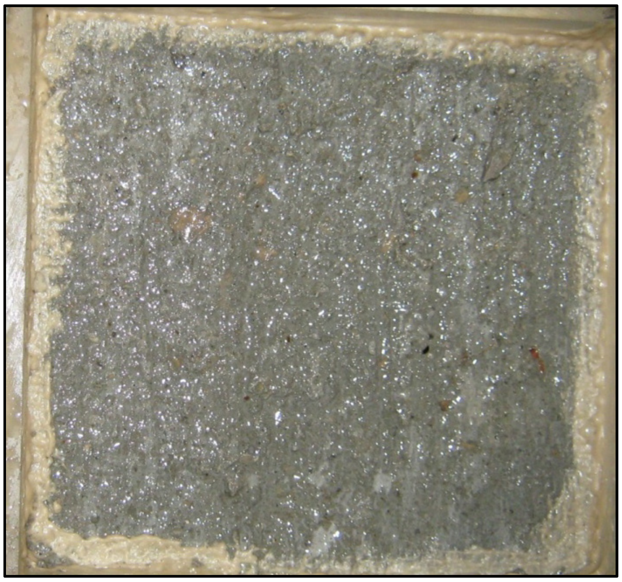

Figure 44. Visual rating of 2 (slight to moderate scaling)

Figure 45. Visual rating of 3 (moderate scaling, some coarse aggregate visible)

Figure 46. Visual rating of 4 (moderate to severe scaling)

**Figure 47. Visual rating of 5 (severe scaling, coarse aggregate visible over entire surface) scaling results**

The visual ratings assigned to each specimen for cycles 0, 5, 10, 15, 25, and 50 for completed specimens are given below. Due to the length of the test, many mixtures have not yet been tested. Table 80 displays the visual conditions of the tested mixture designs that have been completed at this time.

**Table 80. Visual condition of specimen**

| | Condition of Surface | | | | | |
|---|---|---|---|---|---|---|
| MIXTURE ID | Cycle 0 | Cycle 5 | Cycle 10 | Cycle 15 | Cycle 25 | Cycle 50 |
| 60TI/20F/20G120S | 0 | 1.5 | 1.5 | 2.5 | 3.5 | 3.5 |
| 65TI/30F/5SF | 0 | 3 | 3 | 3 | 3 | 4.5 |
| 65TI/30F/5M | 0 | 2 | 2 | 2.5 | 3 | 3.5 |
| 50TI/35G120S/15F | 0 | 3 | 3 | 3 | 3.5 | 4 |
| 62TI/35G120S/3SF | 0 | 3 | 4 | 4 | 4 | 5 |
| 60TI/35G120S/5M | 0 | 1 | 1 | 1 | 2 | 3 |
| 85TIP/15F | 0 | 1.5 | 1.5 | 2 | 2 | 2 |
| 95TIP/5M | 0 | 2.5 | 2.5 | 2.5 | 3 | 4 |
| 80E/20F | 0 | 1.5 | 2 | 2 | 2 | 3 |
| 80E/20G120S | 0 | 1 | 1 | 1 | 1 | 1.5 |

### Scaling Discussion

#### *Class F Fly Ash*

Mixtures containing Class F fly ash preformed best when used with limestone blended cement and Type IP cement. Moderate scaling occurred when used with Grade 120 slag. Severe scaling occurred when used with silica fume.

#### *Grade 120 Slag*

Grade 120 slag preformed well when used with limestone blended cement. Moderate scaling occurred in slag mixtures with Type I cement and Class F fly ash, as well as mixtures with Type I cement and metakaolin.

#### *Silica Fume*

Mixtures containing silica fume performed very poorly. Moderate to severe scaling occurred. After only five freeze-thaw cycles, moderate scaling was present.

#### *Metakaolin*

Mixtures containing metakaolin showed moderate to severe scaling.

### Scaling Conclusion

Surface scaling was seen in all mixture designs tested. The addition of silica fume and metakaolin generally did not reduce the severity of the scaling. However, the addition of fly ash or GGBFS did reduce the severity of the surface scaling.

## HOT AND COLD WEATHER TESTING

### Hot and Cold Weather Testing Methods

Fourteen mixtures were exposed to "hot" and "cold" weather curing; then, they were tested for ASTM C39 compressive strength, ASTM C672 scaling, and ASTM C403 setting time. Specimens exposed to cold curing conditions were produced and cured at 10°C, whereas hot curing specimens were produced and cured at 38°C. Samples from both hot and cold mixtures were submerged in water tanks and stored in chambers that had been set at the required temperatures. At 14 days, they were removed from the water tanks and placed on shelves in 50% humidity at the required temperatures. At 21 days, the hot samples were stored at 70°F and 50% humidity until tested. Thermal cycling for the ASTM C672 tests was started at 56 days. Setting time samples were prepared at the given temperature, but tested in a standard laboratory environment.

## Hot and Cold Weather Results

Table 81 and Table 82 give the compressive strength findings for hot and cold cured mixtures, respectively. Table 83 shows the curing method and visual scaling rating of the mixtures that were tested for scaling. Table 84 and Table 85 show the initial and final setting time for mixtures exposed to hot and cold weather, respectively.

**Table 81. Compressive strength results for hot cured mixtures**

| | Compressive Strength (psi) | | | | | |
|---|---|---|---|---|---|---|
| **Mixture ID** | **1 Day** | **3 Day** | **7 Day** | **14 Day** | **28 Day** | **56 Day** |
| **100TI** | 3000 | 3850 | 4495 | 5145 | 6080 | 6160 |
| **50TI/30F/20G120S** | 1040 | 3045 | 4670 | 6905 | 7680 | 7650 |
| **60TI/20F/20G120S** | 1595 | 3795 | 5430 | 6735 | 8660 | 8290 |
| **60TI/30C/10F** | 1860 | 4790 | 6060 | 7500 | 8545 | 8930 |
| **60TI/20F2/20G120S** | 1630 | 4230 | 6000 | 7400 | 8990 | 8955 |

**Table 82. Compressive strength results for cold cured mixtures**

| | Compressive Strength (psi) | | | | | |
|---|---|---|---|---|---|---|
| **Mixture ID** | **1 Day** | **3 Day** | **7 Day** | **14 Day** | **28 Day** | **56 Day** |
| **100TI** | 2640 | 3365 | 3970 | 4470 | 5840 | 5975 |
| **77TI/20F/3SF** | 2540 | 3660 | 4250 | 4730 | 5390 | 6710 |
| **77TI/20F2/3SF** | 1920 | 2490 | 3235 | 4190 | 3915 | 4965 |
| **97TIP/3SF** | 2775 | 4105 | 5530 | 5960 | 7345 | 8330 |
| **95TIP/5M** | 3495 | 4760 | 6135 | 6455 | 8965 | 8860 |
| **75TI/20F/5SF** | 1785 | 2470 | 3515 | 4490 | 4785 | 5725 |
| **85TIP/15F** | 2550 | 4240 | 5145 | 5505 | 6840 | 7915 |
| **85TIP/15F2** | 3145 | 4340 | 4815 | 6010 | 6800 | 8260 |
| **85TIP/15C** | 2045 | 3905 | 4800 | 5320 | 7225 | 7670 |
| **62TI/35G120S/3SF** | 1920 | 2490 | 3235 | 4190 | 3915 | 4965 |
| **60TI/20F/20G120S** | 2680 | 3885 | 5025 | 6055 | 8115 | 8515 |
| **60TI/30C/10F** | 2425 | 3425 | 4520 | 5345 | 7175 | 8050 |
| **60TI/20F2/20G120S** | 1105 | 1945 | 2480 | 3245 | 4275 | 5095 |
| **65TIP/35G120S** | 1665 | 3155 | 4675 | 5440 | 7580 | 7140 |

**Table 83. Visual scaling condition of specimens**

| Mixture ID | Curing Type | Surface Condition 50 Cycles |
|---|---|---|
| **100TI** | Hot | 1 |
| **50TI/30F/20G120S** | Hot | 4 |
| **60TI/20F/20G120S** | Hot | 3 |
| **60TI/30C/10F** | Hot | 1 |
| **60TI/20F2/20G120S** | Hot | 1 |
| **100TI** | Cold | 1 |
| **77TI/20F/3SF** | Cold | 3 |
| **77TI/20F2/3SF** | Cold | 1 |
| **75TI/20F/5SF** | Cold | 3 |
| **62TI/35G120S/3SF** | Cold | 1 |
| **60TI/20F/20G120S** | Cold | 3 |
| **60TI/30C/10F** | Cold | 2 |
| **60TI/20F2/20G120S** | Cold | 1 |

**Table 84. Setting time for hot cured mixtures**

| | Setting Time (hours) | |
|---|---|---|
| Mixture ID | Initial | Final |
| **100TI** | 3.3 | 5.4 |
| **50TI/30F/20G120S** | 6.6 | 8.6 |
| **60TI/20F/20G120S** | 5.1 | 7.0 |
| **60TI/30C/10F** | 5.2 | 7.7 |
| **60TI/20F2/20G120S** | 4.3 | 6.2 |

**Table 85. Setting time for cold cured mixtures**

| | Setting Time (hours) | |
|---|---|---|
| **Mixture ID** | **Initial** | **Final** |
| **100TI** | 5.8 | 7.3 |
| **77TI/20F/3SF** | 7.0 | 9.2 |
| **77TI/20F2/3SF** | 4.8 | 6.4 |
| **97TIP/3SF** | 4.3 | 5.8 |
| **95TIP/5M** | 3.1 | 4.2 |
| **75TI/20F/5SF** | 5.0 | 6.8 |
| **85TIP/15F** | 4.4 | 5.8 |
| **85TIP/15F2** | 5.0 | 6.6 |
| **85TIP/15C** | 5.9 | 7.8 |
| **62TI/35G120S/3SF** | 5.6 | 7.0 |
| **60TI/20F/20G120S** | 4.7 | 6.8 |
| **60TI/30C/10F** | 4.4 | 6.1 |
| **60TI/20F2/20G120S** | 7.2 | 9.5 |
| **65TIP/35G120S** | 5.3 | 7.0 |

### Hot and Cold Weather Discussion

Figure 48 and Figure 49 display the compressive strength gain curves for the hot and cold cured specimens, respectively. Four mixture designs were exposed to both the hot and cold curing regimens: 100TI, 60TI/20F/20G120S, 60TI/20F2/20G120S, and 60TI/30C/10F.

Table 86 displays the 7 and 28 day compressive strength, as well as the $F_c$ ratio, which is the 28 day divided by the 7 day strength. The desirable range for $F_c$ is from 1.25 to 1.67. Heat curing led to higher compressive strengths for every measurement. Heat curing also led to the strength curve leveling off quicker than it did for the cold cured specimens. Therefore, the heat cured specimens have lower long term $F_c$ values than the cold cured specimens. By 28 days, the mixtures, either hot or cold cured, have reasonably similar compressive strengths, except for the 60TI/20F2/20G120S mixture, which has a 28 day compressive strength difference of more than 4,700 psi. The significantly different compressive strength is contributed either to the Class F2 fly ash or to the interaction between the Class F2 fly ash and the Grade 120 GGBFS.

The setting data are mixed. In two cases (both with 60%TI), the samples mixed hot took longer to set than those mixed cold. This is contrary to expectations and cannot be explained. Both mixtures contain the F fly ash, which, as discussed above, did exhibit apparent incompatibility that is likely to be exacerbated by elevated temperature.

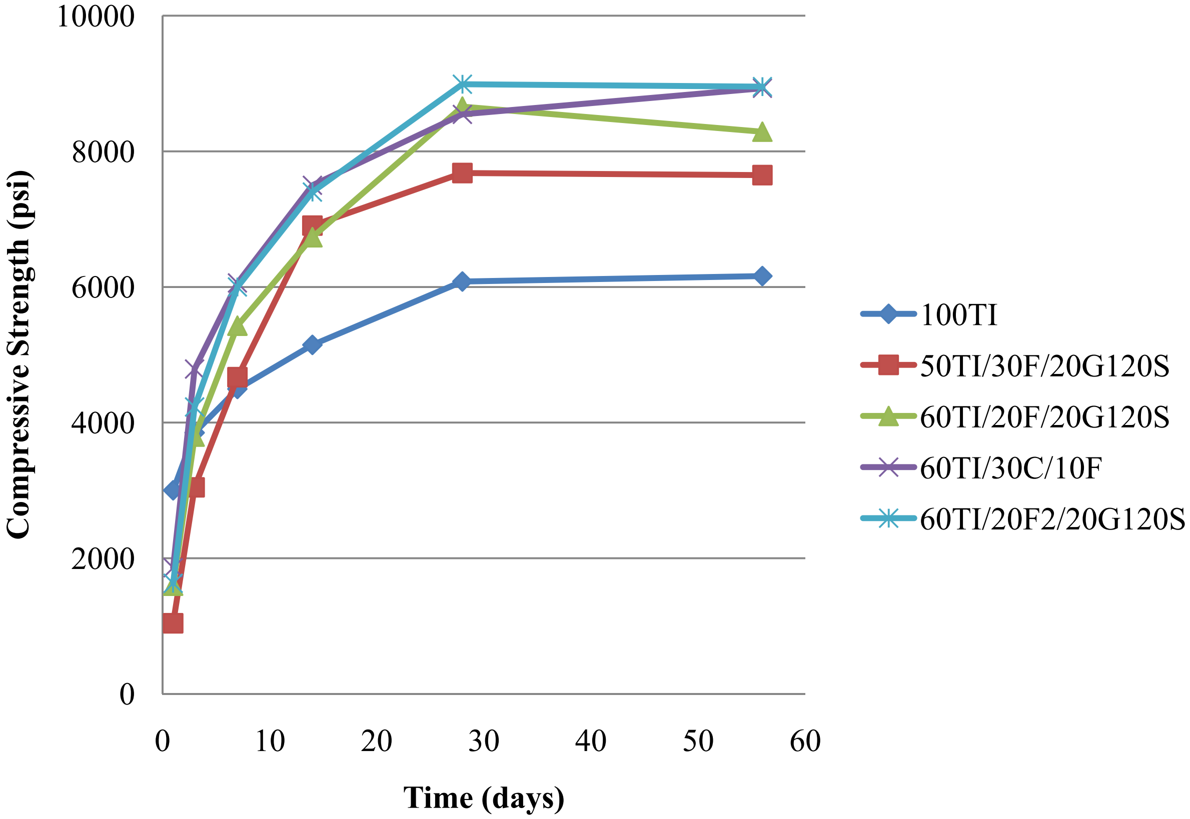

Figure 48. ASTM C39 compressive strength for hot cured mixtures

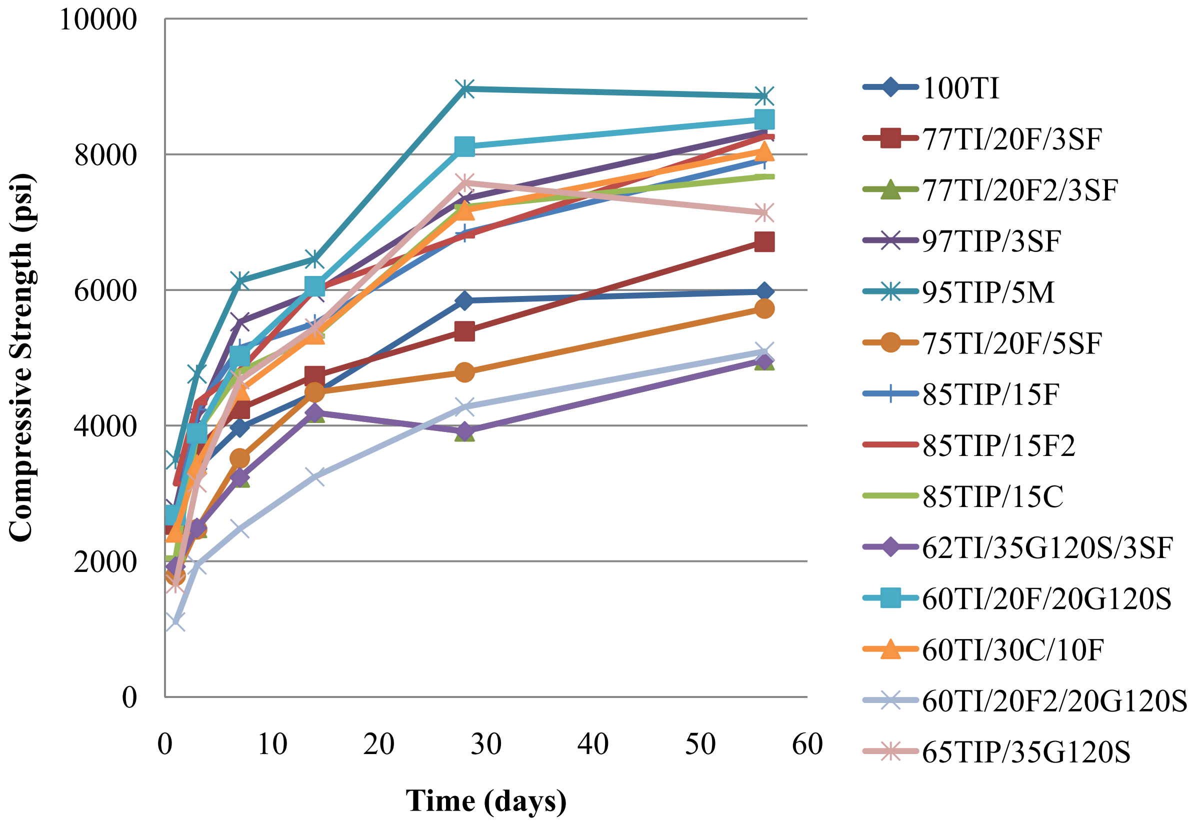

Figure 49. ASTM C39 compressive strength for cold cured mixtures

**Table 86. Comparison of compressive strength for mixture designs exposed to both hot and cold curing**

| | Compressive Strength (psi) | | | | | |
|---|---|---|---|---|---|---|
| | Hot Cure | | | Cold Cure | | |
| **Mixture ID** | **7 Day** | **28 Day** | **$F_c$** | **7 Day** | **28 Day** | **$F_c$** |
| **100TI** | 4495 | 6080 | 1.35 | 3970 | 5840 | 1.47 |
| **60TI/20F/20G120S** | 5430 | 8660 | 1.59 | 5025 | 8115 | 1.61 |
| **60TI/30C/10F** | 6060 | 8545 | 1.41 | 4520 | 7175 | 1.59 |
| **60TI/20F2/20G120S** | 6000 | 8990 | 1.50 | 2480 | 4275 | 1.72 |

The ratio of initial/final setting times for all of the mixtures, except the 100TI control, irrespective of composition or temperature, was in the range 0.7 to 0.8 and mostly 0.76. This is useful because finishing activities, such as sawing, can be planned once the initial set of a mixture has been observed in the field.

With respect to the scaling data, it is interesting that the mixing and curing temperature had little effect, with those tested at both temperatures showing similar performance. This is likely because of the time allowed for curing before testing started.

All of the mixtures containing F2 fly ash performed well, while, five of the seven mixtures containing F fly ash had ratings of 3 or greater. No trends were seen related to the presence of GGBFS or TIP cement. The silica fume performed poorly with F fly ash and the TIP cement, but satisfactorily with slag. The single mixture containing metakaolin did not perform well. It would appear that the chemistry of the cementitious system will affect performance, and that a given fly ash, even of the same type, will not show the same potential durability as another.

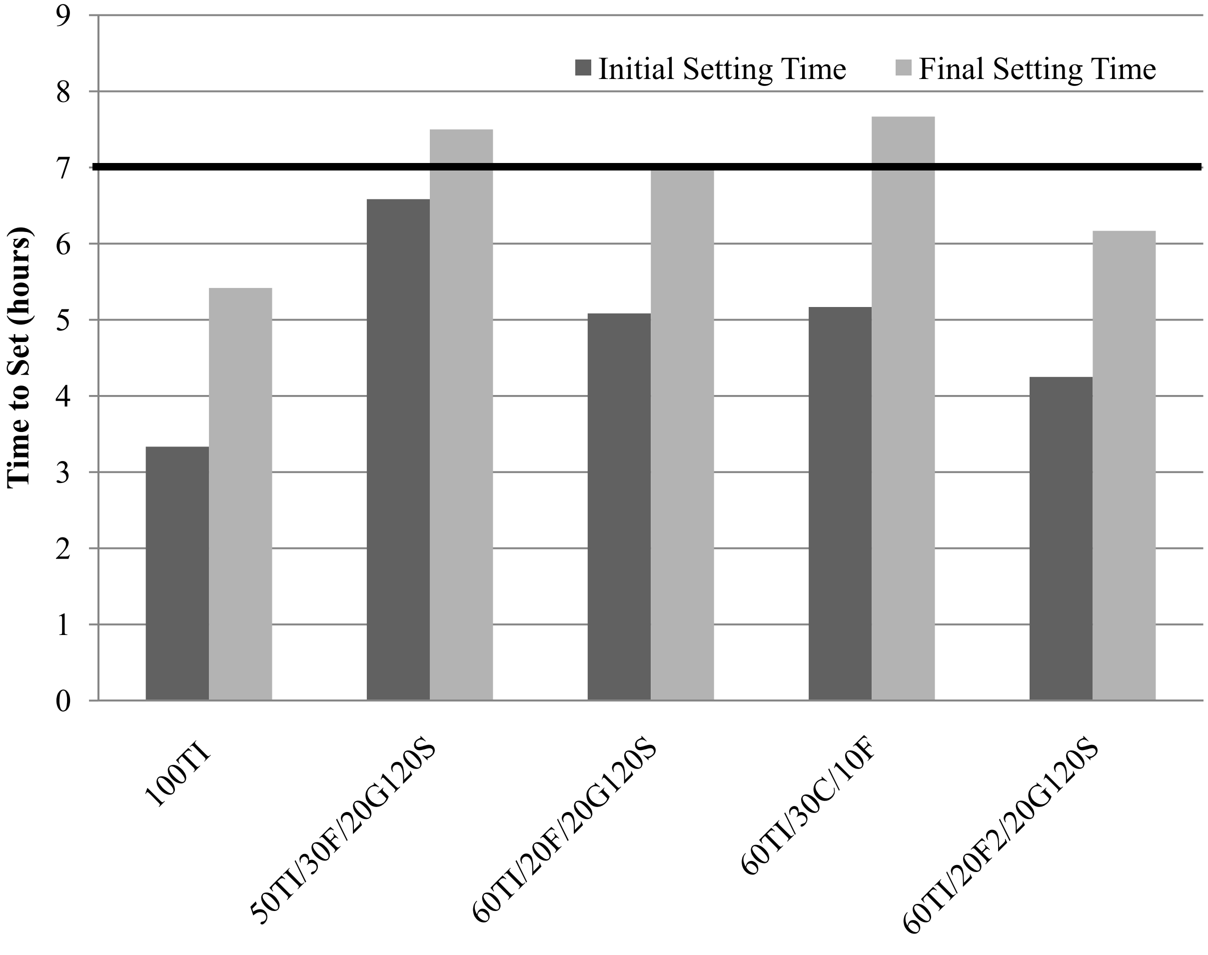

**Figure 50. ASTM C403 setting time for hot cured mixture designs**

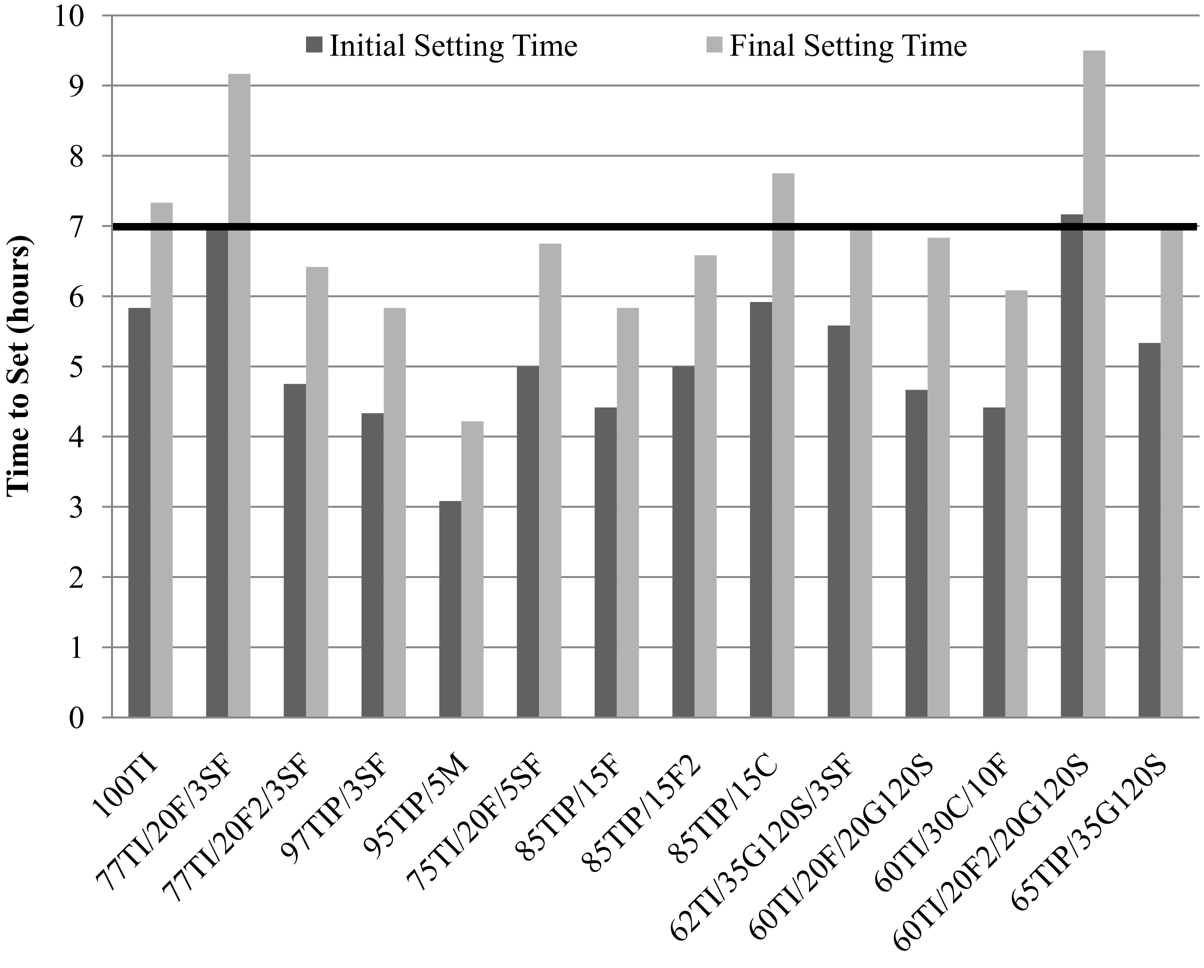

**Figure 51. ASTM C403 setting time for cold cured mixture designs**

## Hot and Cold Weather Conclusions

Compressive strengths were similar for all the ternary mixtures at 28 days, regardless of the mixing temperature.

Setting times appeared to vary without a clear trend being apparent.

Scaling resistance of the mixtures was varied, predominantly controlled by the type of SCMs in the mixture, while mixing and curing temperatures did not appear to affect performance significantly.

## CARBON DIOXIDE EMISSIONS

### Introduction to $CO_2$ Emissions

Many sources in the industry state about 0.9 pounds of $CO_2$ emitted per pound of finished cement, but the amount of $CO_2$ can vary depending on the process used, plant power sources, and type of cement produced (Martin et al., 1999). There is a need to create a more deterministic calculation of the $CO_2$ signature of a defined blended cementitious system for industrial sources or projects, especially if the concrete industry faces challenges from cap and trade or other emissions-reducing policies. Such a calculation may be a more accurate value for $CO_2$ per unit volume of finished concrete for a particular construction or market sector. It is important to note that the signature for cement at certain cement plants and combinations of cementitious materials will vary, and this research takes into account these variations of the $CO_2$ signature of the entire cementitious system. This part of the study addresses the need for a system to recommend options for green infrastructure; namely, make a case for structures built with more sustainable materials like ternary concrete mixtures and those designed to have a long life span for decreased cost over the life of the structure.

The main objective of this research is to create a methodology to inventory the amount of $CO_2$ for each component of the process of making and blending cementitious systems; this includes manufacturing, transportation, and any other directly involved process. This covers the main contributing factors of $CO_2$ in concrete. This objective includes an inventory of impacts for Class F fly ash, Class C fly ash, GGBFS, silica fume, metakaolin, and natural pozzolan. Finally, a $CO_2$ inventory of the process of aggregate production is included.

### Carbon Dioxide Emission Sources

The goals for these concrete mixtures are to use a standard amount of 564 pounds of cementitious material per cubic yard and to maintain a 0.45 water to cementitious materials ratio. Also, these mixtures were to have at least 4,000 psi strength at 28 days, be less than 2000 coulombs of chloride ion permeability at 56 days, and meet sulfate resistance and ASR standards.

The bounds of analysis in this research address the energy from the quarry for limestone and aggregates and transportation; energy sources to the kiln, coolers, pre-calciners, and packaging; carbon dioxide from the calcination of limestone to make clinker; energy for transportation of supplementary cementitious materials; and the energy to grind blast furnace slag, natural pozzolan (if needed), and cement. Figure 52 shows the system boundary of the concrete plant operations.

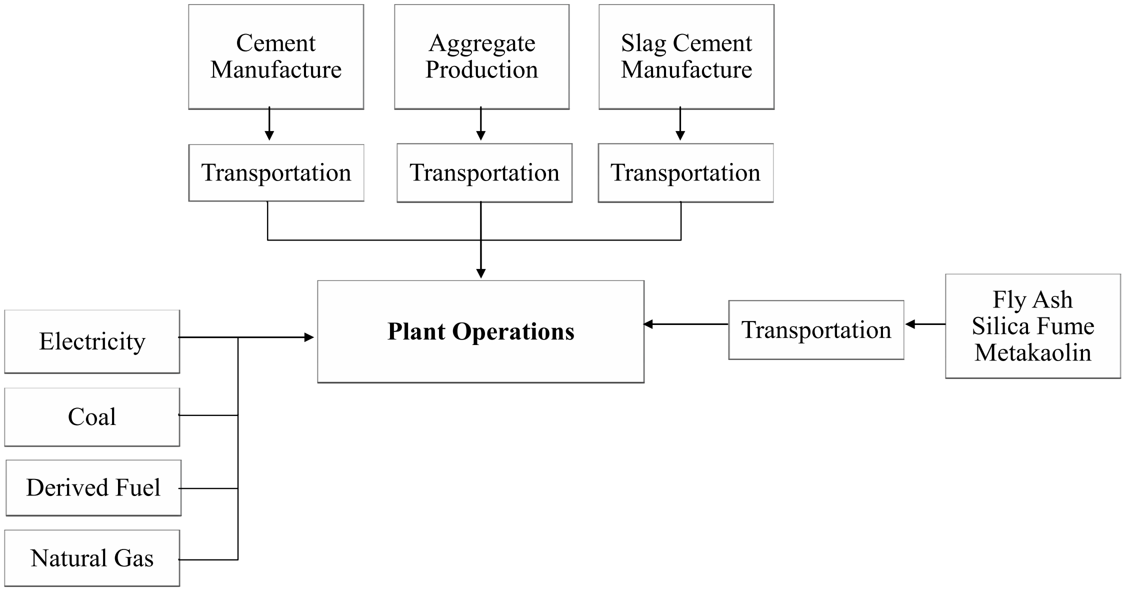

**Figure 52. System boundary chart**

*Carbon Dioxide Signature Development*

Three main parts contribute to the carbon dioxide signature of cement. First, there are the carbon dioxide emissions related to the calcination of raw limestone to create clinker, as defined by the chemistry and quantity of limestone. Second, there are the carbon dioxide emissions related to the energy intensity of producing cement or stationary output. For these emissions, there is carbon intensity related to the fuel as defined by the Department of Energy (DOE) (Schipper, M. 2006). The energy required to heat the limestone to make cement and the energy required to grind the cement to the appropriate fineness are considered. Third, there are the carbon dioxide emissions related to mobile output, or transportation of the cementitious materials. This is defined by the amount of fuel and types of fuel used to mine, grind, and deliver the raw materials, which have their own carbon dioxide signatures. This report considers the transportation to the cement plant for the components of blended cement, not the carbon signature of transportation of cement to the final destination.

Together, these three parts constitute a carbon dioxide signature that is unique to the cement plant that manufactures it. Each part of the signature is broken down to show that emissions from plant to plant can be very different and to demonstrate the variables that affect this difference.

*Carbon Intensity*

The Energy Information Administration (EIA) of the DOE has defined the overall carbon intensity of a manufacturing process to be the ratio of its total carbon dioxide emissions, C, to its total output, Y (Schipper, 2006). This ratio is equal to the aggregate carbon intensity of energy demand times the energy intensity. Carbon intensity of energy demand is defined as carbon dioxide emissions, C, per unit of energy consumed, E. The energy intensity is defined as the energy consumed, E, per unit of gross output, Y. This relationship is indicated by equation (13).

$$\frac{\mathrm{C}}{\mathrm{Y}} = \frac{C}{\mathrm{E}} \times \frac{\mathrm{E}}{\mathrm{Y}} \tag{13}$$

where:
$C$ = total carbon dioxide emissions
$Y$ = total output
$E$ = energy consumed

*Carbon Intensity from Calcinations*

About 60% of the carbon emissions related to cement manufacturing is due to the calcination of limestone to create clinker (Nisbet, 2003). Somewhere between 1.5 and 1.7 tons of raw materials are needed to make 1 ton of cement (Greer et al., 1992). Cement requires calcium oxide (CaO), which is produced by heating calcium carbonate ($CaCO_3$) limestone. Stoichiometry shows that every pound of limestone yields 0.439 pounds of $CO_2$.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{14}$$

$$\frac{453.59g\ CaCO_3}{1\ lb\ CaCO_3} \times \frac{1\ mol\ CaCO_3}{100.086g\ CaCO_3} \times \frac{1\ mol\ CO_2}{1\ mol\ CaCO_3} \times \frac{44.009g\ CO_2}{1\ mol\ CO_2} \times \frac{1\ lb\ CO_2}{453.59g\ CO_2} = 0.439\ \frac{lb\ CO_2}{lb\ CaCO_3} \tag{15}$$

Values will change depending on the type of raw material used. For example, if calcium magnesium carbonate is used, stoichiometry shows that 0.477 pounds of carbon dioxide could be produced per pound of calcium magnesium carbonate.

$$CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2 \tag{16}$$

$$\frac{453.59g\ CaMg(CO_3)_2}{1\ lb\ CaMg(CO_3)_2} \times \frac{1\ mol\ CaMg(CO_3)_2}{184.398g\ CaMg(CO_3)_2} \times \frac{2\ mol\ CO_2}{1\ mol\ CaMg(CO_3)_2} \times \frac{44.009g\ CO_2}{1\ mol\ CO_2} \times \frac{1\ lb}{453.59g} = 0.477 \frac{lb\ CO_2}{lb\ CaMg(CO_3)_2} \tag{17}$$

Metakaolin also requires the calcination of kaolinite; but kaolinite in its pure form is $Al_2Si_2O_5(OH)_4$, which does not contain the carbon (C) to create carbon dioxide.

Pozzolans such as slag, fly ash and silica fume, do not require calcination at the cement plant prior to use with cement, and therefore have no carbon intensity due to calcination, but they may have carbon intensity due to transportation or grinding.

### *Carbon Intensity of Wet and Dry Kiln*

To decarbonate limestone to make clinker, kilns require large amounts of energy. Depending on whether the process is a wet kiln or dry kiln system, the energy is different. The type of fuels used have carbon dioxide signatures; coal has been the primary fuel source for kilns in the US since the 1970s (Martin et al., 1999).

In a wet rotary kiln, raw meal contains about 36% moisture that is first evaporated in the low temperature zone of the kiln; this requires a long kiln with length to diameter ratios up to 38 and lengths up to 252 yards (Marin et al., 1999). Martin shows that large kiln units have been shown to produce nearly 3,970 tons of clinker per day; fuel for wet kilns vary with the amount of energy required for evaporation and can vary from 4.6 to 6.1 million British Thermal Units (MBtu) per ton of clinker, with the average being around 5.7 MBtu. Martin estimated the energy usage for wet kilns in preparing raw materials is 26 kilowatt hours (kWh) per ton; clinker production for wet kilns on the average fuel intensity in 1994 is 5.7 MBtu per ton of clinker. Fuel preparation and operation of the kiln, fans, and coolers for wet kilns has electricity requirements of about 27 kWh per ton.

For dry kilns, raw material has only 0.5% moisture content, which allows the kiln to be shorter in length (Martin et al., 1999). Martin shows that modern day dry kiln systems have multistage suspension preheating or shaft preheating, which reduces the amount of energy required by the kiln. Fuel consumption of a dry kiln with a four- or five-stage preheating process can be between 2.7 and 3.0 MBtu per ton of clinker. Pre-calciner kilns are the most efficient at about 2.5 MBtu per ton of clinker. For raw material preparation, dry kilns use about 31 kWh per ton. In clinker production, dry kilns have a fuel intensity of about 3.7 MBtu per ton. Electricity required for fuel preparation, operation of the kiln, fans and coolers averages 32 kWh per ton for dry kilns.

Table 87 is an adapted table from “Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Cement Industry” (Martin et al., 1999). As shown in Table 87, the amount of carbon dioxide emitted to produce one pound of finished cement is 1.02 pounds for wet process plants and 0.9 pounds of carbon dioxide per pound of finished cement for dry process plants.

**Table 87 Estimates of energy intensity, carbon, and carbon dioxide intensity**

| Type of Process | Stage of Process | Energy Intensities | | Amount of $CO_2$ | | Carbon Intensity (lb C/lb) | $CO_2$ Intensity (lb $CO_2$/lb) |
|---|---|---|---|---|---|---|---|
| | | Fuel (MBtu/t) | Electricity (kWh/t) | Energy (MtC) | Calcination (MtC) | | |
| Wet | Feed Preparation | 0.0 | 26 | 0.2 | 0.0 | 0.005 | |
| | Clinker Production | 5.2 | 27 | 3.2 | 3.0 | 0284 | |
| | Finish Grinding | 0.0 | 52 | 0.2 | 0.0 | 0.009 | |
| | Total | | | | | 0.279 | 1.02 |
| Dry | Feed Preparation | 0.0 | 31 | 0.6 | 0.0 | 0.005 | |
| | Clinker Production | 3.7 | 32 | 5.8 | 7.5 | 0.246 | |
| | Finish Grinding | 0.0 | 52 | 0.6 | 0.0 | 0.009 | |
| | Total | | | | | 0.245 | 0.90 |

Besides electricity and fuel sources, there are methods of using waste-derived fuels to offset some of the energy needs for a kiln operation. The carbon dioxide emission reduction depends on the amount of carbon in the waste and whether or not the kiln uses incineration with heat recovery (Martin et al, 1999). Martin reports a study in Canada of waste tire fuel showed an energy savings of 0.6 gigajoules per ton when 20% of the kiln energy was supplemented by the tires with 3.0 gigajoules per ton fuel.

### *Carbon Intensity of Natural Pozzolans, GGBFS, and Aggregate*

Pozzolans such as slag, fly ash, silica fume, and metakaolin have smaller carbon intensities than portland cement. As mentioned earlier, pozzolans do not have carbon intensity, due to calcination. They have carbon intensity due to transportation and any grinding that may be needed.

The mode of transportation is the primary factor with distance travelled as the secondary factor. In cases where trucks were used for transport, the amount of gallons used is an easy indicator for carbon dioxide intensity. The amount of carbon dioxide for transportation that requires fuel is determined by how much carbon is in the fuel (Coe, 2005). Gasoline contains 2421 grams of carbon per gallon and diesel contains 2778 grams of carbon per gallon. The Environmental Protection Agency (EPA) calculates carbon dioxide emissions from a gallon of fuel according to the guidelines of the Intergovernmental Panel for Climate Change (IPCC), which require an assumption that 1% of the carbon in a given gasoline will not oxidize into carbon dioxide, and therefore an oxidation factor of 0.99 is used. The following equations show the calculation for carbon dioxide in gasoline and diesel, respectively.

For gasoline:

$$\frac{2421\, g\, C}{gallon} \times 0.99(portion\ oxidized) \times \frac{44 g\, CO_2}{12 g\, C} \times \frac{1\, lb}{453.59 g} = 19.4\, \frac{lb\, CO_2}{gallon} \tag{18}$$

For diesel:

$$\frac{2778\, g\, C}{gallon} \times 0.99(portion\ oxidized) \times \frac{44 g\, CO_2}{12 g\, C} \times \frac{1\, lb}{453.59 g} = 22.2 \frac{lb\, CO_2}{gallon} \tag{19}$$

Table 88 shows values for energy intensity for road, rail and shipping vehicles (Marceau et al., 2007). For the distillate fuel oil and residual fuel oil calculations of carbon intensity, values for carbon emissions were adapted to calculate carbon dioxide emissions. Residual fuel oil has 0.020 million tonnes of carbon per petajoule consumed and distillate fuel oil has 0.019 million tonnes of carbon per petajoule (Martin et al., 1999).

**Table 88. Energy and carbon intensity of transportation vehicles**

| Mode | Vehicle Type | Carbon Intensity ($lb\ CO_2/gal$) | Energy Intensity (Gallons/1000 tons·mile) | (Btu/ ton×mile) |
|---|---|---|---|---|
| **Road** | Gasoline Dump Truck | 19.4[1] | 4.10 | 513 |
| | Diesel Dump Truck | 22.2 | 3.37 | 468 |
| | Diesel Truck Tractor | 22.2 | 8.28 | 1148 |
| | Diesel Enclosed Van | 22.2 | 5.38 | 746 |
| | Natural Gas | 16.1[2] | NA | NA |
| **Rail** | Diesel Locomotive | 22.2 | 2.49 | 345 |
| **Shipping** | Distillate Fuel Oil | 22.4[3] | 1.03 | 143 |
| | Residual Fuel Oil | 25.5[4] | 2.19 | 328 |

[1] Adapted from "Table 3. Transportation Energy Intensity Factors," pg 6 in *Life Cycle Inventory of Portland Cement Concrete*. 2007.

[2] Adapted from "Table A.1 Emission Factors of Fuel Combustion," pg 4 in Appendix *GREET 1.5 Transportation Fuel Cycle Model*, 1999.

[3] Value from "Table of Voluntary Reporting of Greenhouse Gases Program Fuel and Energy Source Codes and Emission Coefficients," 2008. http://www.eia.doe.gov/oiaf/1605/coefficients.html

[4] Adapted from "Table 2. Energy Consumption, Carbon emissions coefiicients, and carbon emissions from Energy Consumption, and Carbon Dioxide Emissions from calcination for the U.S. Cement Industry in 1994," pg 17 in *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Cement Industry*, 1999.

The following is the calculation of pounds of carbon dioxide formed from one pound of carbon.

$$C + O_2 \rightarrow CO_2 \tag{20}$$

$$1\, lb\, C \times \frac{453.59\, g}{1\, lb} \times \frac{44\, g\, CO_2}{12\, g\, C} \times \frac{1\, lb\, CO_2}{453.59 g\, CO_2} = 3.66\, lb\, CO_2 \tag{21}$$

Therefore, every million tons of carbon released into the atmosphere has the potential to create 3.66 million tons of carbon dioxide; carbon can form carbon dioxide or carbon monoxide, and, for the purposes of this study, the main gas considered is carbon dioxide. To develop the values for pounds of carbon dioxide per gallon of residual fuel oil, values for Btu per gallon were determined to be 124,000 (Coe, 2005). The Btu per gallon were then converted to petajoules and then multiplied by million tons carbon (MtC) per petajoule values of 0.020 for residual fuel oil (Martin et al., 1999). Using the amount of carbon dioxide per pound of carbon, it is determined, residual fuel oil has 25.5 pounds of carbon dioxide per gallon (see Table 88). The amount of carbon dioxide in pounds per gallon for distillate fuel oil was found to be 22.4 (Voluntary Reporting of Greenhouse Gases Program). For natural gas, there are 1,030 Btu per cubic foot and approximately 58,000 grams of carbon dioxide per million Btu (Wang). Many companies buy natural gas by the gasoline gallon equivalent (GGE), which is the amount of natural gas equal to the Btu of a gallon of gasoline, or nearly 124,800 Btu (About Natural Gas Vehicles).

From Table 88, carbon intensities can be determined for the amount of supplementary cementitious materials, such as fly ash, silica fume, metakaolin, and slag, as well as any aggregate and cement transportation. For example, driving 1,000 tons of fly ash from a coal burning power plant 50 miles away in a gasoline dump truck with an energy intensity of 4.10 gallons per 1,000 tons per mile uses 205 gallons of gasoline, which emits 3,977 pounds of carbon dioxide. Whereas, using diesel locomotive transportation for the same 1,000 tons of fly ash from a coal plant 50 miles away with energy intensity of 2.49 gallons per 1,000 tons per mile uses 124.5 gallons of diesel fuel and emits 2,763 pounds of carbon dioxide. This example shows a decrease in carbon dioxide emissions of nearly 44%.

To put the energy intensity values into perspective, for 27.6 lbs of $CO_2$ emissions, a diesel semi-truck, rail, and barge can move a ton of cement 150, 499, and 1,196 miles, respectively. This means that, for the same amount of carbon dioxide, cementitious materials can be transported by train 3.3 times further than by diesel semi-truck. For barge transport of cementitious materials, it is nearly 8 times further distance than transport by diesel semi-truck for the same carbon dioxide emissions.

### *Carbon Intensity of Admixtures*

When determining the carbon intensity of concrete, admixtures comprise the smallest part of a concrete mixture, often being less than 1% of the total mass of the concrete. If the mass of an input is less than 1%, it, has no significant amount of energy consumption and does not have much contribution to toxic emissions, and it is not required for determining the life cycle analysis according to the Society of Environmental Toxicology and Chemistry (SETAC) guidelines of 1993 (Marceau et al., 2007). It is also believed that any emissions or effluent contamination will stay in the concrete once cured because of the chemical bond that likely develops.

**Sample Calculation for Carbon Dioxide Emissions**

Carbon dioxide intensities were determined assuming 0.9 pounds of carbon dioxide per pound of finished cement for dry plant operations and 1.2 pounds of carbon dioxide per pound of finished cement for wet plant operations, based on industry averages (Table 89). Carbon dioxide intensities from transportation assumes rail transport of 370 miles for fly ash, 390 miles for class C fly ash, 400 miles for slag, and 1,000 miles for both metakaolin and silica fume. An additional 10 miles of semi-truck trailer transport for each of the pozzolans is included.

**Table 89. Summary of carbon dioxide per example**

| | | Grinding | | Rail | | Diesel Semi | | Total |
|---|---|---|---|---|---|---|---|---|
| **Material** | **Production** | **Energy** | **$CO_2$** | **Miles** | **$CO_2$/lb** | **Miles** | **$CO_2$/lb** | **lb $CO_2$/lb** |
| **TI** | 0.9 | | | | | | | 0.9 |
| **F** | | | | 370 | 0.0102 | 10 | 0.00092 | 0.011 |
| **G120S** | | 55 | 0.01996 | 400 | 0.0111 | 10 | 0.00092 | 0.032 |

Comparing the calculations of the ternary mixture of 50% TI, 35% slag, and 15% fly ash to the calculations of carbon dioxide intensity for a mixture that is 100% TI yields a carbon dioxide savings of 49%, a savings of about $6 per ton, and superior performance properties (See Table 90.)

Grinding energy for slag is calculated using a grinding energy of 55 kWh per ton of slag. The energy is assumed to be supplied through power provided by coal, so 212.7 pounds of carbon dioxide per MBtu is also used.

The carbon dioxide intensities with the mentioned assumptions resulted in 0.724 pounds of carbon dioxide per pound of TIP cement: 0.685 pounds of carbon dioxide per pound of TISM cement, 0.813 per pound of TIPM cement, 0.012 per pound of fly ash, 0.032 per pound of slag, and 0.030 per pound of silica fume and metakaolin.

Another important factor to the success of sustainable solutions besides its performance and durability characteristics is the economics. For example, a sustainable solution that is more expensive than a normal portland cement mixture is not easily marketable. Blended cements and ternary mixture designs allow for an optimization of performance, cost, and sustainability.

Table 90 and Table 91 show the approximate cost per ton for the blended cement mixtures and limestone cement mixtures. These tables were developed from market-based price estimates with portland cement at $90 per ton, silica fume at $500 per ton, fly ash at $50 per ton, slag at $90 per ton, metakaolin at $400 per ton, and local natural pozzolan at $40 per ton. (Prices are subject to change due to local conditions, availability, and seasonal factors.) The values in the tables are to help provide an approximate comparison of cost between mixtures and are not intended to be an exact/actual cost.

The steps required for the calculations to form the table require knowledge of where the fuel is coming from to operate the plant. Knowing what percent of each type of fuel is going into the plant operations and what is used for transportation of materials is the primary data for determining the carbon dioxide signature; the total yield of limestone and cement is also useful in this determination. Assuming that the grinding of slag, cement and natural pozzolan for this plant are run by electricity from the grid, and therefore from coal the carbon intensity can be determined.

For this example, a comparison will be made between a ternary mixture that is 50% TI cement, 35% slag, and 15% Class F fly ash.

This problem is increasingly easier using the known inputs into a plant. For example, the plant will know how many gallons of gasoline, diesel, and natural gas it has used in its operations. These calculations back calculate according to the amount of gasoline needed to transport a certain tonnage a set distance.

For this example, the carbon intensity of the fly ash can be calculated using $2.49\text{x}10^{3}$ gallons per ton per mile for rail transport to find out a value for gallons per ton of $9.213\text{x}10^{-1}$, since the source of fly ash is 370 miles from the plant.

$$2.49\,\frac{gallons}{1000\;tons\times mile}\times 370\;miles = 0.9213\,\frac{gallons}{ton\;fly\;ash} \tag{22}$$

Converting $9.213\text{x}10^{-1}$ gallons per ton to gallons per pound it is determined that $4.61\text{x}10^{4}$ gallons are needed per pound of fly ash. Multiplying by 22.2 pounds of carbon dioxide per gallon for diesel fuel it shows that $1.02\text{x}10^{2}$ pounds of carbon dioxide are emitted per pound of fly ash.

$$0.9213\,\frac{gallons\;diesel}{ton\;fly\;ash}\times\frac{1\;ton\;fly\;ash}{2000\;lb\;fly\;ash}\times 22.2\,\frac{lb\;CO_2}{gallon\;diesel} = 0.0102\,\frac{lb\;CO_2}{lb\;fly\;ash} \tag{23}$$

For the slag, a similar calculation is made using 400 miles to attain a carbon intensity of $1.11\text{x}10^{2}$ pounds carbon dioxide per pound of slag for transport by train.

In addition to train transport, there are 10 miles of semi-truck trailer transport. Semi truck transport requires $8.28\text{x}10^{3}$ gallons per ton per mile. For 10 miles, this yields a carbon intensity of $9.2\text{x}10^{-4}$ pounds of carbon dioxide per pound of transported material.

$$8.28\,\frac{gallons}{1000\;tons\times mile}\times 10\;miles = 0.0828\,\frac{gallons\;diesel}{ton\;material} \tag{24}$$

$$0.0828\,\frac{gallons\;diesel}{ton\;material}\times\frac{1\;ton}{2000\;lb}\times 22.2\,\frac{lb\;CO_2}{gallon\;diesel} = 0.00092\,\frac{lb\;CO_2}{lb\;material} \tag{25}$$

This example assumes a carbon dioxide intensity of finished cement of 0.9 pounds of carbon dioxide per pound of finished cement. This takes into account all of the energy of the kiln, grinding energy, and decarbonation required to develop it.

Next in this example is the calculation of the energy required to grind the slag. The energy to grind slag in this example is assumed to be 55 kWh. Since the energy is assumed to be provided by coal power plants, then 212.7 pounds of carbon dioxide per MBtu is also used and results in $1.99\text{x}10^2$ pounds of carbon dioxide per pound of slag.

$$\frac{55kWh}{ton\,slag} \times \frac{1MBtu}{293kWh} \times \frac{212.7lb\,CO_2}{MBtu} = 0.0199\frac{lb\,CO_2}{lb\,slag} \tag{26}$$

In summary, our total carbon dioxide in pounds per pound of cementitious material is 0.9 for TI cement, 0.011 for Class F fly ash, and 0.032 for grade 120 slag (See Table 89). The number provided in Table 89 is from proportioning these values for the mixture design for 50% TI cement, 35% G120 slag, and 15% fly ash to result in a total carbon dioxide per pound of cement of 0.46.

$$0.900\frac{lb\,CO_2}{lb\,TI}(50\%) + 0.032\frac{lb\,CO_2}{lb\,slag}(35\%) + 0.011\frac{lb\,CO_2}{lb\,fly\,ash}(15\%) = 0.46\frac{lb\,CO_2}{lb\,cement} \tag{27}$$

**Table 90. 100TI vs. 50TI/35 G120S/ 15F**

| | 100 TI | 50TI /35 G120S/ 15F |
|---|---|---|
| **lb $CO_2$/lb cement** | 0.90 | 0.46 |
| **Cost ($/ton)** | 90 | 84 |

### Emission Results for Study Mixture Designs

Table 91 has the mixtures of the Pooled Fund Study of Ternary Mixture Designs at the University of Utah and their approximate carbon dioxide signatures. Table 91 show the difference in carbon dioxide signature intensity between the use of a wet plant, according to the average emissions of the industry, and a dry plant, in pounds of carbon dioxide per pound of finished cement.

**Table 91. Cost per ton and carbon dioxide savings of blended cement mixtures**

| Mixture ID | Dry Plant $CO_2$ (lb/lb cement) | Wet Plant $CO_2$ (lb/lb cement) | Cost per Ton ($/ton) | $CO_2$ Savings (%) |
|---|---|---|---|---|
| **100TI** | 0.90 | 1.02 | 90 | 0 |
| **80TI/20C** | 0.72 | 0.82 | 82 | 20 |
| **60TI/20C/20F** | 0.54 | 0.61 | 74 | 40 |
| **60TI/20C/20F2** | 0.54 | 0.61 | 74 | 40 |
| **60TI/30C/10F** | 0.54 | 0.61 | 74 | 40 |
| **60TI/30C/10F2** | 0.54 | 0.61 | 74 | 40 |
| **80TI/20F** | 0.72 | 0.82 | 82 | 20 |
| **60TI/20F/20F2** | 0.54 | 0.61 | 74 | 40 |
| **75TI/20F/5SF** | 0.68 | 0.77 | 103 | 25 |
| **77TI/20F/3SF** | 0.69 | 0.79 | 94 | 23 |
| **60TI/20F/20G120S** | 0.54 | 0.62 | 82 | 40 |
| **75TI/20F/5M** | 0.68 | 0.77 | 98 | 25 |
| **60TI/30F/10F2** | 0.54 | 0.61 | 74 | 40 |
| **65TI/30F/5SF** | 0.59 | 0.66 | 99 | 35 |
| **67TI/30F/3SF** | 0.60 | 0.68 | 90 | 33 |
| **50TI/30F/20G120S** | 0.45 | 0.51 | 78 | 50 |
| **65TI/30F/5M** | 0.59 | 0.66 | 94 | 35 |
| **80TI/20F2** | 0.72 | 0.82 | 82 | 20 |
| **75TI/20F2/5SF** | 0.68 | 0.77 | 103 | 25 |
| **77TI/20F2/3SF** | 0.69 | 0.79 | 94 | 23 |
| **60TI/20F2/20G120S** | 0.54 | 0.62 | 82 | 40 |
| **75TI/20F2/5M** | 0.68 | 0.77 | 98 | 25 |
| **60TI/30F2/10C** | 0.54 | 0.61 | 74 | 40 |
| **65TI/30F2/5SF** | 0.59 | 0.66 | 99 | 35 |
| **67TI/30F2/3SF** | 0.60 | 0.68 | 90 | 33 |
| **65TI/30F2/5M** | 0.59 | 0.66 | 94 | 35 |
| **65TI/35G120S** | 0.59 | 0.67 | 90 | 34 |
| **50TI/35G120S/15F2** | 0.46 | 0.52 | 84 | 49 |
| **62TI/35G120S/3SF** | 0.57 | 0.64 | 102 | 37 |
| **60TI/35G120S/5M** | 0.55 | 0.62 | 111 | 39 |
| **50TI/35G120S/15F** | 0.46 | 0.52 | 84 | 49 |
| **100TIP** | 0.72 | 0.82 | 82 | 20 |
| **85TIP/15C** | 0.61 | 0.70 | 77 | 32 |
| **85TIP/15F** | 0.61 | 0.70 | 77 | 32 |
| **85TIP/15F2** | 0.61 | 0.70 | 77 | 32 |
| **65TIP/35G120S** | 0.48 | 0.54 | 85 | 47 |
| **97TIP/3SF** | 0.70 | 0.80 | 95 | 22 |
| **95TIP/5M** | 0.69 | 0.78 | 98 | 24 |
| **75TIP/25C** | 0.54 | 0.62 | 74 | 40 |
| **75TIP/25F** | 0.54 | 0.62 | 74 | 40 |

| | | | | |
|---|---|---|---|---|
| **75TIP/25F2** | 0.54 | 0.62 | 74 | 40 |
| **50TIP/50G120S** | 0.37 | 0.42 | 86 | 59 |
| **100TISM** | 0.68 | 0.78 | 90 | 24 |
| **75TISM/25C** | 0.51 | 0.59 | 80 | 43 |
| **75TISM/25F2** | 0.51 | 0.59 | 80 | 43 |
| **65TISM/35G120S** | 0.45 | 0.52 | 90 | 50 |
| **97TISM/3SF** | 0.66 | 0.76 | 102 | 26 |
| **100TIPM** | 0.81 | 0.92 | 86 | 10 |
| **100 E** | 0.81 | 0.92 | 40 | |
| **80E/20S** | 0.65 | 0.74 | 40 | |
| **80E/20F** | 0.65 | 0.74 | 42 | |
| **80E/20F2** | 0.65 | 0.74 | 42 | |
| **80E/20G120S** | 0.66 | 0.75 | 50 | |
| **80E/20C** | 0.65 | 0.74 | 42 | |
| **95E/5SF** | 0.77 | 0.87 | 63 | |
| **95E/5M** | 0.77 | 0.87 | 58 | |
| **80TI/20S** | 0.73 | 0.82 | 80 | |

### Discussion of Carbon Dioxide Emissions

This example shows how even in a cap and trade system, a concrete company that has ternary concrete mixture assets can diversify in a way that does not compromise much profit or performance, while adhering to stringent governmental policies. In the previous example, a company could produce nearly twice as much yield of cement of the ternary mixture design for the same amount of carbon dioxide emissions as the plant producing 100% TI cement.

Another example is to consider a concrete company that has two plants: one that produces cement at 0.9 pounds of carbon dioxide per pound of cement and the other that produces 0.6 pounds of carbon dioxide per pound of cement. Altogether, the environmental impact of this concrete company is 0.75 pounds of carbon dioxide per pound of cement on average, which is a decrease from another company that may be operating all plants at 0.9 pounds of carbon dioxide per pound of cement, while producing the same amount of concrete or more.

Making a comparison between the carbon dioxide intensities of a wet plant operating at efficiencies of the 1970s and the carbon dioxide intensities of the plant in the previous example, producing 100TI cement, there is a decrease in carbon dioxide intensity from 1.2 to 0.9 lb $CO_2$/lb cement, which is a reduction of nearly 33%. When compared to the ternary mixture carbon intensity in Table 90 of 0.46 pounds of carbon dioxide per pound of cement, the carbon intensity savings are nearly 1.6 times more efficient.

The cement industry is facing some major obstacles in the years to come, especially with regard to carbon dioxide emissions. Some agencies may think that importing our cement eliminates the problem of carbon dioxide emissions for the US. Allowing our cement to be imported from other countries would take the US away from the emissions problem but it also takes the US away from the quality control of where the cement is being produced, which is significant to the manner in which the cement can be used. Displacing the problem will not solve the emissions dilemma, and may even worsen the emissions of our planet at a faster rate.

It is in the global environment's best interest to keep cement production within the US. The estimated carbon dioxide emissions are 0.9 pounds per pound of cement. This number could be substantially higher in China and South America given their standards of emissions are not as strict as the US. It is highly likely that some plants in the US are producing even less than 0.9 pounds of carbon dioxide per pound of finished cement.

The cement industry sets a good example for other industries of the US through its trends of decreasing energy use while increasing production. Cement industries decreased their energy use from 550 PJ (521 trillion Btu) in 1970 to 470 PJ (445 trillion Btu) in 1997, while increasing their production in those years (Nathan Martin). The overall energy intensity of cement production decreased 30% between 1970 and 1997, from 7.5 million Btu per ton of cement to 5.3 million Btu per ton of cement (Nathan Martin). This report aims to show that policies on carbon dioxide emissions for the concrete industry should take into consideration what is involved in the carbon intensity of producing cement. For example, it would be impractical to impose policy on the cement industry that caps carbon dioxide emissions at carbon dioxide intensities below that required to decarbonate limestone to produce cement, given it is an amount that cannot be reduced physically.

Other potential policies that may be imposed on the industry are carbon taxes or carbon credits. Carbon taxes are based on the amount of carbon dioxide emission reductions compared to a previous amount. For example, one plant that changes from wet plant to a dry plant would be rewarded while a plant that has already installed their dry plant would not. This would encourage those plants that have not made sustainable improvements to their plants or production to change, but provides little benefit to those that have already contributed to lowering their environmental impact. Carbon credits, on the other hand, would provide incentives for both the plants that are making sustainable changes and those that have yet to make changes to the ways their plants operate.

This report shows the carbon dioxide emission savings in cement plants that produce ternary concrete mixtures by adding silos of cementitious materials, such as fly ash, silica fume, and slag. By producing ternary mixtures, cement manufacturers can produce the same amount of same or higher quality cement for less carbon dioxide emissions and the same or slightly higher price.

The US cement industry is one of the leaders in the national effort to reduce carbon dioxide emissions. Keeping cement productions in the US can ensure better quality cement and a smaller carbon dioxide intensity compared to countries without strict quality control and emissions policies. Adding silos of pozzolans to a cement operation can provide better concrete with less cement for the same or less carbon dioxide emissions. The methodology presented provides a framework for documenting the carbon dioxide signature of a concrete mixture. This could be used in specifications, as an incentive, or for planning programs for the industry.

### Recommendations Regarding Carbon Dioxide Emissions

In the coming years, carbon dioxide emissions may become regulated or restricted in the cement industry. The following recommendation provides a standardized methodology for reporting carbon dioxide emissions for determining the carbon footprint of cementitious materials.

Carbon dioxide emissions should be computed and reported monthly and the data should be placed on cement mill reports and provided to cement customers. The steps required for calculating cement plant carbon dioxide intensity are shown in Table 53.

**Table 92. Cement plant carbon dioxide calculation steps**

| Step | Task |
|---|---|
| 1 | Determine the total energy used by the cement facility during a month. The energy total must include the total electrical kilowatt hours used in a month and all the energy required to grind raw materials, precalcine raw feed, operate the kiln, preheat materials, and grind the clinker and gypsum. (This value will be used to determine the amount of carbon dioxide, which is then divided by the total output.) |
| 2 | Determine the carbon dioxide released from raw materials during calcination. |
| 3 | Calculate carbon dioxide intensity for the cement using the previous equation for carbon dioxide from step 2 and the amount of carbon dioxide associated with the energy in step 1. |
| 4 | Determine either the total amount of fuel consumed for all transported material or total distances travelled per material. |
| 5 | Calculate carbon dioxide intensity for transportation. |
| 6 | Determine any additional energy intensity due to grinding or blending of natural pozzolan or other pozzolans for use with the cement. |
| 7 | Sum steps 3, 5, and 6 to attain the total carbon dioxide intensity in pounds of carbon dioxide per pound of cementitious materials. |
| 8 | Incorporate the carbon dioxide signature into the mill report. |

## Summary and Conclusions for Laboratory Study on Concrete

This study investigated the age-related distress mechanisms in ternary blended cementitious materials in concrete and any related barriers to using ternary blended cementitious materials in ready mix concrete. While this is not a final for the entire project report, preliminary findings from this phase of the study, as documented in this report, will extend into the final phase of the study. The final phase will include the field demonstration projects.

- 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 (PCC) mixtures.
- Ternary blended cement concrete mixtures greatly reduce the carbon dioxide and other greenhouse gas emissions related to the concrete industry. These mixtures can save more than 10,000 tons of carbon dioxide from being emitted into the atmosphere for just 10 miles of a six-lane concrete pavement.
- The initial cost of a ternary blended cement concrete pavement is dependent on the SCMs used and their proximity to the project location. The initial cost can generally be lowered if fly ash or GGBFS is used. Life cycle costs of ternary blended cement mixtures containing these materials, as well as silica fume, metakaolin and other pozzolans are also reduced.
- 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 most efficient means of optimizing a ternary concrete mixture is through trial batching using the mixture designs in this report as a starting point.
- Ready mix plants can 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 10,000 $yd^3$ of concrete.
- Pre-blended cements can be beneficial because the SCMs are well distributed and the gypsum content has been optimized during the cement production. These cements also meet all applicable standards. There is no capital investment by the ready mix producers from using pre-blended cements.
- States should update their specification to remove limitations on total SCMs and use performance-based tests to determine acceptable concrete mixture properties.
- Different SCMs are appropriate for general use and others for special projects. Different SCMs are also appropriate for different environments. Each state should use SCMs that best suit the project and its environment.

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# APPENDIX

## ASTM C1012 Sulfate Mortar Bar Expansion Tables

**Table 93. ASTM C1012 mortar bar expansions of control mixtures**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 100TI | 0.013 | 0.02 | 0.024 | 0.029 | 0.044 | 0.062 | 0.071 | 0.109 | 0.314 | 0.500 | 0.500 | 0.500 |
| 80TI/20C | 0.010 | 0.015 | 0.019 | 0.022 | 0.028 | 0.054 | 0.073 | 0.115 | 0.500 | 0.500 | 0.500 | 0.500 |
| 80TI/20F | 0.008 | 0.009 | 0.013 | 0.013 | 0.013 | 0.024 | 0.023 | 0.024 | 0.034 | 0.035 | 0.036 | 0.042 |
| 80TI/20F2 | 0.008 | 0.008 | 0.013 | 0.014 | 0.014 | 0.027 | 0.027 | 0.028 | 0.040 | 0.042 | 0.046 | 0.058 |
| 65TI/35G100S | 0.006 | 0.009 | 0.012 | 0.012 | 0.010 | 0.02 | 0.016 | 0.018 | 0.024 | | 0.022 | 0.028 |
| 65TI/35G120S | 0.008 | 0.010 | 0.013 | 0.015 | 0.014 | 0.026 | 0.021 | 0.026 | 0.035 | | 0.040 | 0.053 |
| 100TI-II | 0.002 | 0.005 | 0.007 | 0.007 | 0.013 | 0.02 | 0.017 | 0.026 | 0.036 | 0.046 | 0.059 | 0.071 |
| 80TI-II/20G120S | 0.003 | 0.007 | 0.007 | 0.007 | 0.012 | 0.02 | 0.013 | 0.021 | 0.027 | 0.034 | 0.039 | 0.049 |
| 100TIP | 0.003 | 0.007 | 0.008 | 0.009 | 0.012 | 0.019 | 0.014 | 0.02 | 0.025 | 0.025 | 0.028 | 0.034 |
| 100TISM | 0.003 | 0.006 | 0.006 | 0.007 | 0.014 | 0.023 | 0.027 | 0.025 | 0.037 | 0.047 | 0.057 | 0.070 |
| 100TIPM | 0.002 | 0.005 | 0.005 | 0.003 | 0.007 | 0.011 | 0.010 | 0.01 | 0.015 | 0.019 | 0.017 | 0.023 |
| 60TI/40F2 | 0.011 | 0.017 | 0.028 | 0.028 | 0.040 | 0.041 | 0.042 | 0.048 | 0.058 | 0.067 | 0.068 | 0.076 |

**Table 94. ASTM C1012 mortar bar expansions of mixtures containing Class C fly ash**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 60TI/20C/20F2 | 0.006 | 0.017 | 0.023 | 0.027 | 0.038 | 0.048 | 0.054 | 0.067 | 0.100 | 0.159 | 0.230 | 0.355 |
| 75TI/20C/5SF | 0 | 0.003 | 0.021 | 0.037 | 0.032 | 0.037 | 0.040 | 0.033 | 0.040 | 0.059 | 0.080 | 0.115 |
| 77TI/20C/3SF | 0 | 0.004 | 0.018 | 0.022 | 0.031 | 0.039 | 0.040 | 0.037 | 0.045 | 0.084 | 0.130 | 0.388 |
| 60TI/20C/20G100S | 0.013 | 0.025 | | 0.029 | 0.037 | 0.043 | 0.048 | 0.054 | 0.058 | 0.074 | 0.107 | 0.167 |
| 60TI/20C/20G120S | 0.010 | 0.020 | 0.021 | 0.023 | 0.034 | 0.037 | 0.039 | 0.039 | 0.045 | 0.052 | 0.057 | 0.102 |
| 75TI/20C/5M | 0.026 | 0.034 | 0.038 | 0.041 | 0.055 | 0.061 | 0.060 | 0.058 | 0.093 | 0.166 | 0.307 | |
| 60TI/30C/10F | 0.01 | 0.016 | 0.023 | 0.029 | 0.035 | 0.04 | 0.037 | 0.044 | 0.058 | 0.097 | 0.131 | 0.197 |
| 60TI/30C/10F2 | 0.011 | 0.016 | 0.024 | 0.031 | 0.041 | 0.052 | 0.057 | 0.078 | 0.175 | 0.189 | 0.287 | 0.403 |
| 65TI/30C/5SF | 0.008 | 0.012 | 0.018 | 0.021 | 0.027 | 0.027 | 0.026 | 0.028 | 0.033 | 0.039 | 0.040 | 0.042 |
| 67TI/30C/3SF | 0.01 | 0.013 | 0.019 | 0.022 | 0.030 | 0.032 | 0.032 | 0.035 | 0.045 | 0.064 | 0.098 | 0.089 |
| 50TI/30C/20G100S | 0.010 | 0.015 | 0.020 | 0.023 | 0.028 | 0.029 | 0.033 | 0.035 | 0.037 | 0.049 | 0.065 | 0.092 |
| 50TI/30C/20G120S | 0.009 | 0.013 | 0.020 | 0.023 | 0.03 | 0.034 | 0.038 | 0.040 | 0.048 | 0.097 | 0.196 | 0.376 |
| 65TI/30C/5M | 0.013 | 0.021 | 0.027 | 0.029 | 0.04 | 0.047 | 0.054 | 0.066 | 0.131 | 0.415 | | |
| 50TI/35G100S/15C | 0.014 | 0.023 | 0.026 | 0.030 | 0.033 | 0.03 | 0.031 | 0.036 | 0.043 | 0.053 | 0.058 | 0.060 |
| 50TI/35G120S/15C | 0.010 | 0.016 | 0.021 | 0.025 | 0.031 | 0.036 | 0.039 | 0.035 | 0.042 | 0.053 | 0.086 | 0.083 |
| 68TI-II/17G120S/15C | | 0 | 0.002 | 0 | 0.001 | | 0.009 | 0.011 | 0.018 | 0.033 | 0.027 | 0.031 |
| 60TI-II/25C/15G120S | 0.008 | 0.012 | 0.014 | 0.016 | 0.018 | 0.019 | 0.026 | 0.031 | 0.059 | 0.016 | 0.280 | 0.464 |
| 85TIP/15C | 0.018 | 0.024 | 0.02 | 0.025 | 0.029 | 0.029 | 0.027 | 0.031 | 0.039 | 0.045 | 0.040 | 0.039 |
| 75TIP/25C | 0.011 | 0.012 | 0.013 | 0.017 | 0.02 | 0.026 | 0.032 | 0.026 | 0.042 | 0.057 | 0.060 | 0.134 |
| 85TISM/15C | 0.006 | 0.009 | 0.011 | 0.013 | 0.018 | 0.019 | 0.026 | 0.026 | 0.032 | 0.049 | 0.098 | 0.117 |
| 75TISM/25C | 0.015 | 0.019 | 0.019 | 0.010 | 0.028 | 0.03 | 0.032 | 0.037 | 0.044 | 0.047 | 0.084 | 0.106 |
| 85TIPM/15C | 0.008 | 0.009 | 0.010 | 0.010 | 0.010 | 0.016 | 0.012 | 0.017 | 0.017 | 0.021 | 0.018 | 0.026 |
| 75TIPM/25C | 0.007 | 0.010 | 0.013 | 0.017 | 0.009 | 0.020 | 0.02 | 0.016 | 0.030 | 0.031 | 0.032 | 0.039 |
| 80TI/20C | 0.010 | 0.015 | 0.019 | 0.022 | 0.028 | 0.054 | 0.073 | 0.115 | 0.500 | 0.500 | 0.500 | 0.500 |

**Table 95. ASTM C1012 mortar bar expansions of mixtures containing Class F fly ash**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 60TI/20F/20F2 | 0.010 | 0.014 | 0.016 | 0.021 | 0.033 | 0.035 | 0.033 | 0.041 | 0.038 | 0.049 | 0.049 | 0.047 |
| 75TI/20F/5SF | 0.007 | 0.01 | 0.011 | 0.014 | 0.022 | 0.022 | 0.019 | 0.022 | 0.024 | 0.030 | 0.029 | 0.027 |
| 77TI/20F/3SF | 0.012 | | 0.021 | | 0.025 | 0.012 | 0.015 | 0.019 | 0.025 | 0.031 | 0.033 | 0.026 |
| 60TI/20F/20G100S | 0.004 | 0.008 | 0.011 | 0.015 | 0.020 | 0.020 | 0.010 | 0.023 | 0.028 | 0.034 | 0.033 | 0.031 |
| 60TI/20F/20G120S | 0.006 | 0.006 | 0.010 | 0.015 | 0.024 | 0.025 | 0.024 | 0.032 | 0.033 | 0.040 | 0.040 | 0.040 |
| 75TI/20F/5M | 0.015 | 0.019 | 0.022 | 0.024 | 0.036 | 0.037 | 0.037 | 0.045 | 0.044 | 0.050 | 0.049 | 0.049 |
| 60TI/30C/10F | 0.010 | 0.016 | 0.023 | 0.029 | 0.035 | 0.040 | 0.037 | 0.044 | 0.058 | 0.097 | 0.131 | 0.197 |
| 60TI/30F/10F2 | 0.006 | 0.013 | 0.018 | 0.020 | 0.028 | 0.028 | 0.031 | 0.032 | 0.036 | 0.046 | 0.052 | 0.047 |
| 65TI/30F/5SF | 0.015 | 0.030 | 0.042 | 0.040 | | 0.040 | 0.047 | 0.052 | 0.065 | 0.070 | 0.087 | 0.067 |
| 67TI/30F/3SF | 0.005 | 0.008 | 0.016 | 0.015 | | 0.018 | 0.020 | 0.022 | 0.029 | 0.031 | 0.040 | 0.082 |
| 50TI/30F/20G100S | 0.006 | 0.012 | 0.016 | 0.018 | 0.019 | 0.026 | 0.025 | 0.025 | 0.029 | 0.032 | 0.039 | 0.034 |
| 50TI/30F/20G120S | 0.008 | 0.013 | 0.019 | 0.019 | 0.022 | 0.023 | 0.028 | 0.029 | 0.035 | 0.041 | 0.048 | 0.040 |
| 65TI/30F/5M | 0.008 | 0.013 | 0.019 | 0.018 | 0.024 | 0.026 | 0.031 | 0.032 | 0.039 | 0.043 | 0.050 | 0.043 |
| 50TI/35G100S/15F | 0.014 | 0.019 | 0.02 | 0.023 | 0.026 | 0.022 | 0.024 | 0.026 | 0.031 | 0.037 | 0.045 | 0.041 |
| 50TI/35G120S/15F | 0.006 | 0.014 | 0.019 | 0.02 | 0.028 | 0.028 | 0.029 | | 0.017 | 0.039 | 0.046 | 0.045 |
| 68TI-II/17G120S/15F | | 0 | 0.003 | 0.001 | 0.003 | | 0.01 | 0.012 | 0.018 | 0.023 | 0.023 | 0.024 |
| 60TI-II/25F/15G120S | 0.004 | 0.008 | 0.009 | 0.01 | 0.012 | 0.006 | 0.01 | 0.017 | 0.020 | 0.028 | 0.028 | 0.027 |
| 85TIP/15F | 0.003 | 0.006 | 0.005 | 0.004 | 0.005 | 0.001 | 0.007 | 0.006 | 0.009 | 0.011 | 0.012 | 0.011 |
| 75TIP/25F | 0.011 | 0.012 | 0.012 | 0.016 | 0.017 | 0.021 | 0.025 | 0.017 | 0.028 | 0.028 | 0.029 | 0.033 |
| 85TISM/15F | 0.007 | 0.009 | 0.01 | 0.012 | 0.014 | 0.013 | 0.018 | 0.019 | 0.019 | 0.022 | 0.029 | 0.027 |
| 75TISM/25F | 0.011 | 0.014 | 0.014 | 0.015 | 0.02 | 0.02 | 0.019 | 0.022 | 0.026 | 0.025 | 0.039 | 0.039 |
| 85TIPM/15F | 0.009 | 0.008 | 0.009 | 0.008 | 0.008 | 0.016 | 0.01 | 0.014 | 0.014 | 0.017 | 0.014 | 0.019 |
| 75TIPM/25F | 0.006 | 0.011 | 0.012 | 0.016 | 0.008 | 0.016 | 0.015 | 0.012 | 0.023 | 0.022 | 0.017 | 0.022 |
| 80TI/20F | 0.008 | 0.009 | 0.013 | 0.013 | 0.013 | 0.024 | 0.023 | 0.024 | 0.034 | 0.035 | 0.036 | 0.042 |

**Table 96. ASTM C1012 mortar bar expansions of mixtures containing Class F2 fly ash**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 60TI/20C/20F2 | 0.006 | 0.017 | 0.023 | 0.027 | 0.038 | 0.048 | 0.054 | 0.067 | 0.100 | 0.159 | 0.230 | 0.355 |
| 60TI/20F/20F2 | 0.010 | 0.014 | 0.016 | 0.021 | 0.033 | 0.035 | 0.033 | 0.041 | 0.038 | 0.049 | 0.049 | 0.047 |
| 75TI/20F2/5SF | 0.011 | 0.016 | 0.020 | 0.022 | 0.028 | 0.031 | 0.028 | 0.038 | 0.036 | 0.041 | 0.040 | 0.041 |
| 77TI/20F2/3SF | 0.022 | 0.026 | 0.032 | 0.034 | 0.045 | 0.048 | 0.047 | 0.055 | 0.059 | 0.066 | 0.066 | 0.065 |
| 60TI/20F2/20G100S | 0.005 | 0.006 | 0.010 | 0.016 | 0.025 | 0.026 | 0.026 | 0.030 | 0.035 | 0.040 | 0.043 | 0.042 |
| 60TI/20F2/20G120S | 0.007 | 0.015 | 0.010 | 0.021 | 0.028 | 0.030 | 0.029 | 0.035 | 0.044 | 0.053 | 0.055 | 0.068 |
| 75TI/20F2/5M | 0.011 | 0.020 | 0.024 | | 0.031 | 0.036 | 0.039 | 0.043 | 0.050 | 0.058 | 0.059 | 0.059 |
| 60TI/30C/10F2 | 0.011 | 0.016 | 0.024 | 0.031 | 0.041 | 0.052 | 0.057 | 0.078 | 0.175 | 0.189 | 0.287 | 0.403 |
| 60TI/30F/10F2 | 0.006 | 0.013 | 0.018 | 0.020 | 0.028 | 0.028 | 0.031 | 0.032 | 0.036 | 0.046 | 0.052 | 0.047 |
| 65TI/30F2/5SF | 0.007 | 0.014 | 0.018 | 0.017 | 0.018 | 0.019 | 0.022 | 0.020 | 0.022 | 0.027 | 0.033 | 0.030 |
| 67TI/30F2/3SF | 0.006 | 0.011 | 0.018 | 0.016 | 0.017 | 0.020 | 0.025 | 0.021 | 0.024 | 0.028 | 0.035 | 0.029 |
| 50TI/30F2/20G100S | 0.012 | 0.016 | 0.019 | 0.021 | 0.025 | 0.028 | 0.029 | 0.024 | 0.026 | 0.030 | 0.039 | 0.036 |
| 50TI/30F2/20G120S | 0.010 | 0.014 | 0.018 | 0.021 | 0.026 | 0.030 | 0.031 | 0.027 | 0.030 | 0.036 | 0.046 | 0.043 |
| 65TI/30F2/5M | 0.010 | 0.016 | 0.019 | 0.022 | 0.028 | 0.035 | 0.039 | 0.035 | 0.042 | 0.049 | 0.067 | 0.076 |
| 50TI/35G100S/15F2 | 0.005 | 0.011 | 0.015 | 0.016 | 0.020 | 0.022 | 0.023 | | 0.025 | 0.028 | 0.035 | 0.030 |
| 50TI/35G120S/15F2 | 0.014 | 0.016 | 0.017 | 0.020 | 0.024 | 0.028 | 0.016 | 0.024 | 0.028 | 0.036 | 0.038 | 0.036 |
| 68TI-II/17G120S/15F2 | | 0.000 | 0.003 | 0.003 | 0.005 | | 0.012 | 0.017 | 0.022 | 0.027 | 0.031 | 0.028 |
| 60TI-II/25F2/15G120S | 0.004 | 0.007 | 0.009 | 0.009 | 0.013 | 0.007 | 0.013 | 0.021 | 0.024 | 0.033 | 0.032 | 0.033 |
| 85TIP/15F2 | 0.003 | 0.005 | 0.004 | 0.003 | 0.004 | 0.001 | 0.007 | 0.005 | 0.008 | 0.011 | 0.011 | 0.009 |
| 75TIP/25F2 | 0.010 | 0.012 | 0.013 | 0.018 | 0.017 | 0.022 | 0.028 | 0.021 | 0.034 | 0.034 | 0.035 | 0.042 |
| 85TISM/15F2 | 0.009 | 0.001 | 0.010 | 0.013 | 0.015 | 0.014 | 0.018 | 0.018 | 0.019 | 0.022 | 0.027 | 0.026 |
| 75TISM/25F2 | 0.005 | 0.007 | 0.013 | 0.016 | 0.006 | 0.024 | 0.015 | 0.013 | 0.027 | 0.025 | 0.023 | 0.028 |
| 85TIPM/15F2 | 0.007 | 0.006 | 0.009 | 0.007 | 0.008 | 0.016 | 0.012 | 0.014 | 0.015 | 0.025 | 0.017 | 0.023 |
| 75TIPM/25F2 | 0.008 | 0.010 | 0.013 | 0.012 | 0.009 | 0.018 | 0.015 | 0.016 | 0.023 | 0.020 | 0.017 | 0.022 |
| 80TI/20F2 | 0.008 | 0.008 | 0.013 | 0.014 | 0.014 | 0.027 | 0.027 | 0.028 | 0.040 | 0.042 | 0.046 | 0.058 |
| 60TI/40F2 | 0.011 | 0.017 | 0.028 | 0.028 | 0.040 | 0.041 | 0.042 | 0.048 | 0.058 | 0.067 | 0.068 | 0.076 |

**Table 97. ASTM C1012 mortar bar expansions of mixtures containing Grade 100 GGBFS**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 60TI/20C/20G100S | 0.013 | 0.025 | | 0.029 | 0.037 | 0.043 | 0.048 | 0.054 | 0.058 | 0.074 | 0.107 | 0.167 |
| 60TI/20F2/20G100S | 0.005 | 0.006 | 0.010 | 0.016 | 0.025 | 0.026 | 0.026 | 0.030 | 0.035 | 0.040 | 0.043 | 0.042 |
| 60TI/20F/20G100S | 0.004 | 0.008 | 0.011 | 0.015 | 0.020 | 0.020 | 0.010 | 0.023 | 0.028 | 0.034 | 0.033 | 0.031 |
| 50TI/30C/20G100S | 0.010 | 0.015 | 0.020 | 0.023 | 0.028 | 0.029 | 0.033 | 0.035 | 0.037 | 0.049 | 0.065 | 0.092 |
| 50TI/30F/20G100S | 0.006 | 0.012 | 0.016 | 0.018 | 0.019 | 0.026 | 0.025 | 0.025 | 0.029 | 0.032 | 0.039 | 0.034 |
| 50TI/30F2/20G100S | 0.012 | 0.016 | 0.019 | 0.021 | 0.025 | 0.028 | 0.029 | 0.024 | 0.026 | 0.030 | 0.039 | 0.036 |
| 50TI/35G100S/15C | 0.014 | 0.023 | 0.026 | 0.030 | 0.033 | 0.030 | 0.031 | 0.036 | 0.043 | 0.053 | 0.058 | 0.060 |
| 50TI/35G100S/15F | 0.014 | 0.019 | 0.020 | 0.023 | 0.026 | 0.022 | 0.024 | 0.026 | 0.031 | 0.037 | 0.045 | 0.041 |
| 50TI/35G100S/15F2 | 0.005 | 0.011 | 0.015 | 0.016 | 0.020 | 0.022 | 0.023 | | 0.025 | 0.028 | 0.035 | 0.030 |
| 60TI/35G100S/5SF | 0.011 | 0.016 | 0.018 | 0.018 | 0.021 | 0.014 | 0.014 | 0.017 | 0.020 | 0.027 | 0.033 | 0.029 |
| 62TI/35G100S/3SF | 0.005 | 0.011 | 0.014 | 0.014 | 0.018 | 0.019 | 0.020 | | 0.026 | 0.024 | 0.031 | 0.026 |
| 60TI/35G100S/5M | 0.006 | 0.011 | 0.014 | 0.015 | 0.019 | 0.020 | 0.022 | 0.022 | 0.004 | 0.026 | 0.032 | 0.030 |
| 64TI-II/20G100S/16G120S | 0.005 | 0.006 | 0.008 | 0.010 | | 0.015 | 0.006 | 0.011 | 0.021 | 0.028 | 0.026 | 0.027 |
| 52TI-II/35G100S/13G120S | 0.010 | 0.015 | 0.013 | 0.016 | 0.017 | 0.016 | 0.014 | 0.015 | 0.017 | 0.024 | 0.027 | 0.022 |
| 80TIP/20G100S | 0.009 | 0.010 | 0.009 | 0.014 | 0.013 | 0.018 | 0.020 | 0.015 | 0.026 | 0.023 | 0.025 | 0.032 |
| 65TIP/35G100S | 0.014 | 0.014 | 0.014 | 0.018 | 0.016 | 0.019 | 0.023 | 0.015 | 0.025 | 0.023 | 0.027 | 0.031 |
| 80TISM/20G100S | 0.010 | 0.014 | 0.014 | 0.016 | 0.021 | 0.021 | 0.022 | 0.024 | 0.028 | 0.028 | 0.033 | 0.034 |
| 65TISM/35G100S | 0.004 | 0.011 | 0.014 | 0.017 | 0.007 | 0.015 | 0.014 | 0.018 | 0.025 | 0.019 | 0.017 | 0.022 |
| 80TIPM/20G100S | 0.005 | 0.011 | 0.013 | 0.015 | 0.007 | 0.015 | 0.015 | 0.014 | 0.023 | 0.021 | 0.016 | 0.022 |
| 65TIPM/35G100S | 0.011 | 0.011 | 0.013 | 0.011 | 0.012 | 0.019 | 0.014 | 0.016 | 0.015 | 0.018 | 0.012 | 0.018 |
| 65TI/35G100S | 0.006 | 0.009 | 0.012 | 0.012 | 0.010 | 0.020 | 0.016 | 0.018 | 0.024 | | 0.022 | 0.028 |

**Table 98. ASTM C1012 mortar bar expansions of mixtures containing Grade 120 GGBFS**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 60TI/20C/20G120S | 0.010 | 0.020 | 0.021 | 0.023 | 0.034 | 0.037 | 0.039 | 0.039 | 0.045 | 0.052 | 0.057 | 0.102 |
| 60TI/20F2/20G120S | 0.007 | 0.015 | 0.010 | 0.021 | 0.028 | 0.030 | 0.029 | 0.035 | 0.044 | 0.053 | 0.055 | 0.068 |
| 60TI/20F/20G120S | 0.006 | 0.006 | 0.010 | 0.015 | 0.024 | 0.025 | 0.024 | 0.032 | 0.033 | 0.040 | 0.040 | 0.040 |
| 50TI/30C/20G120S | 0.009 | 0.013 | 0.020 | 0.023 | 0.030 | 0.034 | 0.038 | 0.040 | 0.048 | 0.097 | 0.196 | 0.376 |
| 50TI/30F/20G120S | 0.008 | 0.013 | 0.019 | 0.019 | 0.022 | 0.023 | 0.028 | 0.029 | 0.035 | 0.041 | 0.048 | 0.040 |
| 50TI/30F2/20G120S | 0.010 | 0.014 | 0.018 | 0.021 | 0.026 | 0.030 | 0.031 | 0.027 | 0.030 | 0.036 | 0.046 | 0.043 |
| 50TI/35G120S/15C | 0.010 | 0.016 | 0.021 | 0.025 | 0.031 | 0.036 | 0.039 | 0.035 | 0.042 | 0.053 | 0.086 | 0.083 |
| 50TI/35G120S/15F | 0.006 | 0.014 | 0.019 | 0.020 | 0.028 | 0.028 | 0.029 | | 0.017 | 0.039 | 0.046 | 0.045 |
| 50TI/35G120S/15F2 | 0.014 | 0.016 | 0.017 | 0.020 | 0.024 | 0.028 | 0.016 | 0.024 | 0.028 | 0.036 | 0.038 | 0.036 |
| 60TI/35G120S/5SF | 0.015 | 0.016 | 0.018 | 0.019 | 0.022 | 0.023 | 0.012 | 0.021 | 0.022 | 0.028 | 0.028 | 0.023 |
| 62TI/35G120S/3SF | 0.017 | 0.018 | 0.018 | 0.018 | 0.024 | 0.024 | 0.012 | 0.016 | 0.022 | 0.033 | 0.033 | 0.033 |
| 60TI/35G120S/5M | 0.015 | 0.017 | 0.020 | 0.020 | 0.020 | 0.026 | 0.028 | 0.013 | 0.024 | 0.036 | 0.037 | 0.033 |
| 68TI-II/17G120S/15C | | 0.000 | 0.002 | 0.000 | 0.001 | | 0.009 | 0.011 | 0.018 | 0.033 | 0.027 | 0.031 |
| 68TI-II/17G120S/15F | | 0.000 | 0.003 | 0.001 | 0.003 | | 0.010 | 0.012 | 0.018 | 0.023 | 0.023 | 0.024 |
| 68TI-II/17G120S/15F2 | | 0.000 | 0.003 | 0.003 | 0.005 | | 0.012 | 0.017 | 0.022 | 0.027 | 0.031 | 0.028 |
| 76TI-II/19G120S/5SF | | 0.000 | 0.002 | 0.001 | 0.002 | | 0.007 | 0.011 | 0.016 | 0.018 | 0.023 | 0.022 |
| 78TI-II/19G120S/3SF | 0.005 | 0.006 | 0.008 | 0.011 | 0.014 | 0.015 | 0.008 | 0.012 | 0.022 | 0.030 | 0.027 | 0.032 |
| 64TI-II/20G100S/16G120S | 0.005 | 0.006 | 0.008 | 0.010 | | 0.015 | 0.006 | 0.011 | 0.021 | 0.028 | 0.026 | 0.027 |
| 76TI-II/19G120S/5M | 0.006 | 0.009 | 0.009 | 0.011 | | 0.016 | 0.014 | 0.017 | 0.030 | 0.042 | 0.043 | 0.052 |
| 60TI-II/25C/15G120S | 0.008 | 0.012 | 0.014 | 0.016 | 0.018 | 0.019 | 0.026 | 0.031 | 0.059 | 0.016 | 0.280 | 0.464 |
| 60TI-II/25F/15G120S | 0.004 | 0.008 | 0.009 | 0.010 | 0.012 | 0.006 | 0.010 | 0.017 | 0.020 | 0.028 | 0.028 | 0.027 |
| 60TI-II/25F2/15G120S | 0.004 | 0.007 | 0.009 | 0.009 | 0.013 | 0.007 | 0.013 | 0.021 | 0.024 | 0.033 | 0.032 | 0.033 |
| 52TI-II/35G100S/13G120S | 0.010 | 0.015 | 0.013 | 0.016 | 0.017 | 0.016 | 0.014 | 0.015 | 0.017 | 0.024 | 0.027 | 0.022 |
| 80TIP/20G120S | 0.008 | 0.008 | 0.009 | 0.012 | 0.012 | 0.018 | 0.021 | 0.014 | 0.027 | 0.028 | 0.030 | 0.039 |
| 65TIP/35G120S | 0.010 | 0.011 | 0.012 | 0.014 | 0.013 | 0.017 | 0.021 | 0.014 | 0.028 | 0.028 | 0.030 | 0.037 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80TISM/20G120S | 0.011 | 0.014 | 0.014 | 0.015 | 0.020 | 0.021 | 0.021 | 0.025 | 0.028 | 0.026 | 0.038 | 0.038 |
| 65TISM/35G120S | 0.005 | 0.009 | 0.012 | 0.015 | 0.007 | 0.018 | 0.016 | 0.014 | 0.023 | 0.023 | 0.019 | 0.025 |
| 80TIPM/20G120S | 0.005 | 0.011 | 0.014 | 0.017 | 0.008 | 0.019 | 0.018 | 0.016 | 0.027 | 0.027 | 0.025 | 0.033 |
| 65TIPM/35G120S | 0.011 | 0.011 | 0.014 | 0.013 | 0.014 | 0.022 | 0.018 | 0.020 | 0.020 | 0.025 | 0.022 | 0.029 |
| 65TI/35G120S | 0.008 | 0.010 | 0.013 | 0.015 | 0.014 | 0.026 | 0.021 | 0.026 | 0.035 | | 0.040 | 0.053 |
| 80TI-II/20G120S | 0.003 | 0.007 | 0.007 | 0.007 | 0.012 | 0.020 | 0.013 | 0.021 | 0.027 | 0.034 | 0.039 | 0.049 |

**Table 99. ASTM C1012 mortar bar expansions of mixtures containing silica fume**

| Mixture ID | Mortar Bar Expansion (%)<br>Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75TI/20C/5SF | 0.000 | 0.003 | 0.021 | 0.037 | 0.032 | 0.037 | 0.040 | 0.033 | 0.040 | 0.059 | 0.080 | 0.115 |
| 77TI/20C/3SF | 0.000 | 0.004 | 0.018 | 0.022 | 0.031 | 0.039 | 0.040 | 0.037 | 0.045 | 0.084 | 0.130 | 0.388 |
| 75TI/20F2/5SF | 0.011 | 0.016 | 0.020 | 0.022 | 0.028 | 0.031 | 0.028 | 0.038 | 0.036 | 0.041 | 0.040 | 0.041 |
| 77TI/20F2/3SF | 0.022 | 0.026 | 0.032 | 0.034 | 0.045 | 0.048 | 0.047 | 0.055 | 0.059 | 0.066 | 0.066 | 0.065 |
| 75TI/20F/5SF | 0.007 | 0.010 | 0.011 | 0.014 | 0.022 | 0.022 | 0.019 | 0.022 | 0.024 | 0.030 | 0.029 | 0.027 |
| 77TI/20F/3SF | 0.012 | 0.000 | 0.021 |  | 0.025 | 0.012 | 0.015 | 0.019 | 0.025 | 0.031 | 0.033 | 0.026 |
| 65TI/30C/5SF | 0.008 | 0.012 | 0.018 | 0.021 | 0.027 | 0.027 | 0.026 | 0.028 | 0.033 | 0.039 | 0.040 | 0.042 |
| 67TI/30C/3SF | 0.010 | 0.013 | 0.019 | 0.022 | 0.030 | 0.032 | 0.032 | 0.035 | 0.045 | 0.064 | 0.098 | 0.089 |
| 65TI/30F/5SF | 0.015 | 0.030 | 0.042 | 0.040 |  | 0.040 | 0.047 | 0.052 | 0.065 | 0.070 | 0.087 | 0.067 |
| 67TI/30F/3SF | 0.005 | 0.008 | 0.016 | 0.015 |  | 0.018 | 0.020 | 0.022 | 0.029 | 0.031 | 0.040 | 0.082 |
| 65TI/30F2/5SF | 0.007 | 0.014 | 0.018 | 0.017 | 0.018 | 0.019 | 0.022 | 0.020 | 0.022 | 0.027 | 0.033 | 0.030 |
| 67TI/30F2/3SF | 0.006 | 0.011 | 0.018 | 0.016 | 0.017 | 0.020 | 0.025 | 0.021 | 0.024 | 0.028 | 0.035 | 0.029 |
| 60TI/35G100S/5SF | 0.011 | 0.016 | 0.018 | 0.018 | 0.021 | 0.014 | 0.014 | 0.017 | 0.020 | 0.027 | 0.033 | 0.029 |
| 62TI/35G100S/3SF | 0.005 | 0.011 | 0.014 | 0.014 | 0.018 | 0.019 | 0.020 |  | 0.026 | 0.024 | 0.031 | 0.026 |
| 60TI/35G120S/5SF | 0.015 | 0.016 | 0.018 | 0.019 | 0.022 | 0.023 | 0.012 | 0.021 | 0.022 | 0.028 | 0.028 | 0.023 |
| 62TI/35G120S/3SF | 0.017 | 0.018 | 0.018 | 0.018 | 0.024 | 0.024 | 0.012 | 0.016 | 0.022 | 0.033 | 0.033 | 0.033 |
| 90TI/5M/5SF | 0.008 | 0.011 | 0.011 | 0.011 |  | 0.010 | 0.009 | 0.011 | 0.013 | 0.020 | 0.027 | 0.026 |
| 76TI-II/19G120S/5SF |  | 0.000 | 0.002 | 0.001 | 0.002 |  | 0.007 | 0.011 | 0.016 | 0.018 | 0.023 | 0.022 |
| 78TI-II/19G120S/3SF | 0.005 | 0.006 | 0.008 | 0.011 | 0.014 | 0.015 | 0.008 | 0.012 | 0.022 | 0.030 | 0.027 | 0.032 |
| 95TIP/5SF | 0.009 | 0.016 | 0.012 | 0.008 | 0.009 | 0.004 | 0.014 | 0.009 | 0.018 | 0.022 | 0.024 | 0.021 |
| 97TIP/3SF | 0.008 | 0.013 | 0.011 | 0.008 | 0.010 | 0.005 | 0.014 | 0.011 | 0.019 | 0.024 | 0.025 | 0.022 |
| 95TISM/5SF | 0.010 | 0.012 | 0.012 | 0.014 | 0.016 | 0.016 | 0.019 | 0.019 | 0.021 | 0.025 | 0.030 | 0.029 |
| 97TISM/3SF | 0.008 | 0.012 | 0.012 | 0.015 | 0.020 | 0.021 | 0.021 | 0.024 | 0.029 | 0.027 | 0.036 | 0.039 |
| 95TIPM/5SF | 0.007 | 0.006 | 0.007 | 0.005 | 0.005 | 0.012 | 0.008 | 0.009 | 0.010 | 0.012 | 0.010 | 0.017 |
| 97TIPM/3SF | 0.004 | 0.007 | 0.007 | 0.006 | 0.007 | 0.012 | 0.006 | 0.013 | 0.014 | 0.018 | 0.013 | 0.021 |

**Table 100. ASTM C1012 mortar bar expansions of mixtures containing metakaolin**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 75TI/20C/5M | 0.026 | 0.034 | 0.038 | 0.041 | 0.055 | 0.061 | 0.060 | 0.058 | 0.093 | 0.166 | 0.307 | |
| 75TI/20F2/5M | 0.011 | 0.020 | 0.024 | | 0.031 | 0.036 | 0.039 | 0.043 | 0.050 | 0.058 | 0.059 | 0.059 |
| 75TI/20F/5M | 0.015 | 0.019 | 0.022 | 0.024 | 0.036 | 0.037 | 0.037 | 0.045 | 0.044 | 0.050 | 0.049 | 0.049 |
| 65TI/30C/5M | 0.013 | 0.021 | 0.027 | 0.029 | 0.040 | 0.047 | 0.054 | 0.066 | 0.131 | 0.415 | | |
| 65TI/30F/5M | 0.008 | 0.013 | 0.019 | 0.018 | 0.024 | 0.026 | 0.031 | 0.032 | 0.039 | 0.043 | 0.050 | 0.043 |
| 65TI/30F2/5M | 0.010 | 0.016 | 0.019 | 0.022 | 0.028 | 0.035 | 0.039 | 0.035 | 0.042 | 0.049 | 0.067 | 0.076 |
| 60TI/35G100S/5M | 0.006 | 0.011 | 0.014 | 0.015 | 0.019 | 0.020 | 0.022 | 0.022 | 0.004 | 0.026 | 0.032 | 0.030 |
| 60TI/35G120S/5M | 0.015 | 0.017 | 0.020 | 0.020 | 0.020 | 0.026 | 0.028 | 0.013 | 0.024 | 0.036 | 0.037 | 0.033 |
| 90TI/5M/5SF | 0.008 | 0.011 | 0.011 | 0.011 | | 0.010 | 0.009 | 0.011 | 0.013 | 0.020 | 0.027 | 0.026 |
| 92TI/5M/3SF | 0.009 | 0.012 | 0.012 | 0.012 | | 0.013 | 0.012 | 0.014 | 0.020 | 0.035 | 0.045 | 0.056 |
| 76TI-II/19G120S/5M | 0.006 | 0.009 | 0.009 | 0.011 | | 0.016 | 0.014 | 0.017 | 0.030 | 0.042 | 0.043 | 0.052 |
| 95TIP/5M | 0.009 | 0.008 | 0.008 | 0.011 | 0.011 | 0.014 | 0.019 | 0.011 | 0.025 | 0.023 | 0.025 | 0.033 |
| 95TISM/5M | 0.012 | 0.016 | 0.017 | 0.017 | 0.024 | 0.025 | 0.026 | 0.031 | 0.037 | 0.036 | 0.055 | 0.059 |
| 95TIPM/5M | 0.005 | 0.008 | 0.012 | 0.012 | 0.001 | 0.012 | 0.010 | 0.008 | 0.018 | 0.017 | 0.013 | 0.019 |

**Table 101. ASTM C1012 mortar bar expansions of mixtures containing Type IP cement**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 100TIP | 0.003 | 0.007 | 0.008 | 0.009 | 0.012 | 0.019 | 0.014 | 0.020 | 0.025 | 0.025 | 0.028 | 0.034 |
| 85TIP/15C | 0.018 | 0.024 | 0.020 | 0.025 | 0.029 | 0.029 | 0.027 | 0.031 | 0.039 | 0.045 | 0.040 | 0.039 |
| 85TIP/15F | 0.003 | 0.006 | 0.005 | 0.004 | 0.005 | 0.001 | 0.007 | 0.006 | 0.009 | 0.011 | 0.012 | 0.011 |
| 85TIP/15F2 | 0.003 | 0.005 | 0.004 | 0.003 | 0.004 | 0.001 | 0.007 | 0.005 | 0.008 | 0.011 | 0.011 | 0.009 |
| 95TIP/5SF | 0.009 | 0.016 | 0.012 | 0.008 | 0.009 | 0.004 | 0.014 | 0.009 | 0.018 | 0.022 | 0.024 | 0.021 |
| 97TIP/3SF | 0.008 | 0.013 | 0.011 | 0.008 | 0.010 | 0.005 | 0.014 | 0.011 | 0.019 | 0.024 | 0.025 | 0.022 |
| 80TIP/20G100S | 0.009 | 0.010 | 0.009 | 0.014 | 0.013 | 0.018 | 0.020 | 0.015 | 0.026 | 0.023 | 0.025 | 0.032 |
| 80TIP/20G120S | 0.008 | 0.008 | 0.009 | 0.012 | 0.012 | 0.018 | 0.021 | 0.014 | 0.027 | 0.028 | 0.030 | 0.039 |
| 95TIP/5M | 0.009 | 0.008 | 0.008 | 0.011 | 0.011 | 0.014 | 0.019 | 0.011 | 0.025 | 0.023 | 0.025 | 0.033 |
| 75TIP/25C | 0.011 | 0.012 | 0.013 | 0.017 | 0.020 | 0.026 | 0.032 | 0.026 | 0.042 | 0.057 | 0.060 | 0.134 |
| 65TIP/35G120S | 0.010 | 0.011 | 0.012 | 0.014 | 0.013 | 0.017 | 0.021 | 0.014 | 0.028 | 0.028 | 0.030 | 0.037 |
| 75TIP/25F2 | 0.010 | 0.012 | 0.013 | 0.018 | 0.017 | 0.022 | 0.028 | 0.021 | 0.034 | 0.034 | 0.035 | 0.042 |
| 65TIP/35G100S | 0.014 | 0.014 | 0.014 | 0.018 | 0.016 | 0.019 | 0.023 | 0.015 | 0.025 | 0.023 | 0.027 | 0.031 |
| 75TIP/25F | 0.011 | 0.012 | 0.012 | 0.016 | 0.017 | 0.021 | 0.025 | 0.017 | 0.028 | 0.028 | 0.029 | 0.033 |

**Table 102. ASTM C1012 mortar bar expansions of mixtures containing Type IS(20) cement**

| Mixture ID | Mortar Bar Expansion (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
| 100TISM | 0.003 | 0.006 | 0.006 | 0.007 | 0.014 | 0.023 | 0.027 | 0.025 | 0.037 | 0.047 | 0.057 | 0.070 |
| 85TISM/15C | 0.006 | 0.009 | 0.011 | 0.013 | 0.018 | 0.019 | 0.026 | 0.026 | 0.032 | 0.049 | 0.098 | 0.117 |
| 85TISM/15F | 0.007 | 0.009 | 0.010 | 0.012 | 0.014 | 0.013 | 0.018 | 0.019 | 0.019 | 0.022 | 0.029 | 0.027 |
| 85TISM/15F2 | 0.009 | 0.001 | 0.010 | 0.013 | 0.015 | 0.014 | 0.018 | 0.018 | 0.019 | 0.022 | 0.027 | 0.026 |
| 95TISM/5SF | 0.010 | 0.012 | 0.012 | 0.014 | 0.016 | 0.016 | 0.019 | 0.019 | 0.021 | 0.025 | 0.030 | 0.029 |
| 97TISM/3SF | 0.008 | 0.012 | 0.012 | 0.015 | 0.020 | 0.021 | 0.021 | 0.024 | 0.029 | 0.027 | 0.036 | 0.039 |
| 80TISM/20G100S | 0.010 | 0.014 | 0.014 | 0.016 | 0.021 | 0.021 | 0.022 | 0.024 | 0.028 | 0.028 | 0.033 | 0.034 |
| 80TISM/20G120S | 0.011 | 0.014 | 0.014 | 0.015 | 0.020 | 0.021 | 0.021 | 0.025 | 0.028 | 0.026 | 0.038 | 0.038 |
| 95TISM/5M | 0.012 | 0.016 | 0.017 | 0.017 | 0.024 | 0.025 | 0.026 | 0.031 | 0.037 | 0.036 | 0.055 | 0.059 |
| 75TISM/25C | 0.015 | 0.019 | 0.019 | 0.010 | 0.028 | 0.030 | 0.032 | 0.037 | 0.044 | 0.047 | 0.084 | 0.106 |
| 75TISM/25F | 0.011 | 0.014 | 0.014 | 0.015 | 0.020 | 0.020 | 0.019 | 0.022 | 0.026 | 0.025 | 0.039 | 0.039 |
| 75TISM/25F2 | 0.005 | 0.007 | 0.013 | 0.016 | 0.006 | 0.024 | 0.015 | 0.013 | 0.027 | 0.025 | 0.023 | 0.028 |
| 65TISM/35G100S | 0.004 | 0.011 | 0.014 | 0.017 | 0.007 | 0.015 | 0.014 | 0.018 | 0.025 | 0.019 | 0.017 | 0.022 |
| 65TISM/35G120S | 0.005 | 0.009 | 0.012 | 0.015 | 0.007 | 0.018 | 0.016 | 0.014 | 0.023 | 0.023 | 0.019 | 0.025 |

**Table 103. ASTM C1012 mortar bar expansions of mixtures containing Type IP(6) cement**

| Mixture ID | Mortar Bar Expansion (%)<br>Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100TIPM | 0.002 | 0.005 | 0.005 | 0.003 | 0.007 | 0.011 | 0.010 | 0.010 | 0.015 | 0.019 | 0.017 | 0.023 |
| 85TIPM/15C | 0.008 | 0.009 | 0.010 | 0.010 | 0.010 | 0.016 | 0.012 | 0.017 | 0.017 | 0.021 | 0.018 | 0.026 |
| 85TIPM/15F | 0.009 | 0.008 | 0.009 | 0.008 | 0.008 | 0.016 | 0.010 | 0.014 | 0.014 | 0.017 | 0.014 | 0.019 |
| 85TIPM/15F2 | 0.007 | 0.006 | 0.009 | 0.007 | 0.008 | 0.016 | 0.012 | 0.014 | 0.015 | 0.025 | 0.017 | 0.023 |
| 95TIPM/5SF | 0.007 | 0.006 | 0.007 | 0.005 | 0.005 | 0.012 | 0.008 | 0.009 | 0.010 | 0.012 | 0.010 | 0.017 |
| 97TIPM/3SF | 0.004 | 0.007 | 0.007 | 0.006 | 0.007 | 0.012 | 0.006 | 0.013 | 0.014 | 0.018 | 0.013 | 0.021 |
| 80TIPM/20G100S | 0.005 | 0.011 | 0.013 | 0.015 | 0.007 | 0.015 | 0.015 | 0.014 | 0.023 | 0.021 | 0.016 | 0.022 |
| 80TIPM/20G120S | 0.005 | 0.011 | 0.014 | 0.017 | 0.008 | 0.019 | 0.018 | 0.016 | 0.027 | 0.027 | 0.025 | 0.033 |
| 95TIPM/5M | 0.005 | 0.008 | 0.012 | 0.012 | 0.001 | 0.012 | 0.010 | 0.008 | 0.018 | 0.017 | 0.013 | 0.019 |
| 75TIPM/25C | 0.007 | 0.010 | 0.013 | 0.017 | 0.009 | 0.020 | 0.020 | 0.016 | 0.030 | 0.031 | 0.032 | 0.039 |
| 75TIPM/25F | 0.006 | 0.011 | 0.012 | 0.016 | 0.008 | 0.016 | 0.015 | 0.012 | 0.023 | 0.022 | 0.017 | 0.022 |
| 75TIPM/25F2 | 0.008 | 0.010 | 0.013 | 0.012 | 0.009 | 0.018 | 0.015 | 0.016 | 0.023 | 0.020 | 0.017 | 0.022 |
| 65TIPM/35G100S | 0.011 | 0.011 | 0.013 | 0.011 | 0.012 | 0.019 | 0.014 | 0.016 | 0.015 | 0.018 | 0.012 | 0.018 |
| 65TIPM/35G120S | 0.011 | 0.011 | 0.014 | 0.013 | 0.014 | 0.022 | 0.018 | 0.020 | 0.020 | 0.025 | 0.022 | 0.029 |

**Table 104. ASTM C1012 mortar bar expansions of mixtures containing limestone blended cement**

| Mixture ID | Mortar Bar Expansion (%)<br>Week 1 | Week 2 | Week 3 | Week 4 | Week 8 | Week 13 | Week 15 | Month 4 | Month 6 | Month 9 | Month 12 | Month 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100E | 0.003 | 0.006 | 0.009 | 0.008 | 0.012 | 0.029 |  | 0.029 | 0.045 |  | 0.077 | 0.114 |
| 80E/20F | 0.003 | 0.003 | 0.007 | 0.004 | 0.033 | 0.021 |  | 0.019 | 0.029 |  | 0.033 | 0.048 |
| 80TI/20F2 | 0.007 | 0.009 | 0.013 | 0.011 | 0.016 | 0.030 |  | 0.029 | 0.039 |  | 0.040 | 0.049 |
| 80E/20G120S | 0.006 | 0.010 | 0.011 | 0.011 | 0.013 | 0.023 |  | 0.020 | 0.030 |  | 0.027 | 0.035 |
| 80E/20C | 0.000 | 0.012 | 0.007 | 0.006 | 0.010 | 0.022 |  | 0.021 | 0.033 |  | 0.038 | 0.056 |
| 95E/5SF | 0.003 | 0.004 | 0.005 | 0.003 | 0.005 | 0.014 |  | 0.011 | 0.019 |  | 0.014 | 0.024 |
| 95E/5M | 0.001 | 0.002 | 0.003 | 0.000 | 0.003 | 0.014 |  | 0.013 | 0.024 |  | 0.026 | 0.039 |

## ASTM C1012 Sulfate Mortar Bar Expansion Figures

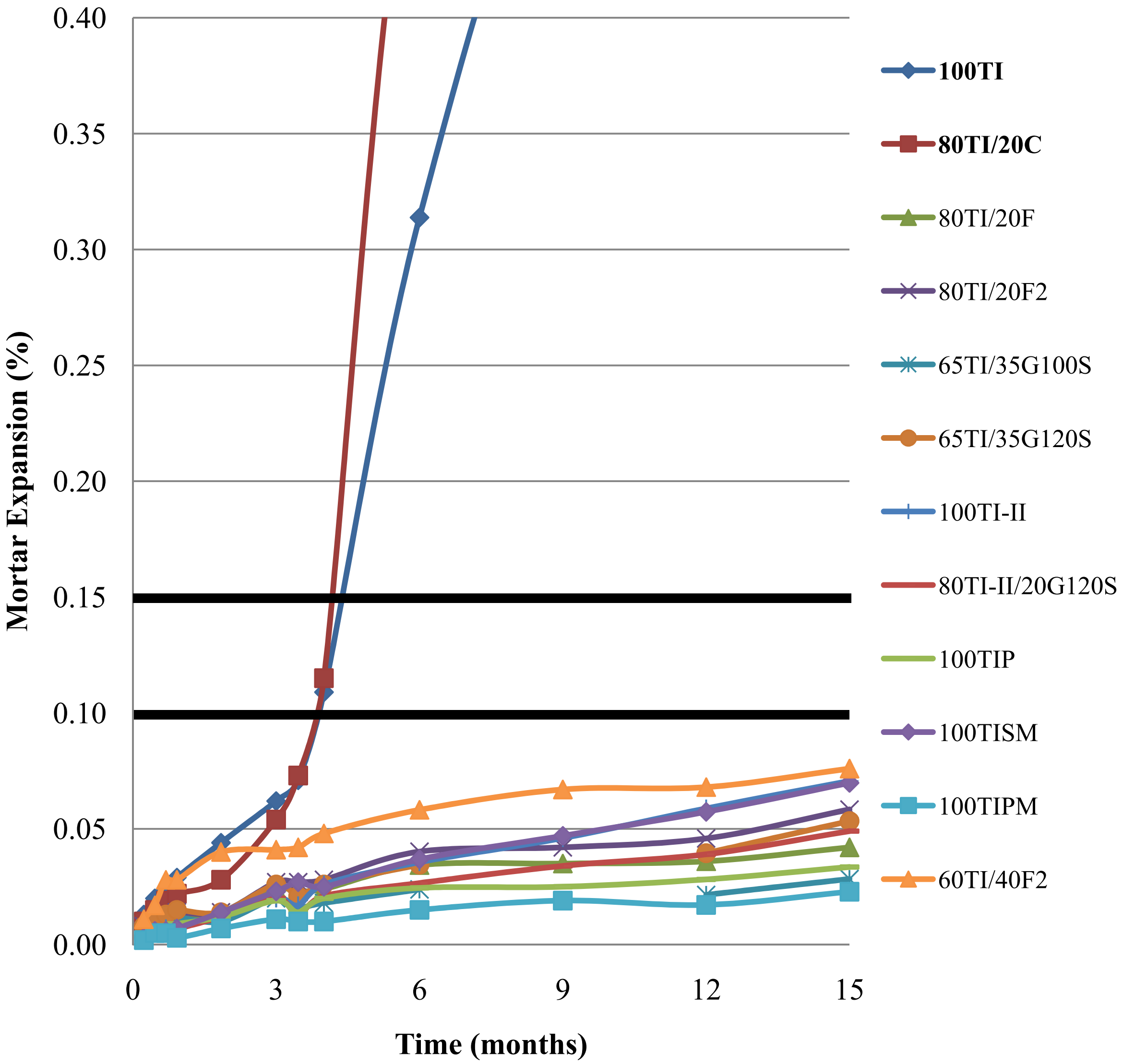

**Figure 53. ASTM C1012 sulfate mortar expansions for control mixtures**

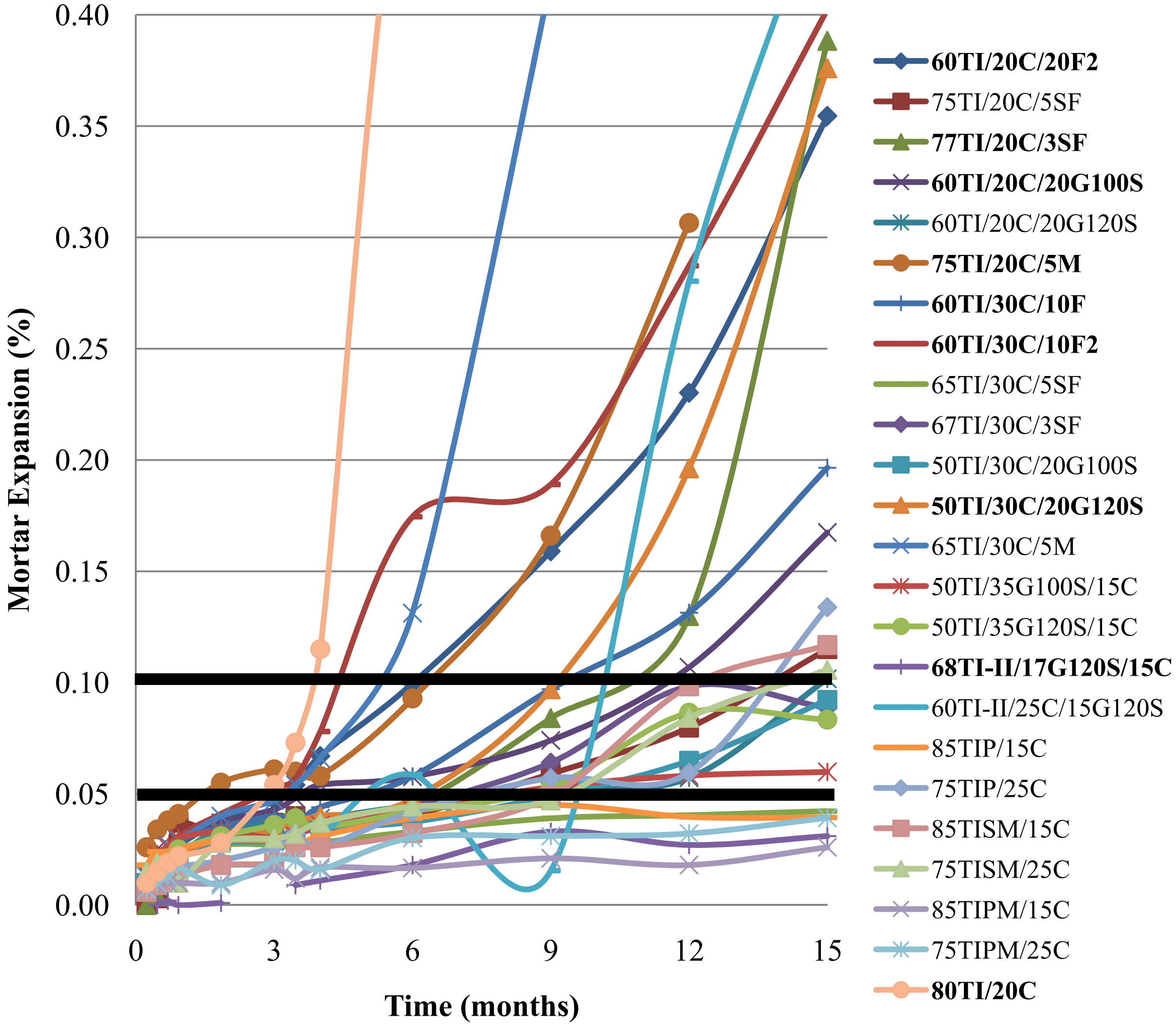

**Figure 54. ASTM C1012 sulfate mortar expansions of mixtures containing Class C fly ash**

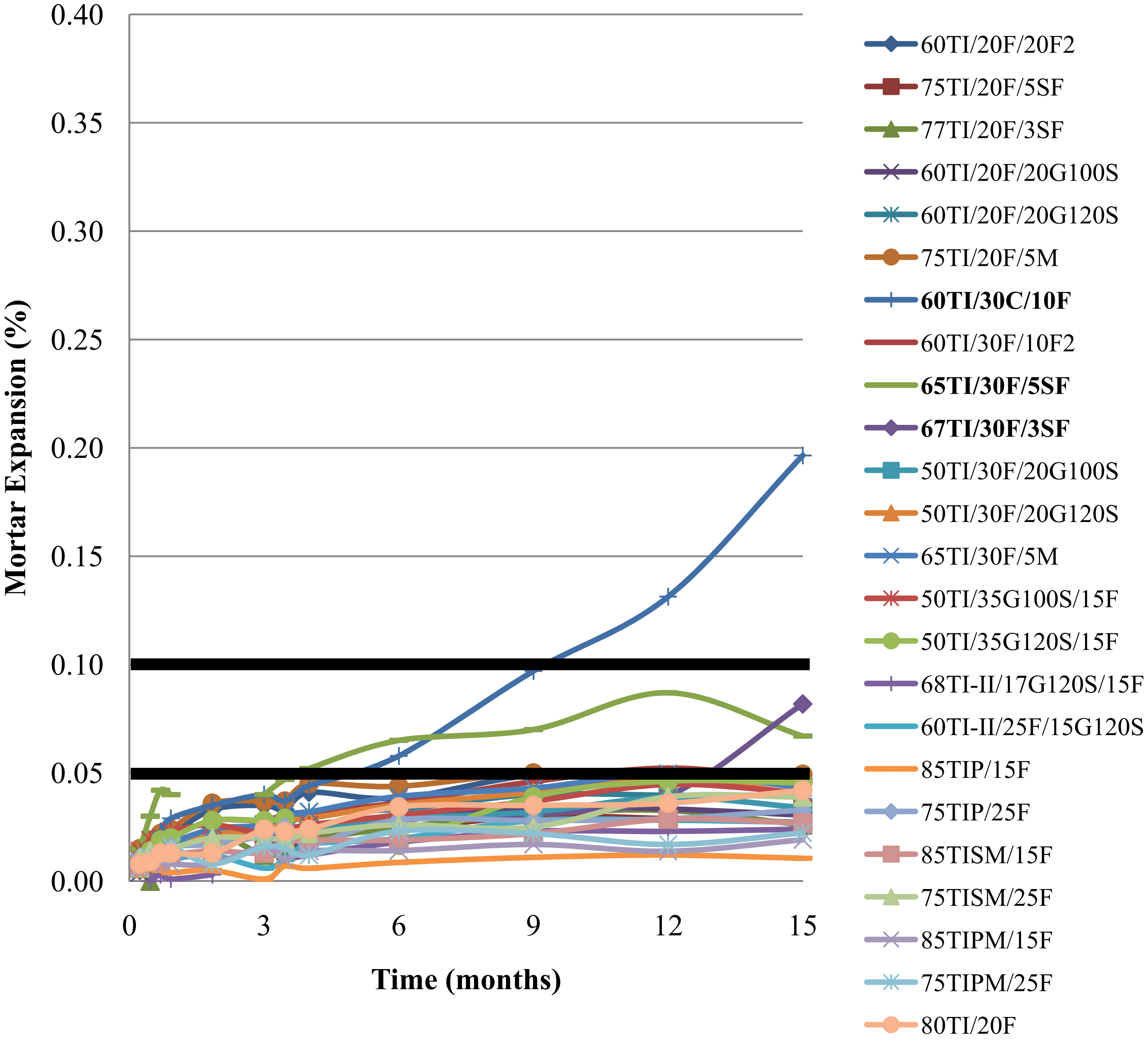

**Figure 55. ASTM C1012 sulfate mortar expansions of mixtures containing Class F fly ash**

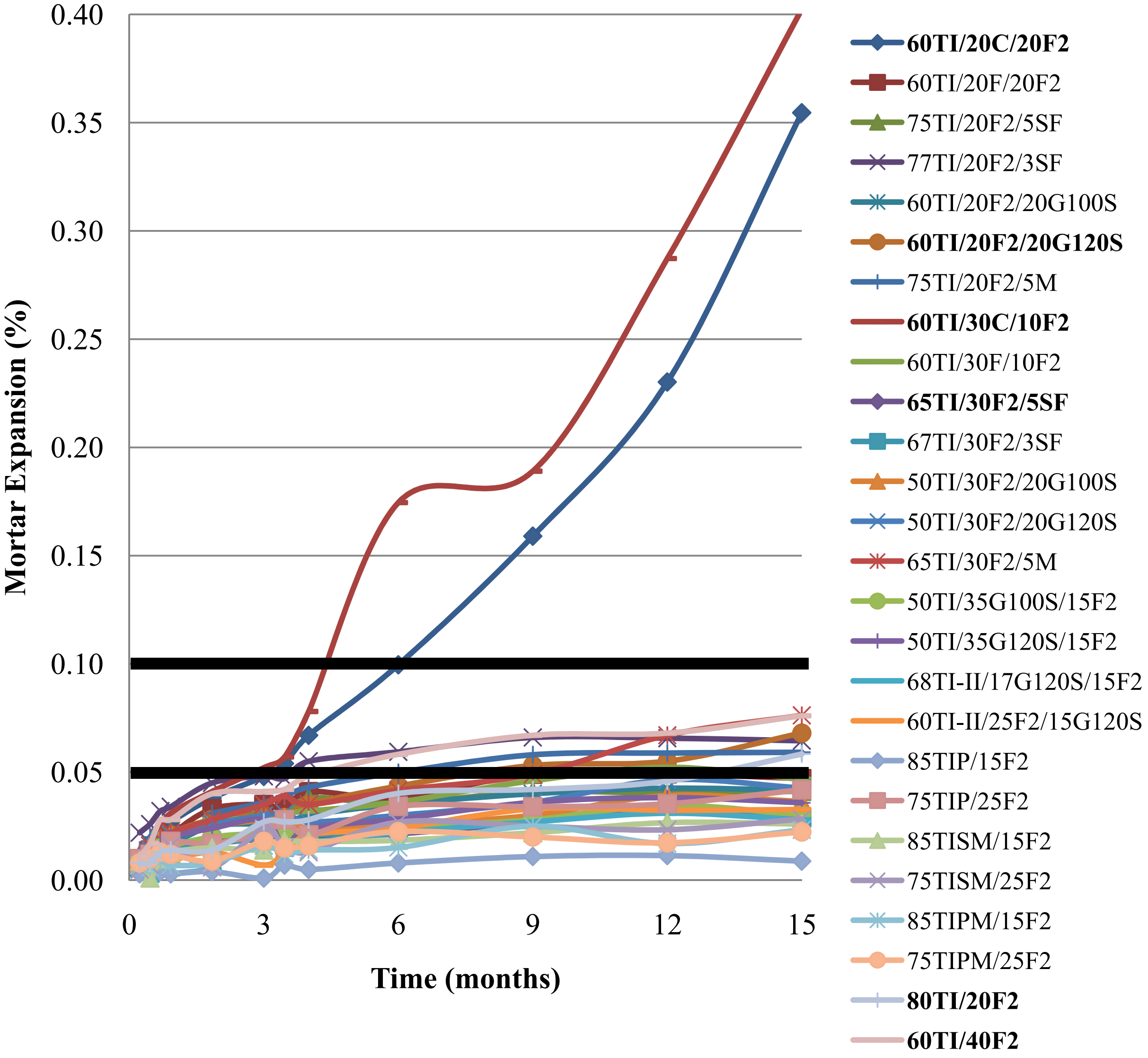

**Figure 56. ASTM C1012 sulfate mortar expansions of mixtures containing Class F2 fly ash**

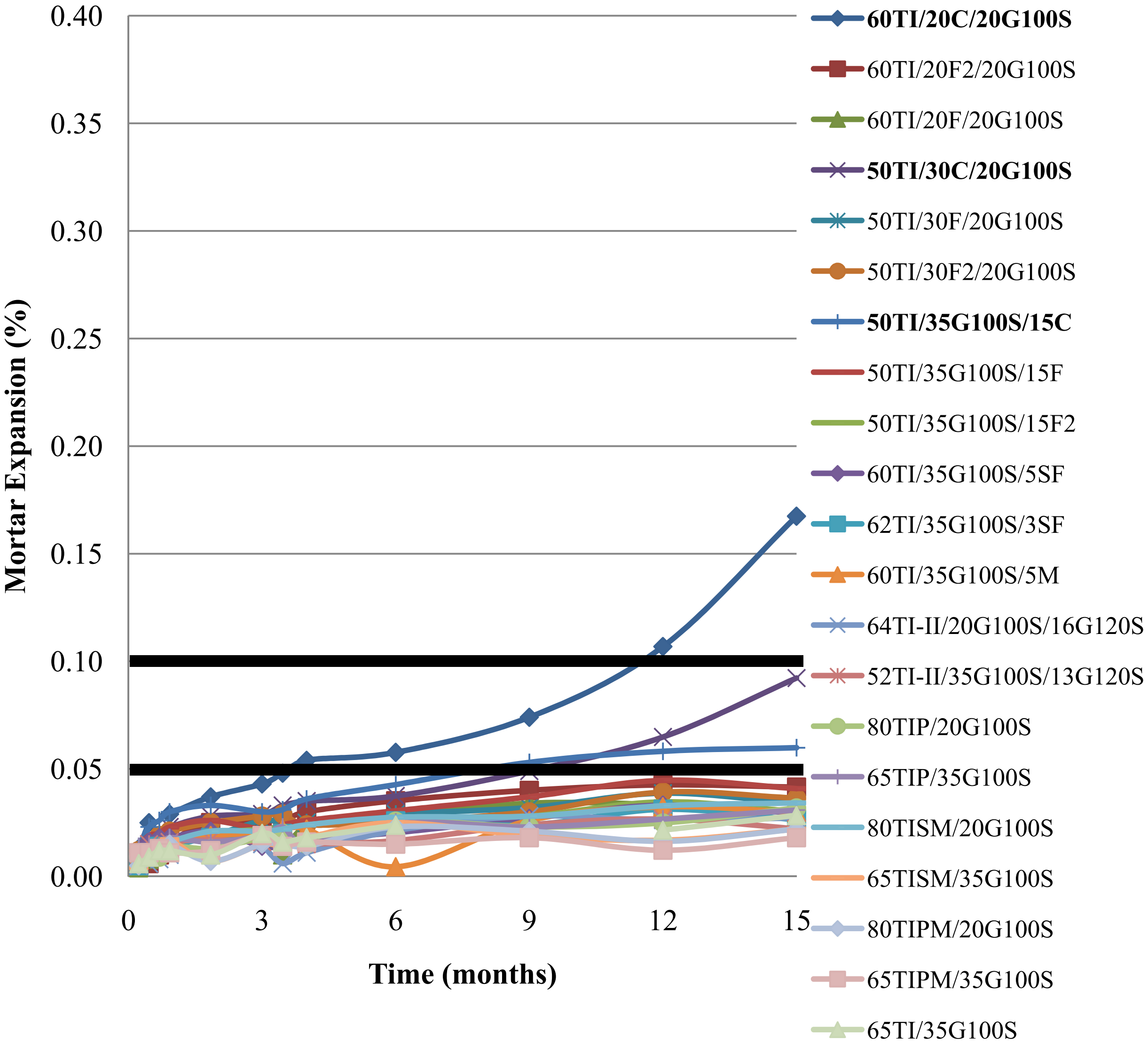

**Figure 57. ASTM C1012 sulfate mortar expansions of mixtures containing Grade 100 GGBFS**

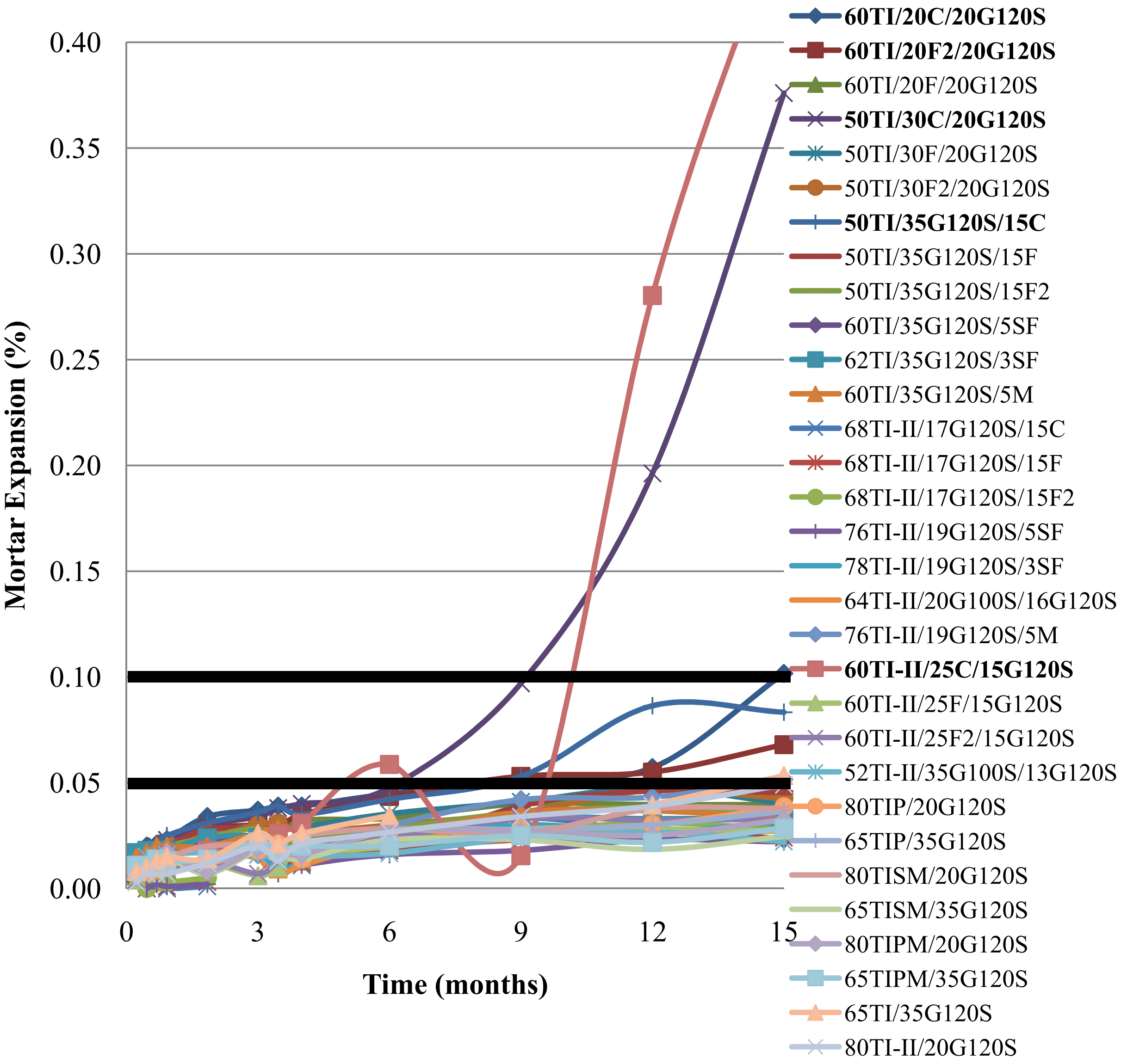

Figure 58. ASTM C1012 sulfate mortar expansions of mixtures containing Grade 120 GGBFS

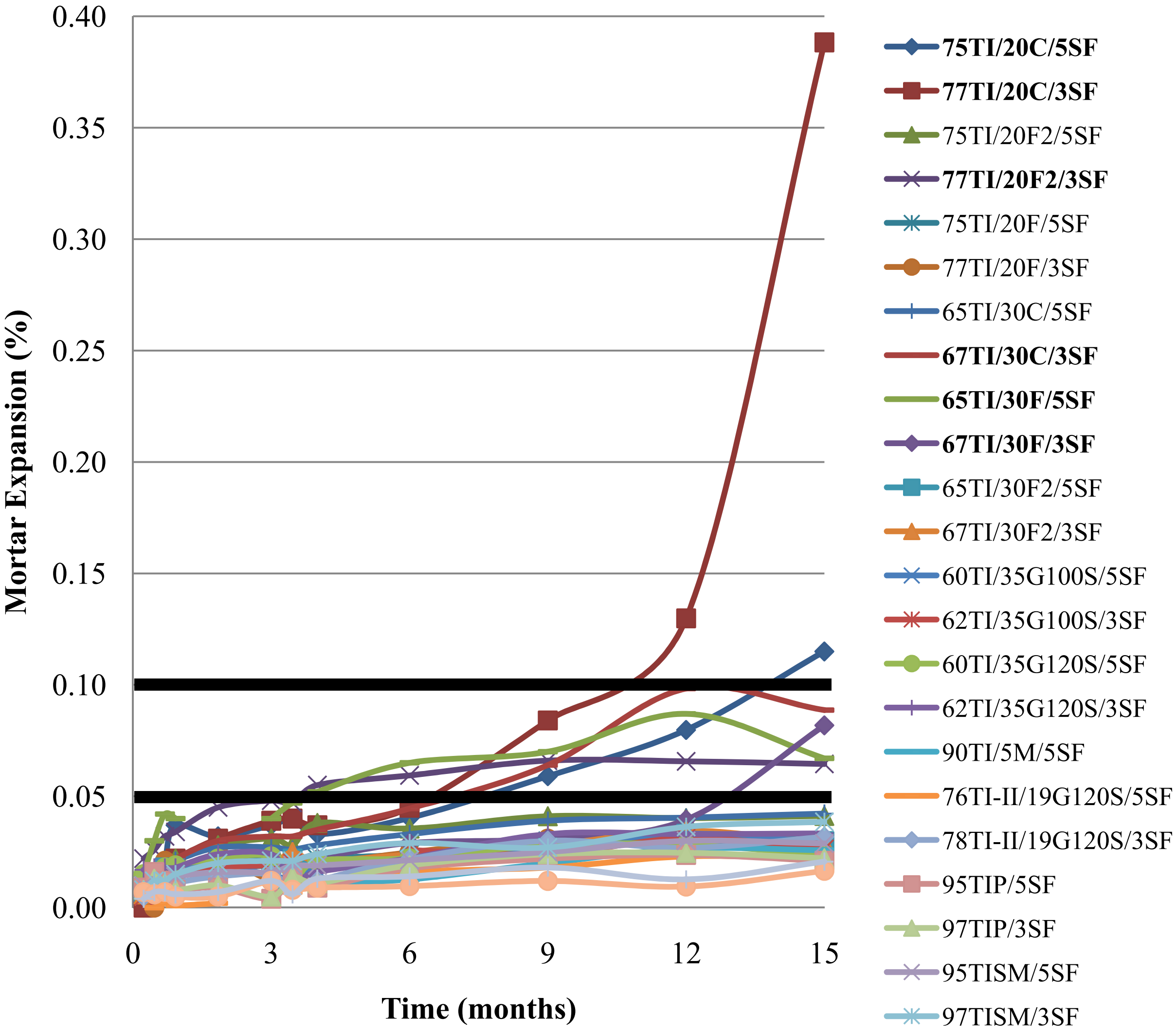

**Figure 59. ASTM C1012 sulfate mortar expansions of mixtures containing silica fume**

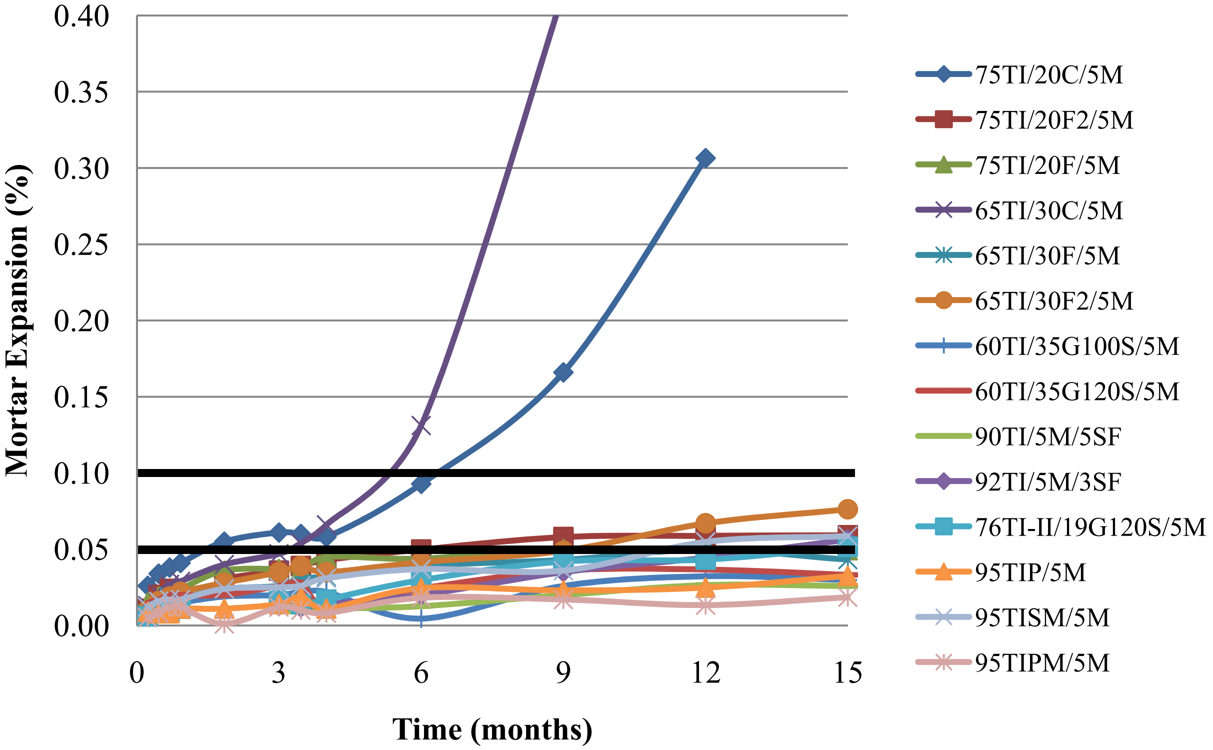

**Figure 60. ASTM C1012 Sulfate Mortar Expansions of Mixtures Containing Metakaolin**

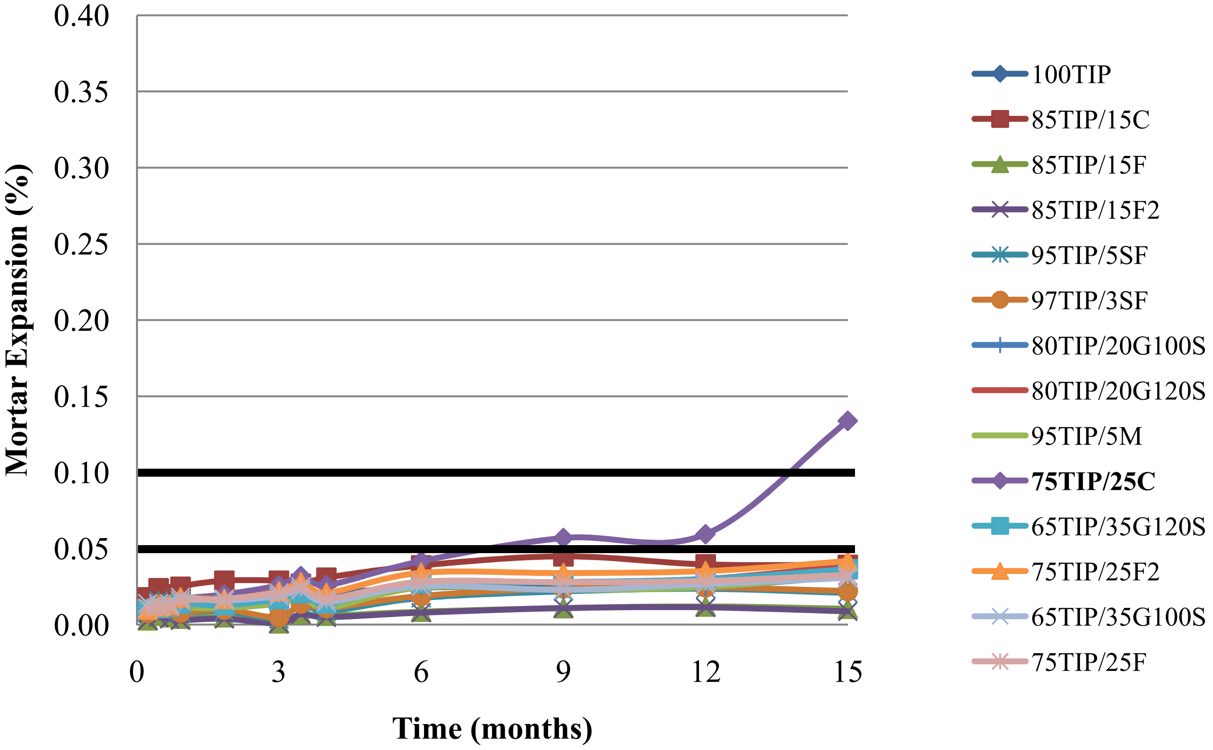

**Figure 61. ASTM C1012 sulfate mortar expansions of mixtures containing TIP cement**

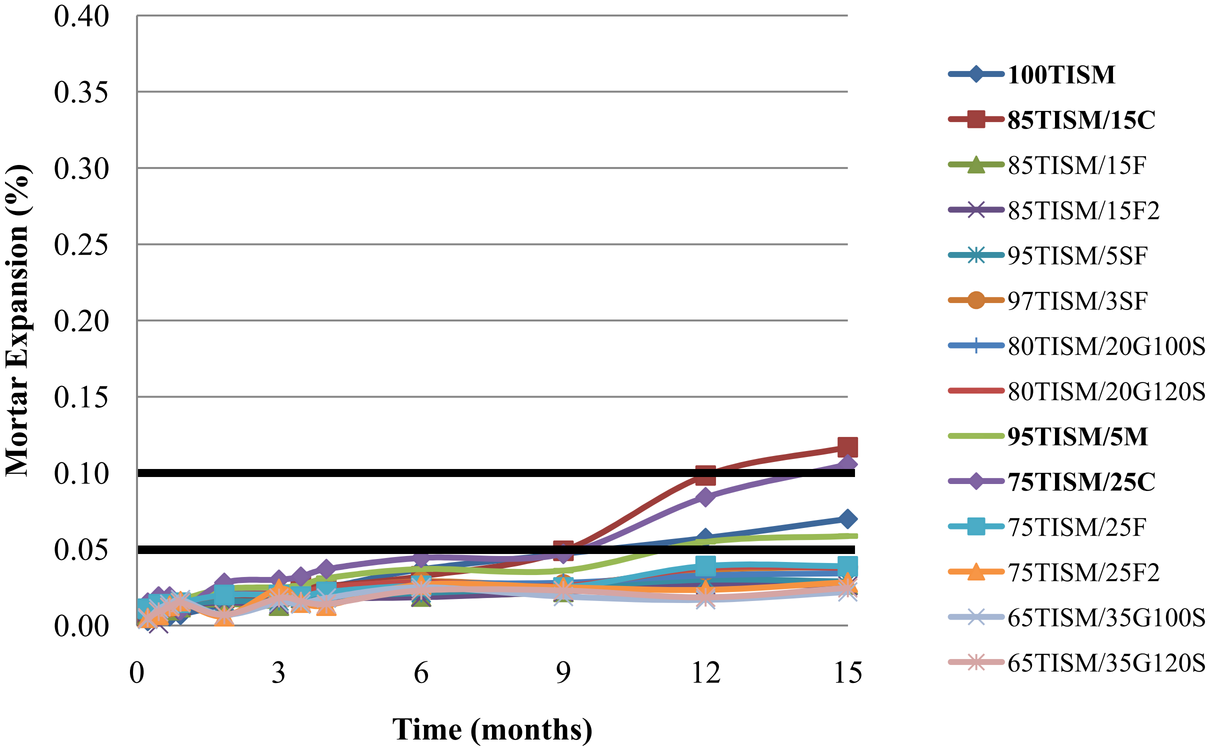

**Figure 62. ASTM C1012 sulfate mortar expansions of mixtures containing Type IS(20) cement**

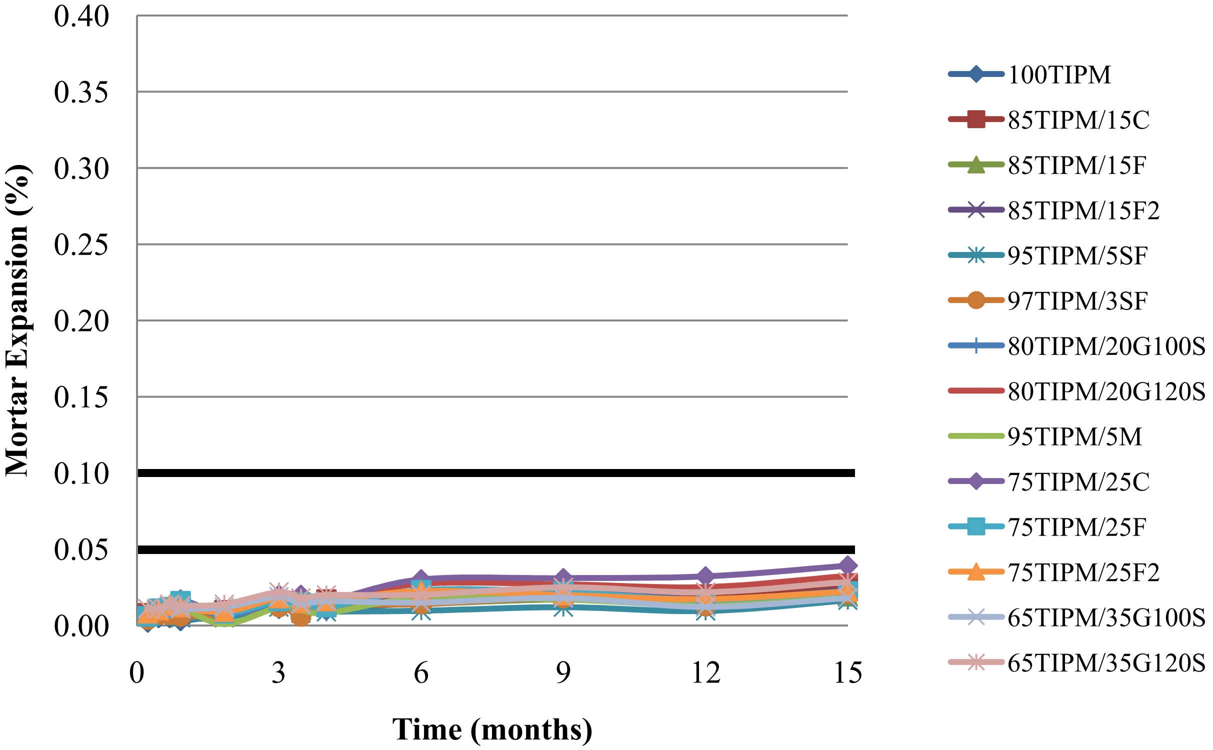

**Figure 63. ASTM C1012 sulfate mortar expansions of mixtures containing Type IP(6) cement**

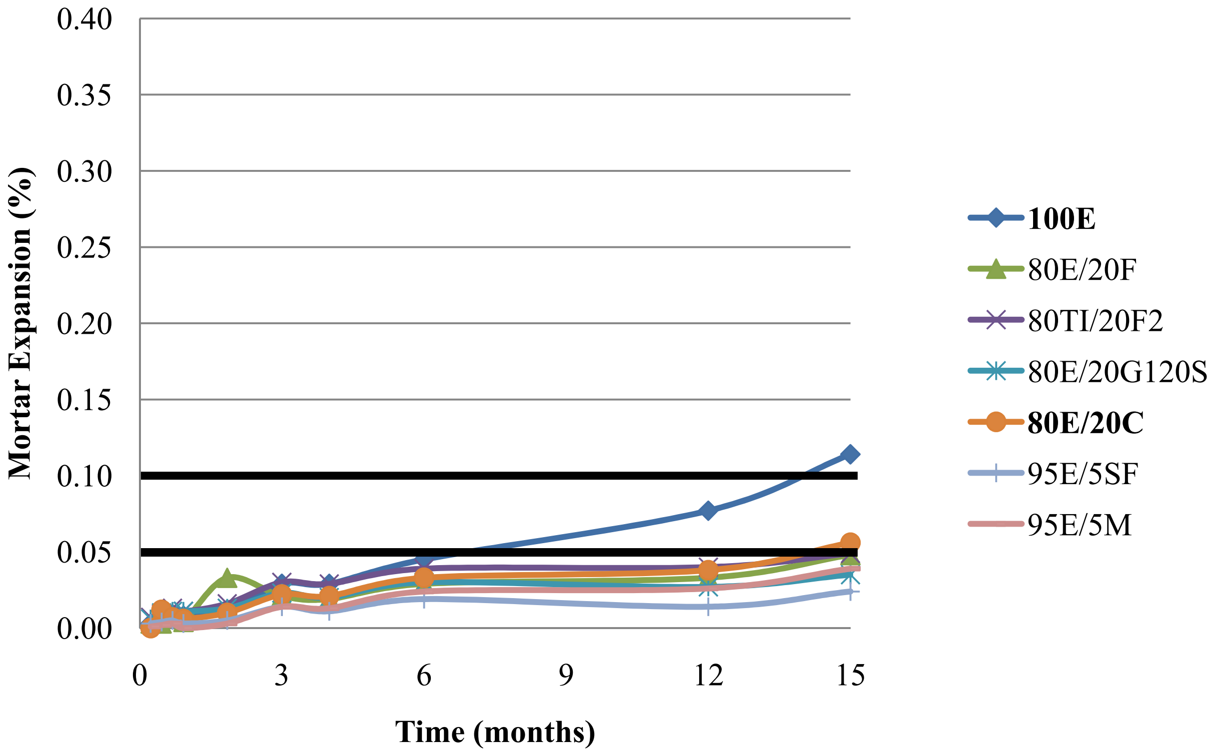

**Figure 64. ASTM C1012 sulfate mortar expansions of mixtures containing limestone blended cement**

### ASTM C1567 ASR Mortar Bar Expansion Tables

**Table 105. ASTM C1567 mortar bar expansions of control mixtures**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 100TI | 0.181 | 0.436 | 0.483 | **0.552** |
| 100TI-II | 0.060 | 0.294 | 0.328 | **0.388** |
| 80TI/20C | 0.113 | 0.425 | 0.460 | **0.512** |
| 80TI/20F | 0.037 | 0.082 | 0.102 | **0.102** |
| 80TI/20F2 | 0.022 | 0.137 | 0.177 | **0.237** |
| 65TI/35G100S** | 0.025 | 0.043 | 0.056 | 0.084 |
| 65TI/35G120S | 0.032 | 0.129 | 0.166 | **0.201** |
| 80TI-II/20G120S | 0.030 | 0.108 | 0.141 | **0.194** |
| 100TIP** | 0.025 | 0.029 | 0.032 | 0.043 |
| 100TISM | 0.028 | 0.088 | 0.113 | **0.168** |
| 100TIPM | 0.028 | 0.047 | 0.065 | **0.115** |
| 100E | 0.258 | 0.338 | 0.573 | **0.623** |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 106. ASTM C1567 mortar bar expansions of mixtures containing Class C fly ash**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 60TI/30C/10F | 0.027 | 0.032 | 0.068 | **0.109** |
| 60TI/20C/20F2** | 0.035 | 0.087 | 0.107 | **0.172** |
| 60TI/30C/10F2 | 0.041 | 0.103 | 0.140 | **0.203** |
| 50TI/35G100S/15C | 0.010 | 0.012 | 0.012 | 0.018 |
| 60TI/20C/20G100S** | 0.039 | 0.058 | 0.076 | **0.116** |
| 50TI/30C/20G100S | 0.030 | 0.033 | 0.040 | 0.039 |
| 50TI/35G120S/15C | 0.018 | 0.027 | 0.030 | 0.032 |
| 60TI/20C/20G120S | 0.046 | 0.134 | 0.165 | **0.257** |
| 50TI/30C/20G120S | 0.030 | 0.037 | 0.053 | 0.061 |
| 68TI-II/17G120S/15C | 0.016 | 0.047 | 0.064 | **0.144** |
| 60TI-II/25C/15G120S | 0.019 | 0.030 | 0.037 | 0.046 |
| 77TI/20C/3SF** | 0.036 | 0.125 | 0.168 | **0.287** |
| 75TI/20C/5SF** | 0.035 | 0.065 | 0.085 | **0.129** |
| 67TI/30C/3SF | 0.049 | 0.093 | 0.153 | **0.252** |
| 65TI/30C/5SF | 0.041 | 0.048 | 0.061 | 0.088 |
| 75TI/20C/5M | 0.044 | 0.167 | 0.204 | **0.307** |
| 65TI/30C/5M | 0.026 | 0.095 | 0.128 | **0.148** |
| 85TIP/15C | 0.010 | 0.016 | 0.017 | **0.100** |
| 75TIP/25C | 0.006 | 0.010 | 0.009 | 0.038 |
| 85TISM/15C | 0.044 | 0.034 | 0.073 | 0.085 |
| 75TISM/25C | 0.026 | 0.036 | 0.044 | 0.057 |
| 85TIPM/15C | 0.018 | 0.021 | 0.034 | 0.042 |
| 75TIPM/25C | 0.007 | 0.009 | 0.014 | 0.022 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 107. ASTM C1567 mortar bar expansions of mixtures containing Class F fly ash**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 60TI/30C/10F | 0.027 | 0.032 | 0.068 | **0.109** |
| 60TI/20F/20F2 | 0.014 | 0.038 | 0.040 | 0.043 |
| 60TI/30F/10F2 | 0.041 | 0.042 | 0.044 | 0.049 |
| 50TI/35G100S/15F | 0.030 | 0.030 | 0.036 | 0.034 |
| 60TI/20F/20G100S | 0.016 | 0.012 | 0.031 | 0.034 |
| 50TI/30F/20G100S | 0.030 | 0.031 | 0.035 | 0.039 |
| 50TI/35G120S/15F | 0.021 | 0.026 | 0.030 | 0.029 |
| 60TI/20F/20G120S | 0.023 | 0.008 | 0.003 | 0.019 |
| 50TI/30F/20G120S | 0.025 | 0.026 | 0.031 | 0.035 |
| 68TI-II/17G120S/15F | 0.023 | 0.026 | 0.030 | 0.041 |
| 60TI-II/25F/15G120S | 0.024 | 0.031 | 0.018 | 0.033 |
| 77TI/20F/3SF | 0.016 | 0.018 | 0.032 | 0.039 |
| 75TI/20F/5SF | 0.019 | 0.021 | 0.041 | 0.055 |
| 67TI/30F/3SF | 0.051 | 0.053 | 0.052 | 0.055 |
| 65TI/30F/5SF | 0.044 | 0.049 | 0.045 | 0.049 |
| 75TI/20F/5M | 0.021 | 0.011 | 0.030 | 0.027 |
| 65TI/30F/5M | 0.023 | 0.025 | 0.030 | 0.038 |
| 85TIP/15F | 0.009 | 0.018 | 0.007 | 0.015 |
| 75TIP/25F | 0.032 | 0.016 | 0.044 | 0.054 |
| 85TISM/15F | 0.041 | 0.021 | 0.049 | 0.059 |
| 75TISM/25F | 0.035 | 0.040 | 0.047 | 0.051 |
| 85TIPM/15F | 0.020 | 0.021 | 0.023 | 0.031 |
| 75TIPM/25F | 0.001 | 0.003 | 0.006 | 0.012 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 108. ASTM C1567 mortar bar expansions of mixtures containing Class F2 fly ash**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 60TI/30C/10F2 | 0.041 | 0.103 | 0.140 | **0.203** |
| 60TI/20C/20F2** | 0.035 | 0.087 | 0.107 | **0.172** |
| 60TI/30F/10F2 | 0.041 | 0.042 | 0.044 | 0.049 |
| 60TI/20F/20F2 | 0.014 | 0.038 | 0.040 | 0.043 |
| 50TI/35G100S/15F2 | 0.028 | 0.032 | 0.038 | 0.037 |
| 60TI/20F2/20G100S | 0.010 | 0.019 | 0.039 | 0.051 |
| 50TI/30F2/20G100S | 0.019 | 0.022 | 0.025 | 0.025 |
| 50TI/35G120S/15F2 | 0.026 | 0.035 | 0.041 | 0.045 |
| 60TI/20F2/20G120S | 0.010 | 0.025 | 0.047 | 0.073 |
| 50TI/30F2/20G120S | 0.022 | 0.025 | 0.027 | 0.031 |
| 68TI-II/17G120S/15F2 | 0.030 | 0.042 | 0.039 | 0.052 |
| 60TI-II/25F2/15G120S | 0.036 | 0.041 | 0.034 | 0.050 |
| 77TI/20F2/3SF | 0.030 | 0.052 | 0.053 | 0.067 |
| 75TI/20F2/5SF | 0.022 | 0.045 | 0.044 | 0.044 |
| 67TI/30F2/3SF | 0.029 | 0.034 | 0.041 | 0.042 |
| 65TI/30F2/5SF | 0.028 | 0.032 | 0.038 | 0.036 |
| 75TI/20F2/5M | 0.016 | 0.041 | 0.076 | **0.164** |
| 65TI/30F2/5M | 0.019 | 0.025 | 0.032 | 0.044 |
| 85TIP/15F2 | 0.007 | 0.014 | 0.009 | 0.020 |
| 75TIP/25F2 | 0.002 | 0.000 | 0.003 | 0.013 |
| 85TISM/15F2 | 0.043 | 0.023 | 0.047 | 0.059 |
| 75TISM/25F2 | 0.030 | 0.036 | 0.046 | 0.050 |
| 85TIPM/15F2 | 0.017 | 0.018 | 0.021 | 0.030 |
| 75TIPM/25F2 | 0.009 | 0.007 | 0.010 | 0.020 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 109. ASTM C1567 mortar bar expansions of mixtures containing Grade 100 GGBFS**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 60TI/20C/20G100S** | 0.039 | 0.058 | 0.076 | **0.116** |
| 50TI/30C/20G100S | 0.030 | 0.033 | 0.040 | 0.039 |
| 50TI/35G100S/15C | 0.010 | 0.012 | 0.012 | 0.018 |
| 60TI/20F/20G100S | 0.016 | 0.012 | 0.031 | 0.034 |
| 50TI/30F/20G100S | 0.030 | 0.031 | 0.035 | 0.039 |
| 50TI/35G100S/15F | 0.030 | 0.030 | 0.036 | 0.034 |
| 60TI/20F2/20G100S | 0.010 | 0.019 | 0.039 | 0.051 |
| 50TI/30F2/20G100S | 0.019 | 0.022 | 0.025 | 0.025 |
| 50TI/35G100S/15F2 | 0.028 | 0.032 | 0.038 | 0.037 |
| 64TI-II/20G100S/16G120S | 0.021 | 0.036 | 0.042 | 0.047 |
| 52TI-II/35G100S/13G120S | 0.036 | 0.033 | 0.027 | 0.043 |
| 62TI/35G100S/3SF | 0.021 | 0.020 | 0.023 | 0.021 |
| 60TI/35G100S/5SF | 0.035 | 0.038 | 0.043 | 0.042 |
| 60TI/35G100S/5M | 0.019 | 0.018 | 0.019 | 0.020 |
| 80TIP/20G100S | 0.007 | 0.010 | 0.018 | 0.015 |
| 65TIP/35G100S | 0.011 | 0.000 | 0.008 | 0.023 |
| 80TISM/20G100S | 0.010 | 0.038 | 0.049 | 0.055 |
| 65TISM/35G100S | 0.021 | 0.020 | 0.022 | 0.029 |
| 80TIPM/20G100S | 0.012 | 0.015 | | 0.024 |
| 65TIPM/35G100S | 0.015 | 0.013 | 0.012 | 0.022 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 110. ASTM C1567 mortar bar expansions of mixtures containing Grade 120 GGBFS**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 60TI/20C/20G120S | 0.046 | 0.134 | 0.165 | **0.257** |
| 50TI/30C/20G120S | 0.030 | 0.037 | 0.053 | 0.061 |
| 50TI/35G120S/15C | 0.018 | 0.027 | 0.030 | 0.032 |
| 60TI-II/25C/15G120S | 0.019 | 0.030 | 0.037 | 0.046 |
| 68TI-II/17G120S/15C | 0.016 | 0.047 | 0.064 | **0.144** |
| 60TI/20F/20G120S | 0.023 | 0.008 | 0.003 | 0.019 |
| 50TI/30F/20G120S | 0.025 | 0.026 | 0.031 | 0.035 |
| 50TI/35G120S/15F | 0.021 | 0.026 | 0.030 | 0.029 |
| 60TI-II/25F/15G120S | 0.024 | 0.031 | 0.018 | 0.033 |
| 68TI-II/17G120S/15F | 0.023 | 0.026 | 0.030 | 0.041 |
| 60TI/20F2/20G120S | 0.010 | 0.025 | 0.047 | 0.073 |
| 50TI/30F2/20G120S | 0.022 | 0.025 | 0.027 | 0.031 |
| 50TI/35G120S/15F2 | 0.026 | 0.035 | 0.041 | 0.045 |
| 60TI-II/25F2/15G120S | 0.036 | 0.041 | 0.034 | 0.050 |
| 68TI-II/17G120S/15F2 | 0.030 | 0.042 | 0.039 | 0.052 |
| 52TI-II/35G100S/13G120S | 0.036 | 0.033 | 0.027 | 0.043 |
| 64TI-II/20G100S/16G120S | 0.021 | 0.036 | 0.042 | 0.047 |
| 62TI/35G120S/3SF | 0.033 | 0.041 | 0.046 | 0.049 |
| 60TI/35G120S/5SF | 0.023 | 0.029 | 0.034 | 0.038 |
| 78TI-II/19G120S/3SF | 0.031 | 0.037 | 0.035 | 0.056 |
| 76TI-II/19G120S/5SF | 0.026 | 0.031 | 0.033 | 0.041 |
| 60TI/35G120S/5M | 0.027 | 0.036 | 0.041 | 0.040 |
| 76TI-II/19G120S/5M | 0.019 | 0.030 | 0.035 | 0.043 |
| 80TIP/20G120S | 0.000 | 0.000 | 0.000 | 0.014 |
| 65TIP/35G120S | 0.004 | 0.012 | 0.007 | 0.011 |
| 80TISM/20G120S | 0.015 | 0.040 | 0.054 | 0.060 |
| 65TISM/35G120S | 0.018 | 0.019 | 0.023 | 0.030 |
| 80TIPM/20G120S | 0.005 | 0.009 | | 0.013 |
| 65TIPM/35G120S | 0.024 | 0.026 | 0.027 | 0.035 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 111. ASTM C1567 mortar bar expansions of mixtures containing silica fume**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 77TI/20C/3SF** | 0.036 | 0.125 | 0.168 | **0.287** |
| 67TI/30C/3SF | 0.049 | 0.093 | 0.153 | **0.252** |
| 75TI/20C/5SF** | 0.035 | 0.065 | 0.085 | **0.129** |
| 65TI/30C/5SF | 0.041 | 0.048 | 0.061 | 0.088 |
| 77TI/20F/3SF | 0.016 | 0.018 | 0.032 | 0.039 |
| 67TI/30F/3SF | 0.051 | 0.053 | 0.052 | 0.055 |
| 75TI/20F/5SF | 0.019 | 0.021 | 0.041 | 0.055 |
| 65TI/30F/5SF | 0.044 | 0.049 | 0.045 | 0.049 |
| 77TI/20F2/3SF | 0.030 | 0.052 | 0.053 | 0.067 |
| 67TI/30F2/3SF | 0.029 | 0.034 | 0.041 | 0.042 |
| 75TI/20F2/5SF | 0.022 | 0.045 | 0.044 | 0.044 |
| 65TI/30F2/5SF | 0.028 | 0.032 | 0.038 | 0.036 |
| 62TI/35G100S/3SF | 0.021 | 0.020 | 0.023 | 0.021 |
| 60TI/35G100S/5SF | 0.035 | 0.038 | 0.043 | 0.042 |
| 78TI-II/19G120S/3SF | 0.031 | 0.037 | 0.035 | 0.056 |
| 62TI/35G120S/3SF | 0.033 | 0.041 | 0.046 | 0.049 |
| 76TI-II/19G120S/5SF | 0.026 | 0.031 | 0.033 | 0.041 |
| 60TI/35G120S/5SF | 0.023 | 0.029 | 0.034 | 0.038 |
| 92TI/5M/3SF | 0.014 | 0.034 | 0.043 | 0.067 |
| 90TI/5M/5SF | 0.029 | 0.037 | 0.038 | 0.043 |
| 95TIP/5SF | 0.006 | 0.012 | 0.016 | 0.014 |
| 97TIP/3SF | 0.011 | 0.016 | 0.023 | 0.030 |
| 95TISM/5SF | 0.000 | 0.030 | 0.046 | 0.052 |
| 97TISM/3SF | 0.011 | 0.034 | 0.055 | 0.063 |
| 95TIPM/5SF | 0.029 | 0.027 | 0.032 | 0.036 |
| 97TIPM/3SF | 0.018 | 0.022 | | 0.030 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 112. ASTM C1567 mortar bar expansions of mixtures containing metakaolin**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 75TI/20C/5M | 0.044 | 0.167 | 0.204 | **0.307** |
| 65TI/30C/5M | 0.026 | 0.095 | 0.128 | **0.150** |
| 75TI/20F/5M | 0.021 | 0.011 | 0.030 | 0.027 |
| 65TI/30F/5M | 0.023 | 0.025 | 0.030 | 0.038 |
| 75TI/20F2/5M | 0.016 | 0.041 | 0.076 | b |
| 65TI/30F2/5M | 0.019 | 0.025 | 0.032 | 0.044 |
| 60TI/35G100S/5M | 0.019 | 0.018 | 0.019 | 0.020 |
| 76TI-II/19G120S/5M | 0.019 | 0.030 | 0.035 | 0.043 |
| 60TI/35G120S/5M | 0.027 | 0.036 | 0.041 | 0.040 |
| 92TI/5M/3SF | 0.014 | 0.034 | 0.043 | 0.067 |
| 90TI/5M/5SF | 0.029 | 0.037 | 0.038 | 0.043 |
| 95TIP/5M | 0.000 | 0.000 | 0.002 | 0.018 |
| 95TISM/5M | 0.027 | 0.036 | 0.043 | 0.055 |
| 95TIPM/5M | 0.009 | 0.009 | 0.013 | 0.018 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 113. ASTM C1567 mortar bar expansions of mixtures containing Type IP cement**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 100TIP | 0.025 | 0.029 | 0.032 | 0.043 |
| 85TIP/15C | 0.010 | 0.016 | 0.017 | **0.101** |
| 75TIP/25C | 0.006 | 0.010 | 0.009 | 0.038 |
| 85TIP/15F | 0.009 | 0.018 | 0.007 | 0.015 |
| 75TIP/25F | 0.032 | 0.016 | 0.044 | 0.054 |
| 85TIP/15F2 | 0.007 | 0.014 | 0.009 | 0.020 |
| 75TIP/25F2 | 0.002 | 0.000 | 0.003 | 0.013 |
| 80TIP/20G100S | 0.007 | 0.010 | 0.018 | 0.015 |
| 65TIP/35G100S | 0.011 | 0.000 | 0.008 | 0.023 |
| 80TIP/20G120S | 0.000 | 0.000 | 0.000 | 0.014 |
| 65TIP/35G120S | 0.004 | 0.012 | 0.007 | 0.011 |
| 97TIP/3SF | 0.011 | 0.016 | 0.023 | 0.030 |
| 95TIP/5SF | 0.006 | 0.012 | 0.016 | 0.014 |
| 95TIP/5M | 0.000 | 0.000 | 0.002 | 0.018 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 114. ASTM C1567 mortar bar expansions of mixtures containing Type IS(20) cement**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 100TISM | 0.028 | 0.088 | 0.113 | **0.168** |
| 85TISM/15C | 0.044 | 0.034 | 0.073 | 0.085 |
| 75TISM/25C | 0.026 | 0.036 | 0.044 | 0.057 |
| 85TISM/15F | 0.041 | 0.021 | 0.049 | 0.059 |
| 75TISM/25F | 0.035 | 0.040 | 0.047 | 0.051 |
| 85TISM/15F2 | 0.043 | 0.023 | 0.047 | 0.059 |
| 75TISM/25F2 | 0.030 | 0.036 | 0.046 | 0.050 |
| 80TISM/20G100S | 0.010 | 0.038 | 0.049 | 0.055 |
| 65TISM/35G100S | 0.021 | 0.020 | 0.022 | 0.029 |
| 80TISM/20G120S | 0.015 | 0.040 | 0.054 | 0.060 |
| 65TISM/35G120S | 0.018 | 0.019 | 0.023 | 0.030 |
| 97TISM/3SF | 0.011 | 0.034 | 0.055 | 0.063 |
| 95TISM/5SF | 0.000 | 0.030 | 0.046 | 0.052 |
| 95TISM/5M | 0.027 | 0.036 | 0.043 | 0.055 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 115. ASTM C1567 mortar bar expansions of mixtures containing Type IP(6) cement**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 100TIPM | 0.028 | 0.047 | 0.065 | **0.115** |
| 85TIPM/15C | 0.018 | 0.021 | 0.034 | 0.042 |
| 75TIPM/25C | 0.007 | 0.009 | 0.014 | 0.022 |
| 85TIPM/15F | 0.020 | 0.021 | 0.023 | 0.031 |
| 75TIPM/25F | 0.001 | 0.003 | 0.006 | 0.012 |
| 85TIPM/15F2 | 0.017 | 0.018 | 0.021 | 0.030 |
| 75TIPM/25F2 | 0.009 | 0.007 | 0.010 | 0.018 |
| 80TIPM/20G100S | 0.012 | 0.015 | | 0.024 |
| 65TIPM/35G100S | 0.015 | 0.013 | 0.012 | 0.022 |
| 80TIPM/20G120S | 0.005 | 0.009 | | 0.013 |
| 65TIPM/35G120S | 0.024 | 0.026 | 0.027 | 0.035 |
| 97TIPM/3SF | 0.018 | 0.022 | | 0.030 |
| 95TIPM/5SF | 0.029 | 0.027 | 0.032 | 0.036 |
| 95TIPM/5M | 0.009 | 0.009 | 0.013 | 0.018 |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

**Table 116. ASTM C1567 mortar bar expansions of mixtures containing limestone blended cement**

| | Mortar Bar Expansion (%)* | | | |
|---|---|---|---|---|
| Mixture ID | Day 2 | Day 7 | Day 9 | Day 14 |
| 100E** | 0.258 | 0.338 | 0.573 | **0.623** |
| 80E/20C** | 0.032 | 0.063 | 0.211 | **0.262** |
| 80E/20F** | 0.024 | 0.031 | 0.037 | 0.049 |
| 80E/20F2** | 0.021 | 0.026 | 0.036 | 0.043 |
| 80E/20G120S** | 0.016 | 0.016 | 0.035 | 0.052 |
| 95E/5SF** | 0.014 | 0.012 | 0.033 | 0.060 |
| 95E/5M** | 0.025 | 0.036 | 0.116 | **0.156** |

* **Bolded** values exceed the allowable 0.100% expansion at 14-days.

** Specimens tested at 4, 7, 11, and 14 days.

## ASTM C1567 ASR Mortar Bar Expansion Figures

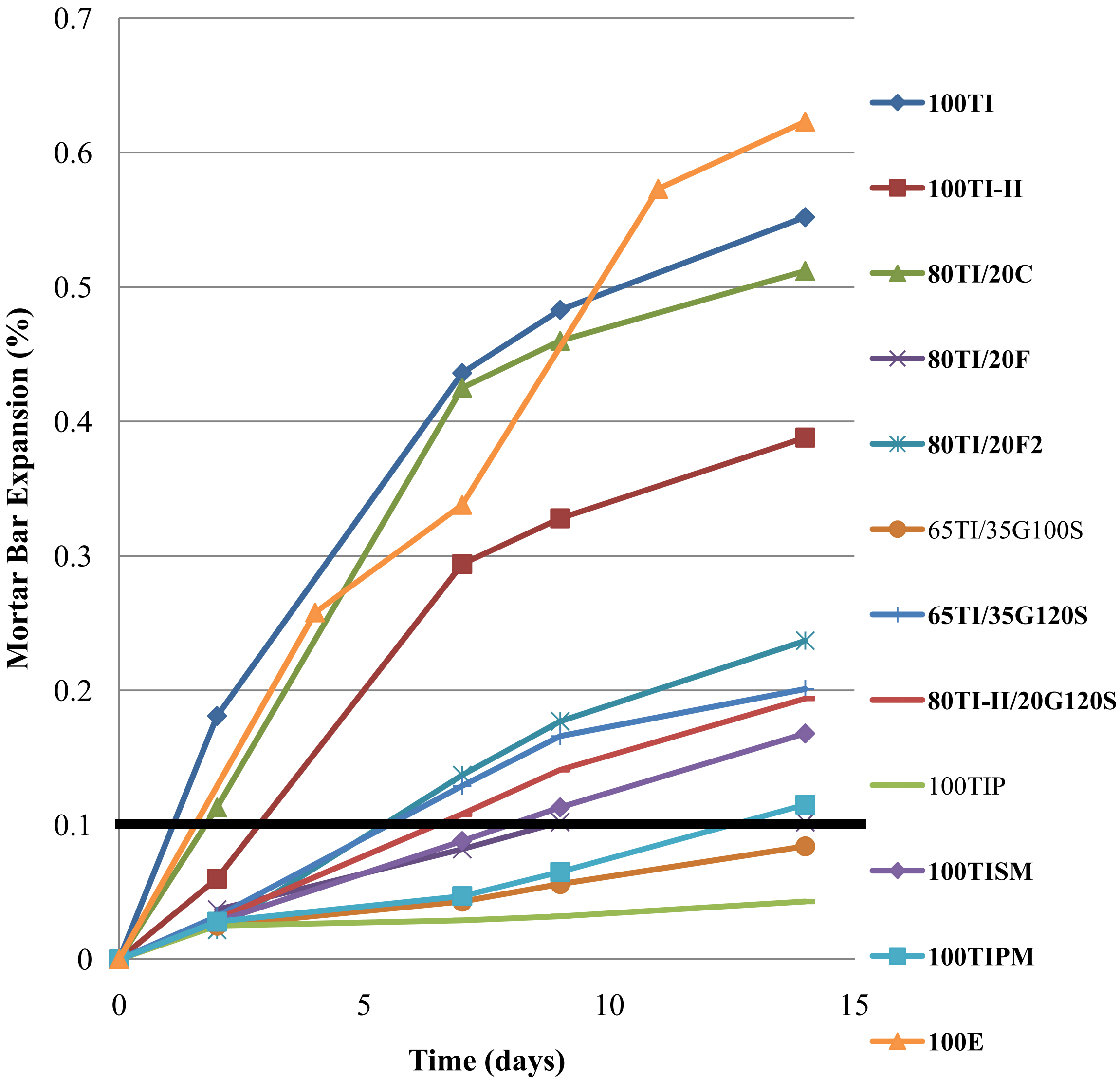

Figure 65. ASTM C1567 ASR mortar expansions of control mixtures

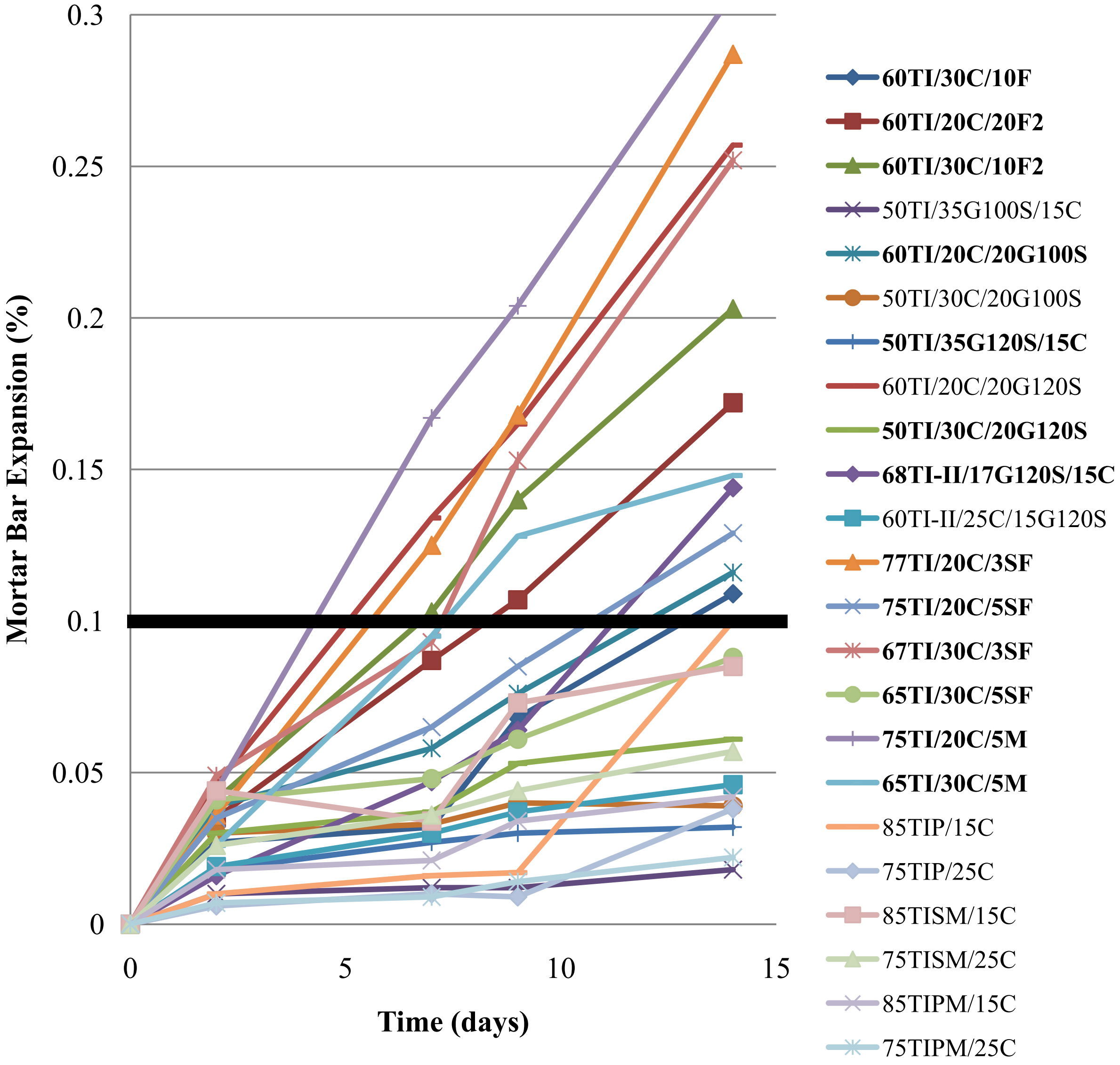

**Figure 66. ASTM C1567 ASR mortar expansions of mixtures containing Class C fly ash**

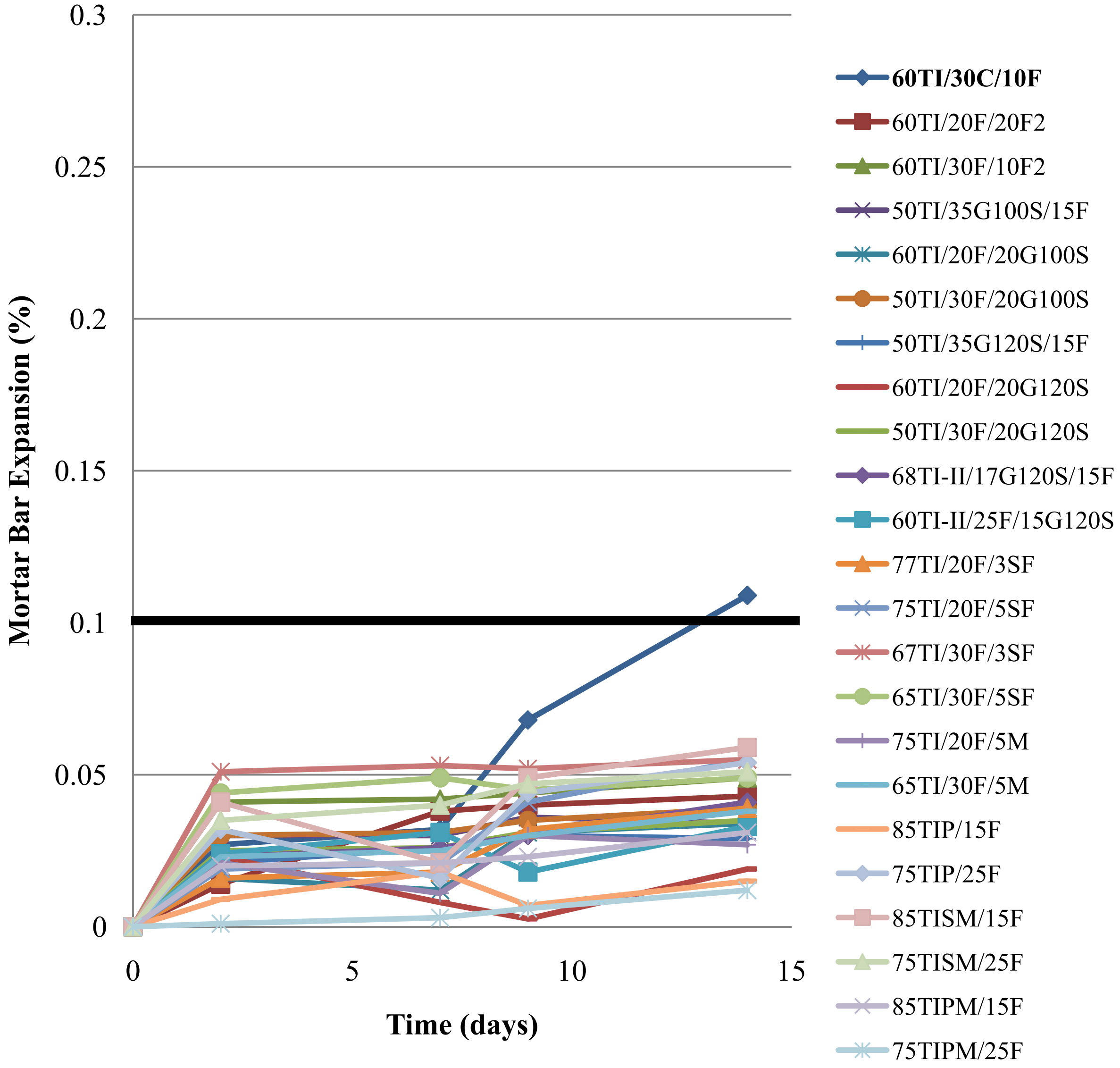

**Figure 67. ASTM C1567 ASR mortar expansions of mixtures containing Class F fly ash**

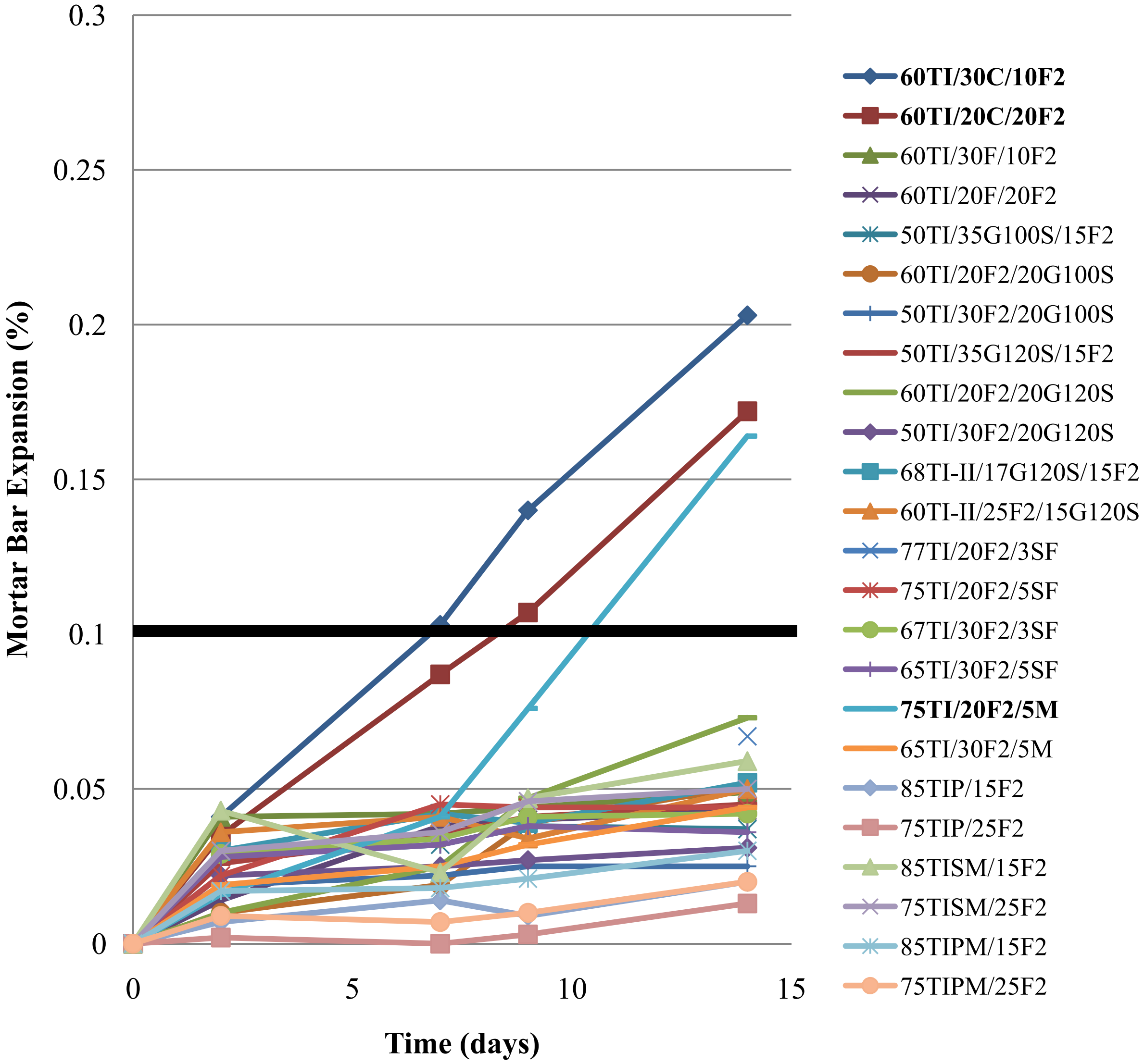

**Figure 68. ASTM C1567 ASR mortar expansions of mixtures containing Class F2 fly ash**

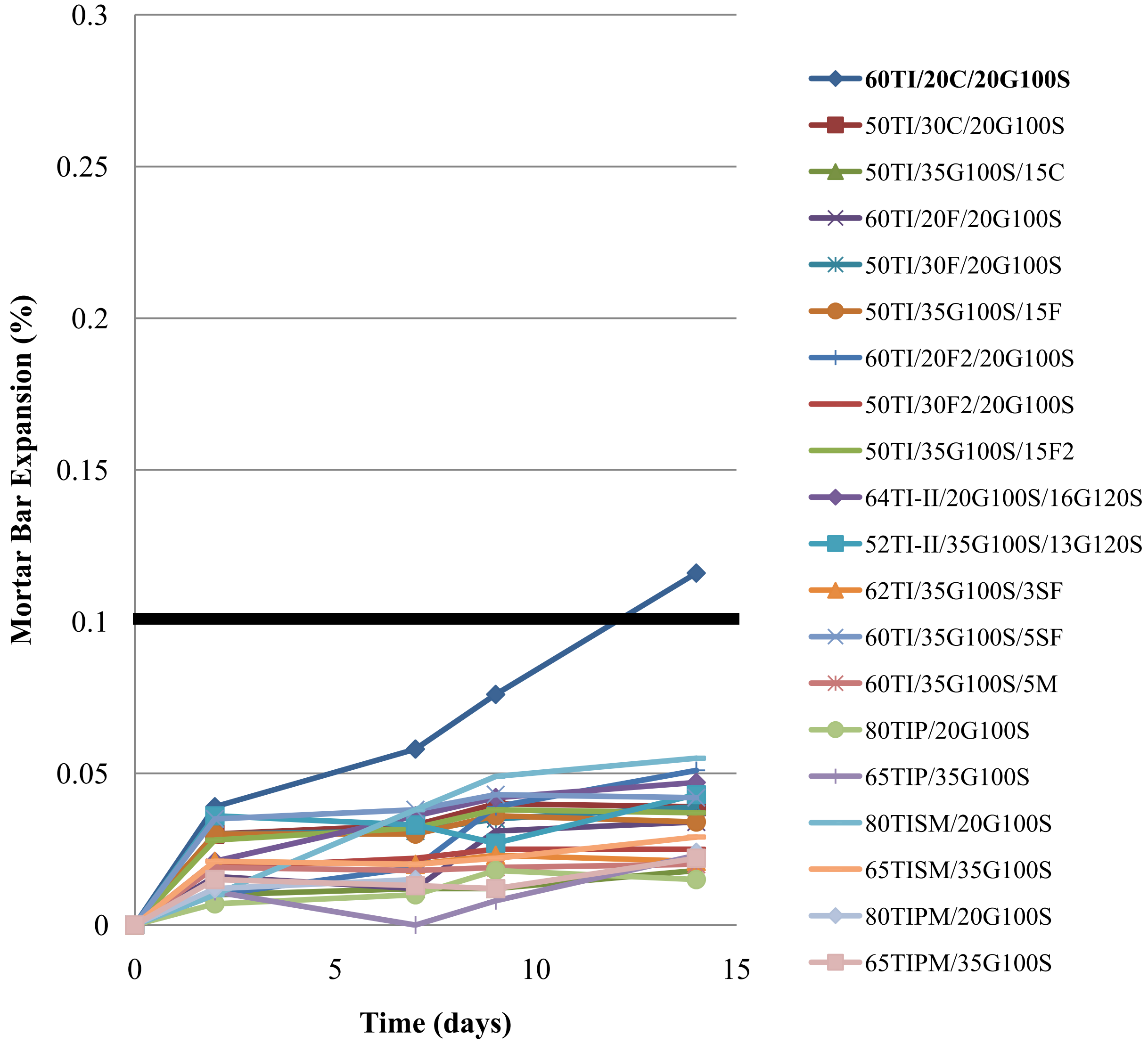

**Figure 69. ASTM C1567 ASR mortar expansions of mixtures containing Grade 100 GGBFS**

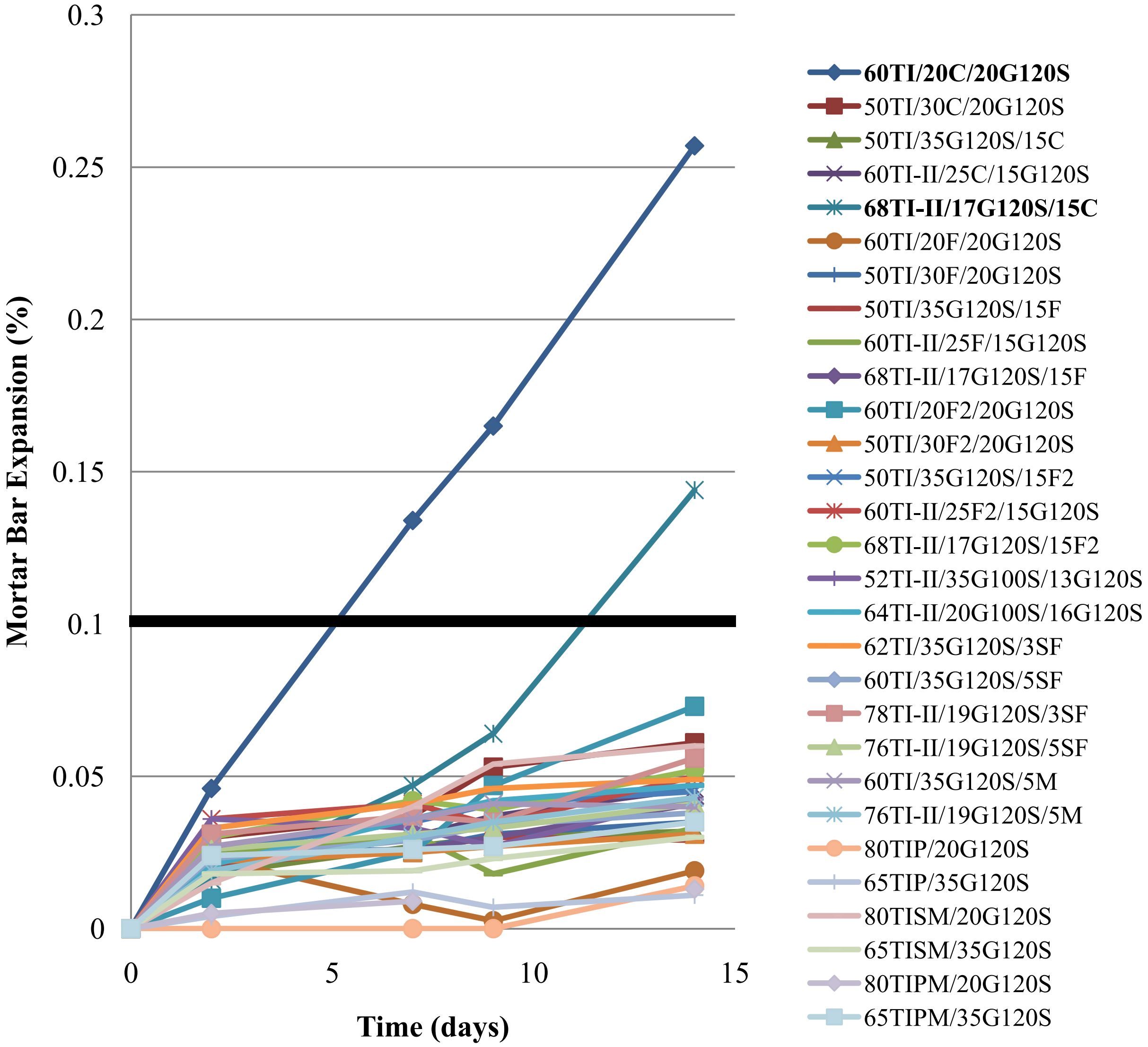

**Figure 70. ASTM C1567 ASR mortar expansions of mixtures containing Grade 120 GGBFS**

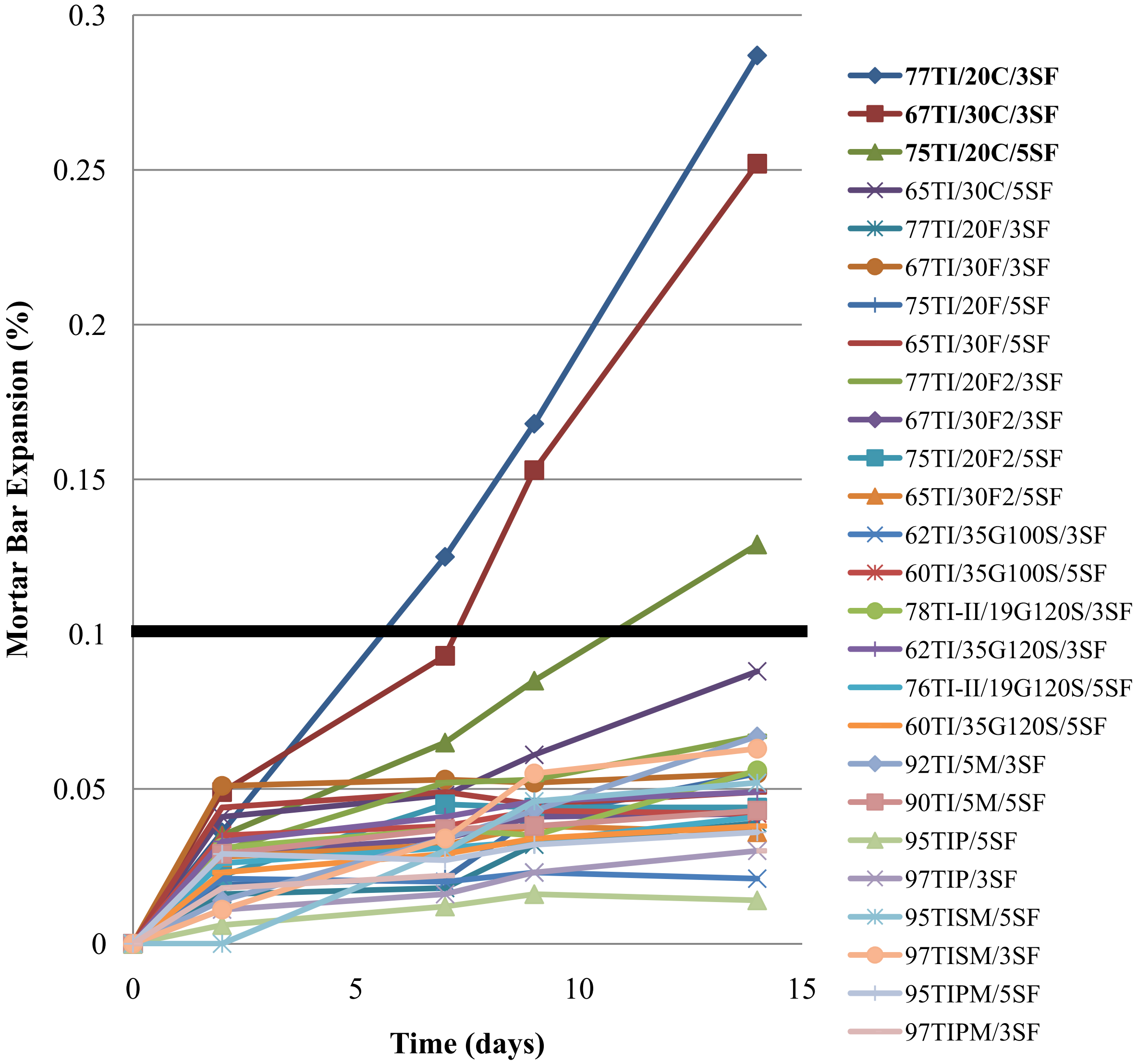

**Figure 71. ASTM C1567 ASR mortar expansions of mixtures containing silica fume**

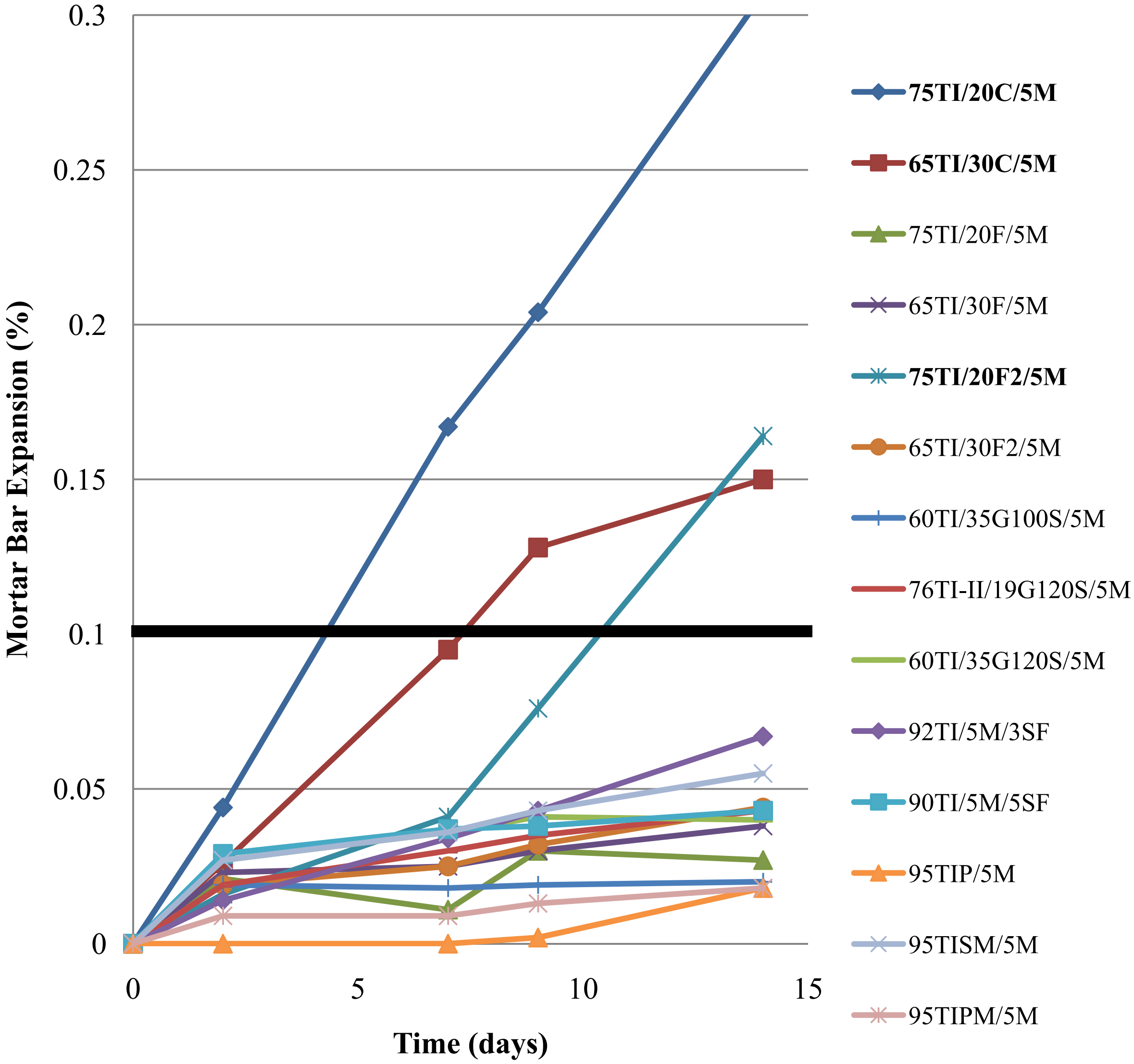

**Figure 72. ASTM C1567 ASR mortar expansions of mixtures containing metakaolin**

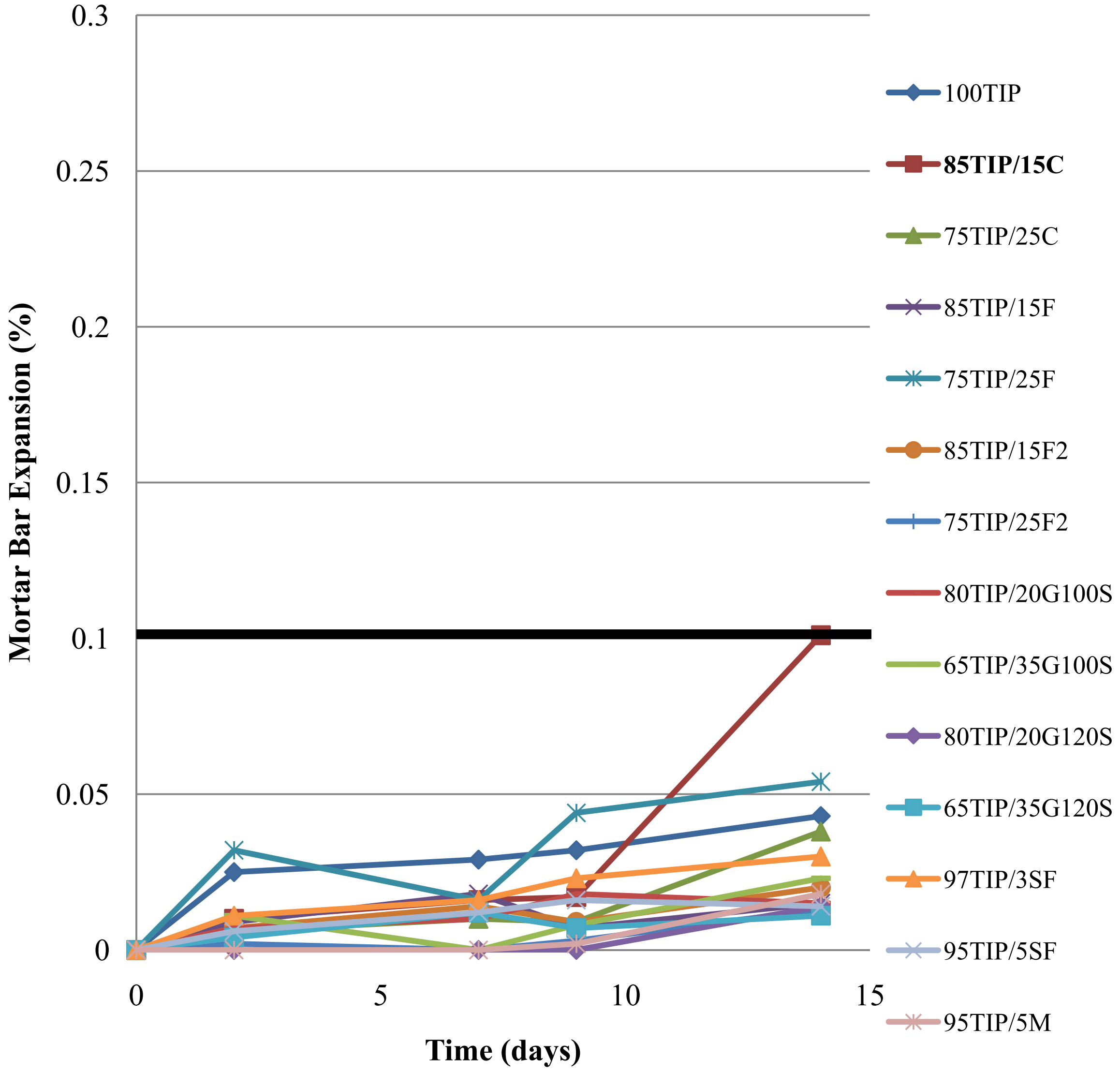

**Figure 73. ASTM C1567 ASR mortar expansions of mixtures containing Type IP cement**

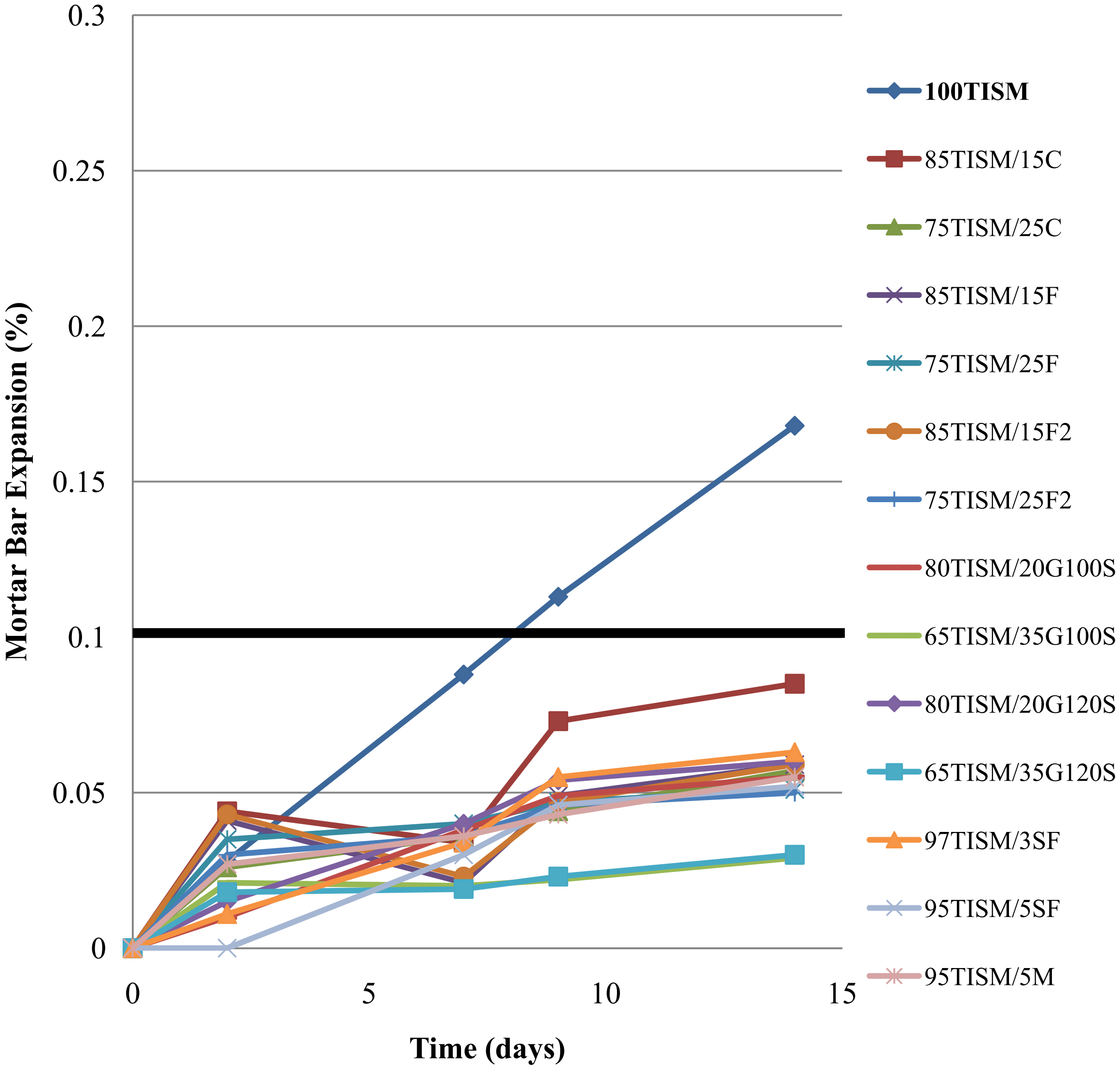

**Figure 74. ASTM C1567 ASR mortar expansions of mixtures containing Type IS(20) cement**

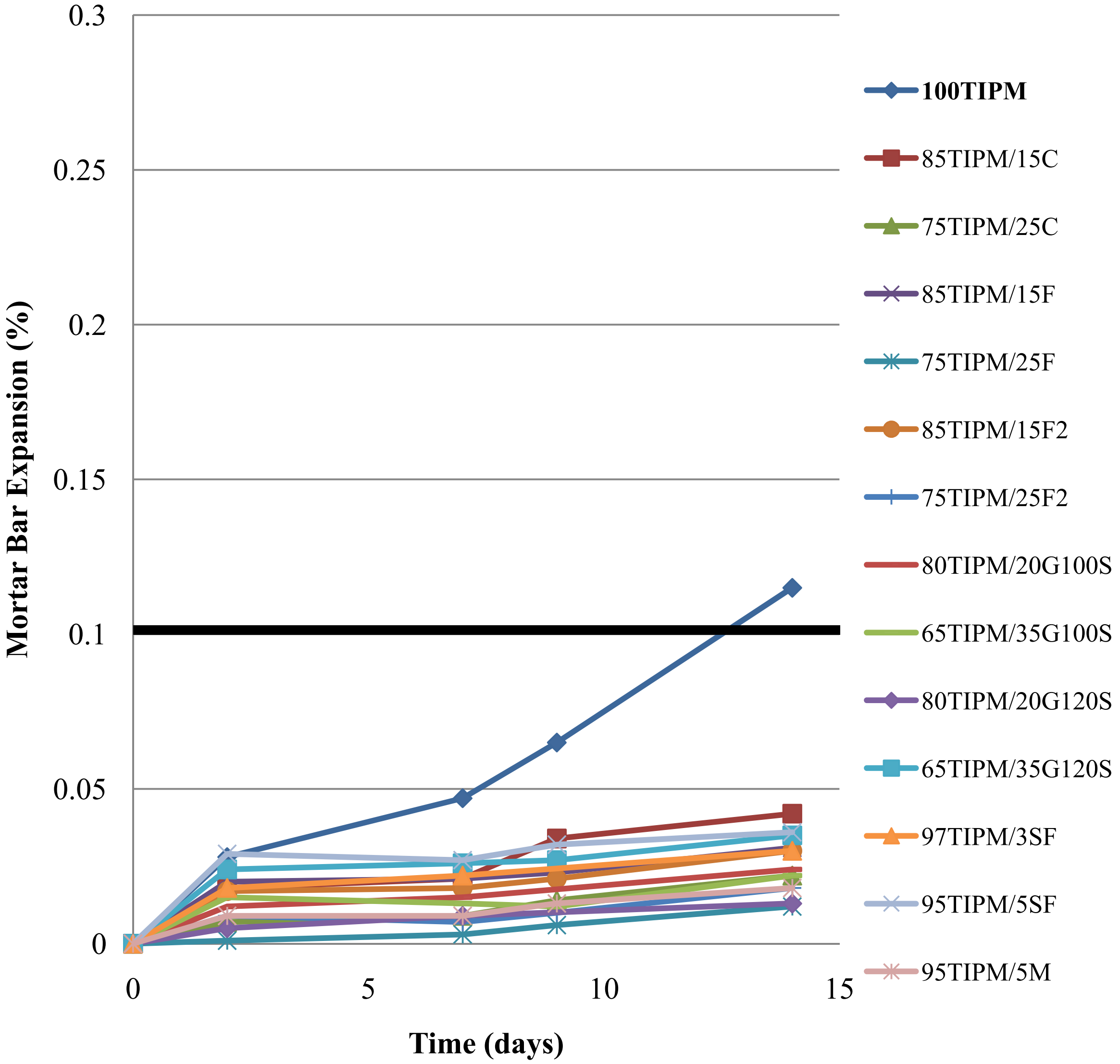

Figure 75. ASTM C1567 ASR mortar expansions of mixtures containing Type IP(6) cement

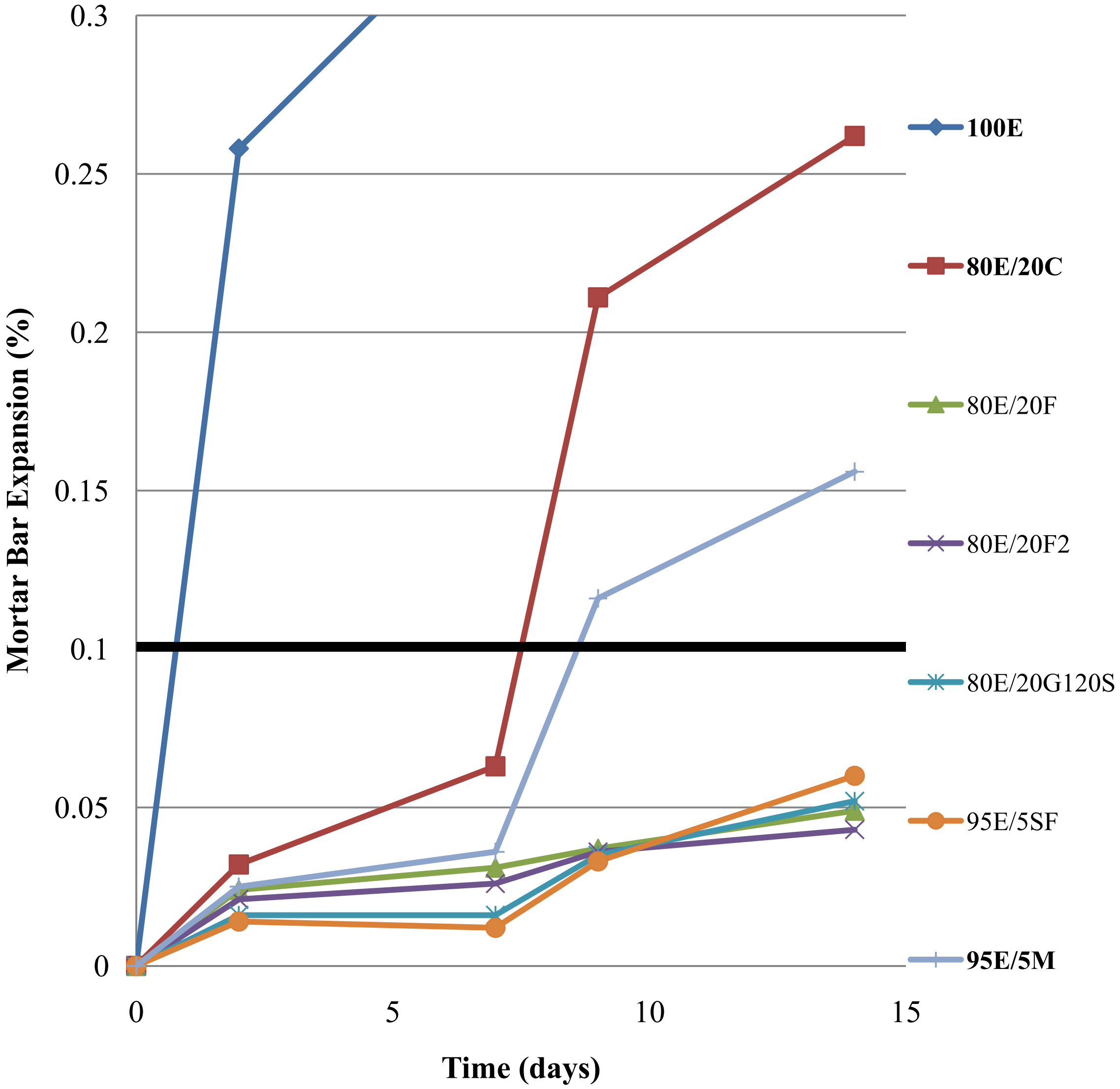

Figure 76. ASTM C1567 ASR mortar expansions of mixtures containing limestone blended cement

## ASTM C39 Concrete Compressive Strength Tables

**Table 117. ASTM C39 concrete compressive strengths of control mixtures**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **100TI** | 2418 | 4331 | 5359 | 6184 | 6354 | 7025 | 7199 |
| **100TIP** | 1315 | 3029 | 3977 | 4506 | 5337 | 5976 | 6520 |
| **100TISM** | 1316 | 2505 | 3100 | 4286 | 5215 | 5885 | 6683 |
| **100E** | 3124 | 3988 | 4932 | 5278 | 5881 | 6334 | 6843 |
| **80TI/20C** | 1700 | 3385 | 4526 | 5406 | 6010 | 6581 | 7088 |
| **80TI/20F** | 2268 | 4410 | 5381 | 5423 | 7260 | 8196 | 8544 |
| **80TI/20F2** | 2357 | 4140 | 5321 | 4089 | 6717 | 7715 | 8545 |
| **65TI/35G120S** | 1823 | 3699 | 5568 | 6681 | 7955 | 7594 | 8645 |

**Table 118. ASTM C39 concrete compressive strengths of mixtures containing Class C fly ash**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **80TI/20C** | 1700 | 3385 | 4526 | 5406 | 6010 | 6581 | 7088 |
| **60TI/20C/20F** | 925 | 2519 | 4914 | 5680 | 6913 | 8262 | 8845 |
| **60TI/20C/20F2** | 634 | 1939 | 2940 | 3708 | 4766 | 5500 | 5105 |
| **60TI/30C/10F** | 574 | 2109 | 4510 | 4520 | 6537 | 7449 | 7470 |
| **60TI/30F2/10C** | 502 | 1662 | 3107 | 3617 | 4706 | 5161 | 5969 |
| **60TI/30C/10F2** | 777 | 2577 | 5130 | 5510 | 7294 | 8138 | 8877 |
| **85TIP/15C** | 1852 | 3705 | 4365 | 5499 | 6070 | 7077 | 7762 |
| **75TIP/25C** | 1114 | 2702 | 3373 | 4356 | 5017 | 5404 | 5894 |
| **75TISM/25C** | 598 | 1760 | 2712 | 3790 | 4505 | 5543 | 6714 |

**Table 119. ASTM C39 concrete compressive strengths of mixtures containing Class F fly ash**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **80TI/20F** | 2268 | 4410 | 5381 | 5423 | 7260 | 8196 | 8544 |
| **60TI/20C/20F** | 925 | 2519 | 4914 | 5680 | 6913 | 8262 | 8845 |
| **60TI/30C/10F** | 574 | 2109 | 4510 | 4520 | 6537 | 7449 | 7470 |
| **60TI/20F/20F2** | 662 | 2279 | 3075 | 3861 | 4622 | 5569 | 6348 |
| **75TI/20F/5SF** | 2725 | 5480 | 7083 | 8427 | 9895 | 10412 | 11201 |
| **77TI/20F/3SF** | 2568 | 4776 | 5643 | 6902 | 8225 | 8862 | 9179 |
| **60TI/20F/20G120S** | 1591 | 3887 | 5577 | 6923 | 8035 | 8298 | 9030 |
| **75TI/20F/5M** | 2423 | 4953 | 6677 | 7876 | 8547 | 9198 | 9249 |
| **60TI/30F/10F2** | 1286 | 2858 | 3736 | 5317 | 6126 | 7369 | 6219 |
| **65TI/30F/5SF** | 2049 | 3432 | 5174 | 6868 | 7953 | 8807 | 9272 |
| **67TI/30F/3SF** | 1838 | 3664 | 4678 | 6426 | 7484 | 8069 | 8742 |
| **50TI/30F/20G120S** | 1272 | 2891 | 4956 | 6684 | 7368 | 8457 | 9011 |
| **65TI/30F/5M** | 985 | 2390 | 4147 | 4979 | 5325 | 5917 | 6617 |
| **50TI/35G120S/15F** | 1242 | 3566 | 5201 | 6535 | 7700 | 8261 | 8339 |
| **85TIP/15F** | 2237 | 3616 | 4632 | 5410 | 5752 | 6703 | 7323 |
| **75TIP/25F** | 717 | 2053 | 2801 | 3114 | 3702 | 5049 | 5221 |

**Table 120. ASTM C39 concrete compressive strengths of mixtures containing Class F2 fly ash**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **80TI/20F2** | 2357 | 4140 | 5321 | 4089 | 6717 | 7715 | 8545 |
| **60TI/20C/20F2** | 634 | 1939 | 2940 | 3708 | 4766 | 5500 | 5105 |
| **60TI/20F/20F2** | 662 | 2279 | 3075 | 3861 | 4622 | 5569 | 6348 |
| **75TI/20F2/5SF** | 1301 | 3132 | 4142 | 5218 | 5946 | 6994 | 6995 |
| **77TI/20F2/3SF** | 1830 | 2204 | 4674 | 5393 | 7319 | 8462 | 8942 |
| **60TI/20F2/20G120S** | 828 | 2098 | 3294 | 4755 | 6518 | 7057 | 7308 |
| **75TI/20F2/5M** | 1402 | 2930 | 4372 | 5998 | 7435 | 7787 | 8187 |
| **60TI/30C/10F2** | 777 | 2577 | 5130 | 5510 | 7294 | 8138 | 8877 |
| **60TI/30F/10F2** | 1286 | 2858 | 3736 | 5317 | 6126 | 7369 | 6219 |
| **60TI/30F2/10C** | 502 | 1662 | 3107 | 3617 | 4706 | 5161 | 5969 |
| **65TI/30F2/5SF** | 1732 | 3396 | 4795 | 5983 | 8110 | 9171 | 10089 |
| **67TI/30F2/3SF** | 1343 | 2679 | 3916 | 5239 | 7387 | 8191 | 9159 |
| **65TI/30F2/5M** | 526 | 1913 | 2821 | 3778 | 4548 | 4535 | 5118 |
| **50TI/35G120S/15F2** | 1362 | 3113 | 5162 | 4517 | 7216 | 8323 | 8331 |
| **85TIP/15F2** | 3410 | 3599 | 5049 | | | 7263 | 7860 |
| **75TIP/25F2** | 1083 | 2522 | 2991 | 3601 | 4328 | 4872 | 7939 |
| **75TISM/25F2** | 658 | 1638 | | 3895 | 5065 | 6087 | 6884 |

**Table 121. ASTM C39 concrete compressive strengths of mixtures containing Grade 120 GGBFS**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **65TI/35G120S** | 1823 | 3699 | 5568 | 6681 | 7955 | 7594 | 8645 |
| **60TI/20F/20G120S** | 1591 | 3887 | 5577 | 6923 | 8035 | 8298 | 9030 |
| **50TI/30F/20G120S** | 1272 | 2891 | 4956 | 6684 | 7368 | 8457 | 9011 |
| **50TI/35G120S/15F** | 1242 | 3566 | 5201 | 6535 | 7700 | 8261 | 8339 |
| **60TI/20F2/20G120S** | 828 | 2098 | 3294 | 4755 | 6518 | 7057 | 7308 |
| **50TI/35G120S/15F2** | 1362 | 3113 | 5162 | 4517 | 7216 | 8323 | 8331 |
| **62TI/35G120S/3SF** | 1266 | 3309 | 4902 | 5741 | 6466 | 7362 | 7563 |
| **60TI/35G120S/5M** | 1091 | 3346 | 5088 | 5559 | 6790 | 7825 | 7543 |
| **65TIP/35G120S** | 2523 | 3219 | 4699 | | | 5695 | 8843 |
| **50TIP/50G120S** | 453 | 1685 | 3076 | 4207 | 5742 | 6872 | 7863 |
| **65TISM/35G120S** | 364 | 1300 | 2171 | 3868 | 5176 | 6344 | 7287 |

**Table 122. ASTM C39 concrete compressive strengths of mixtures containing silica fume**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **75TI/20F/5SF** | 2725 | 5480 | 7083 | 8427 | 9895 | 10412 | 11201 |
| **77TI/20F/3SF** | 2568 | 4776 | 5643 | 6902 | 8225 | 8862 | 9179 |
| **65TI/30F/5SF** | 2049 | 3432 | 5174 | 6868 | 7953 | 8807 | 9272 |
| **67TI/30F/3SF** | 1838 | 3664 | 4678 | 6426 | 7484 | 8069 | 8742 |
| **75TI/20F2/5SF** | 1301 | 3132 | 4142 | 5218 | 5946 | 6994 | 6995 |
| **77TI/20F2/3SF** | 1830 | 2204 | 4674 | 5393 | 7319 | 8462 | 8942 |
| **65TI/30F2/5SF** | 1732 | 3396 | 4795 | 5983 | 8110 | 9171 | 10089 |
| **67TI/30F2/3SF** | 1343 | 2679 | 3916 | 5239 | 7387 | 8191 | 9159 |
| **62TI/35G120S/3SF** | 1266 | 3309 | 4902 | 5741 | 6466 | 7362 | 7563 |
| **97TIP/3SF** | 2600 | 4997 | 5741 | 7506 | 9786 | | |
| **97TISM/3SF** | 1460 | 3019 | 4491 | 5805 | 7315 | 7589 | 8496 |

**Table 123. ASTM C39 concrete compressive strengths of mixtures containing metakaolin**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **75TI/20F/5M** | 2423 | 4953 | 6677 | 7876 | 8547 | 9198 | 9249 |
| **65TI/30F/5M** | 985 | 2390 | 4147 | 4979 | 5325 | 5917 | 6617 |
| **75TI/20F2/5M** | 1402 | 2930 | 4372 | 5998 | 7435 | 7787 | 8187 |
| **65TI/30F2/5M** | 526 | 1913 | 2821 | 3778 | 4548 | 4535 | 5118 |
| **60TI/35G120S/5M** | 1091 | 3346 | 5088 | 5559 | 6790 | 7825 | 7543 |
| **95TIP/5M** | 2866 | 4918 | 6170 | 7638 | 9465 | | |

**Table 124. ASTM C39 concrete compressive strengths of mixtures containing Type IP cement**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **100TIP** | 1315 | 3029 | 3977 | 4506 | 5337 | 5976 | 6520 |
| **85TIP/15C** | 1852 | 3705 | 4365 | 5499 | 6070 | 7077 | 7762 |
| **85TIP/15F** | 2237 | 3616 | 4632 | 5410 | 5752 | 6703 | 7323 |
| **85TIP/15F2** | 3410 | 3599 | 5049 | | | 7263 | 7860 |
| **65TIP/35G120S** | 2523 | 3219 | 4699 | | | 5695 | 8843 |
| **97TIP/3SF** | 2600 | 4997 | 5741 | 7506 | 9786 | | |
| **95TIP/5M** | 2866 | 4918 | 6170 | 7638 | 9465 | | |
| **75TIP/25C** | 1114 | 2702 | 3373 | 4356 | 5017 | 5404 | 5894 |
| **75TIP/25F** | 717 | 2053 | 2801 | 3114 | 3702 | 5049 | 5221 |
| **75TIP/25F2** | 1083 | 2522 | 2991 | 3601 | 4328 | 4872 | 7939 |
| **50TIP/50G120S** | 453 | 1685 | 3076 | 4207 | 5742 | 6872 | 7863 |

**Table 125. ASTM C39 concrete compressive strengths of mixtures containing Type IS(20) cement**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **100TISM** | 1316 | 2505 | 3100 | 4286 | 5215 | 5885 | 6683 |
| **75TISM/25C** | 598 | 1760 | 2712 | 3790 | 4505 | 5543 | 6714 |
| **75TISM/25F2** | 658 | 1638 | | 3895 | 5065 | 6087 | 6884 |
| **65TISM/35G120S** | 364 | 1300 | 2171 | 3868 | 5176 | 6344 | 7287 |
| **97TISM/3SF** | 1460 | 3019 | 4491 | 5805 | 7315 | 7589 | 8496 |

**Table 126. ASTM C39 concrete compressive strengths of mixtures containing limestone blended cement**

| | Concrete Compressive Strength (psi) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture ID** | **Day 1** | **Day 3** | **Day 7** | **Day 14** | **Day 28** | **Day 56** | **Day 91** |
| **100E** | 3124 | 3988 | 4932 | 5278 | 5881 | 6334 | 6843 |
| **80E/20F** | 2775 | 3973 | 4925 | 5362 | 6148 | 7540 | 7118 |
| **80E/20F2** | 2315 | 3416 | 4069 | 4456 | 5229 | 6077 | 6540 |
| **80E/20G120S** | 1962 | 3780 | 5149 | 5887 | 6582 | 6848 | 7435 |
| **80E/20C** | 1858 | 3458 | 4730 | 5413 | 5971 | 6522 | 7009 |
| **95E/5SF** | 2578 | 3973 | 4856 | 5675 | 6904 | 7276 | 7492 |
| **95E/5M** | 3127 | 5207 | 6773 | 7809 | 8174 | 8647 | 9131 |

## ASTM C39 Concrete Compressive Strength Figures

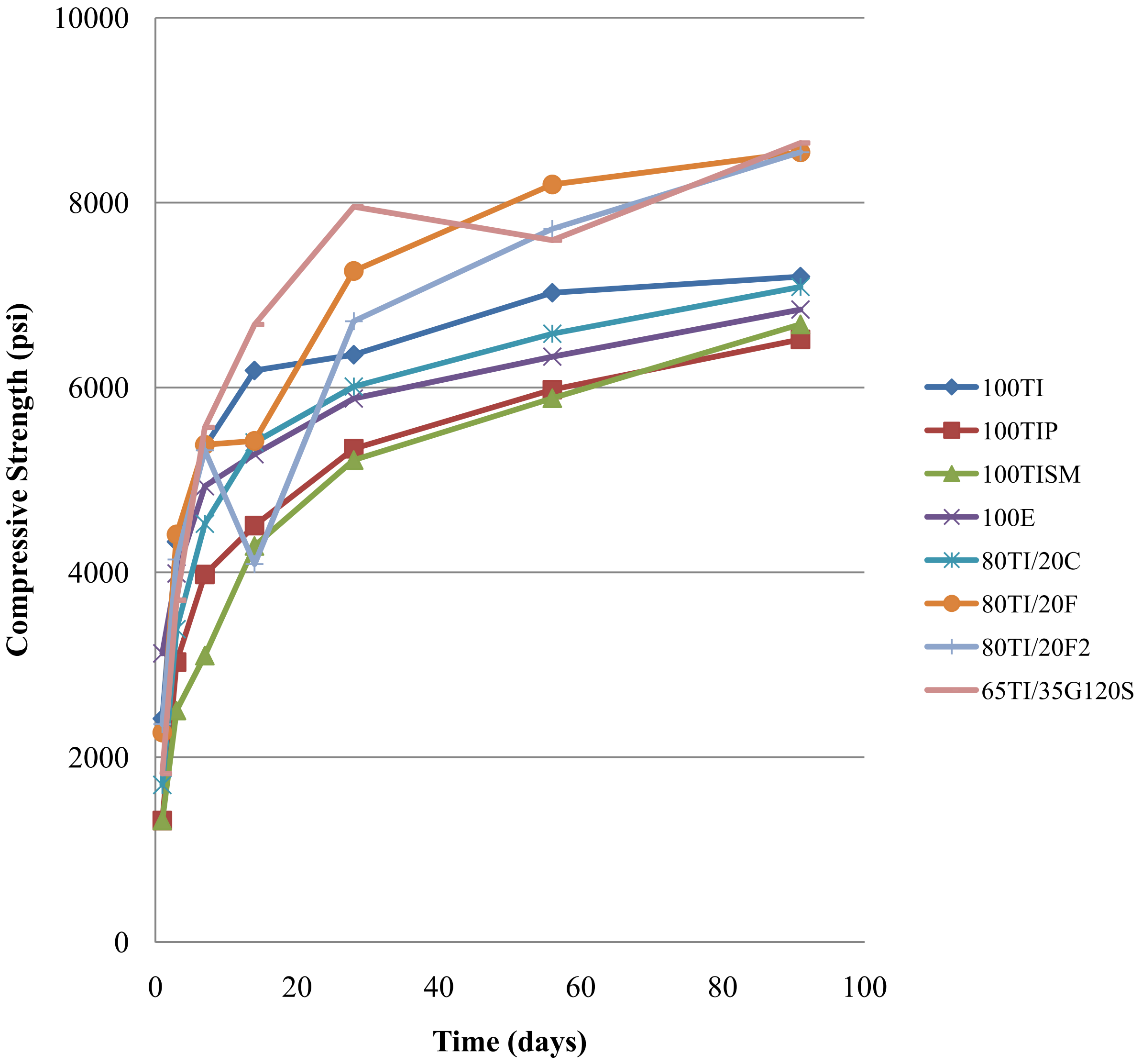

Figure 77. ASTM C39 concrete compressive strengths of control mixtures

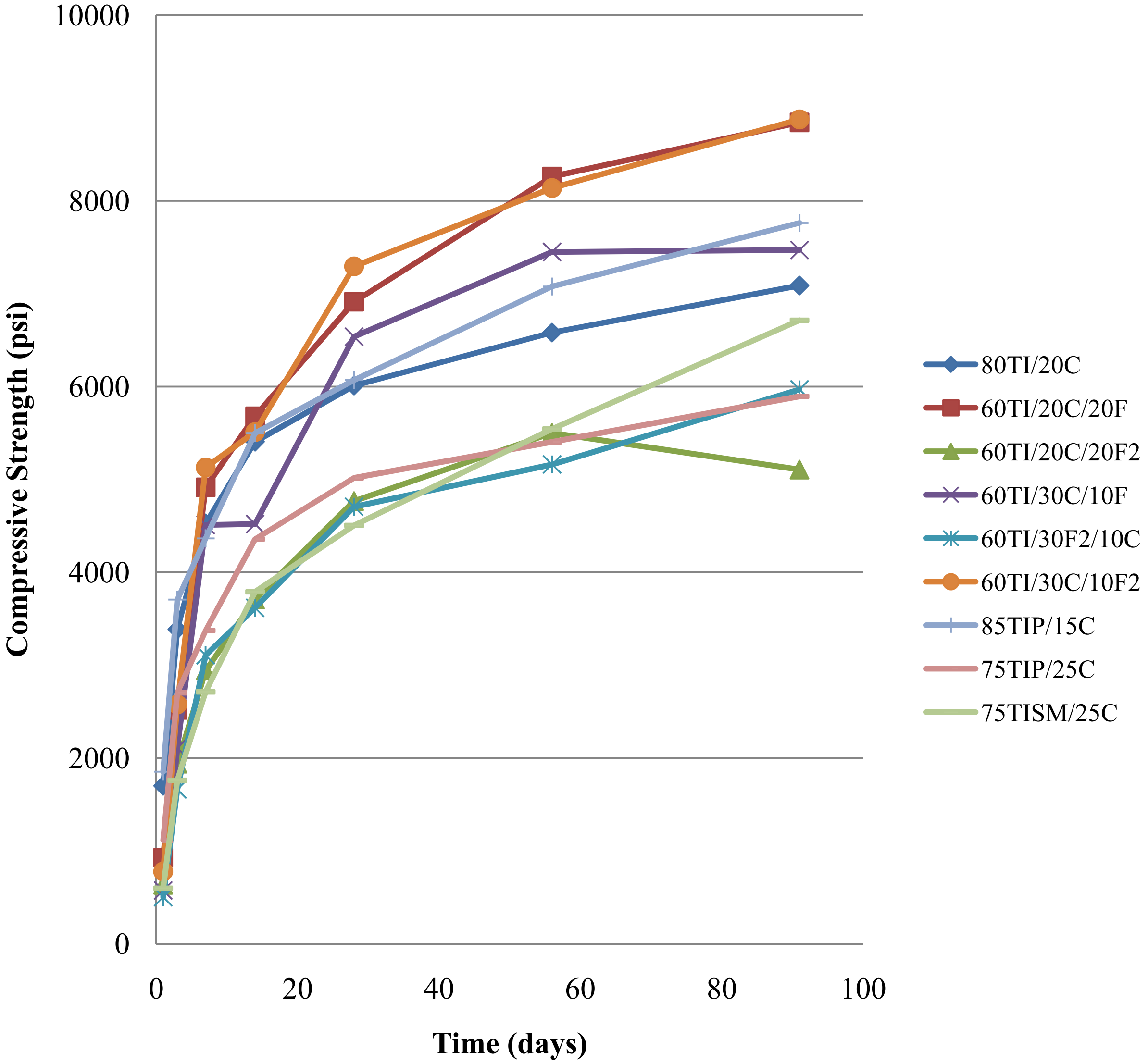

**Figure 78. ASTM C39 concrete compressive strengths of mixtures containing Class C fly ash**

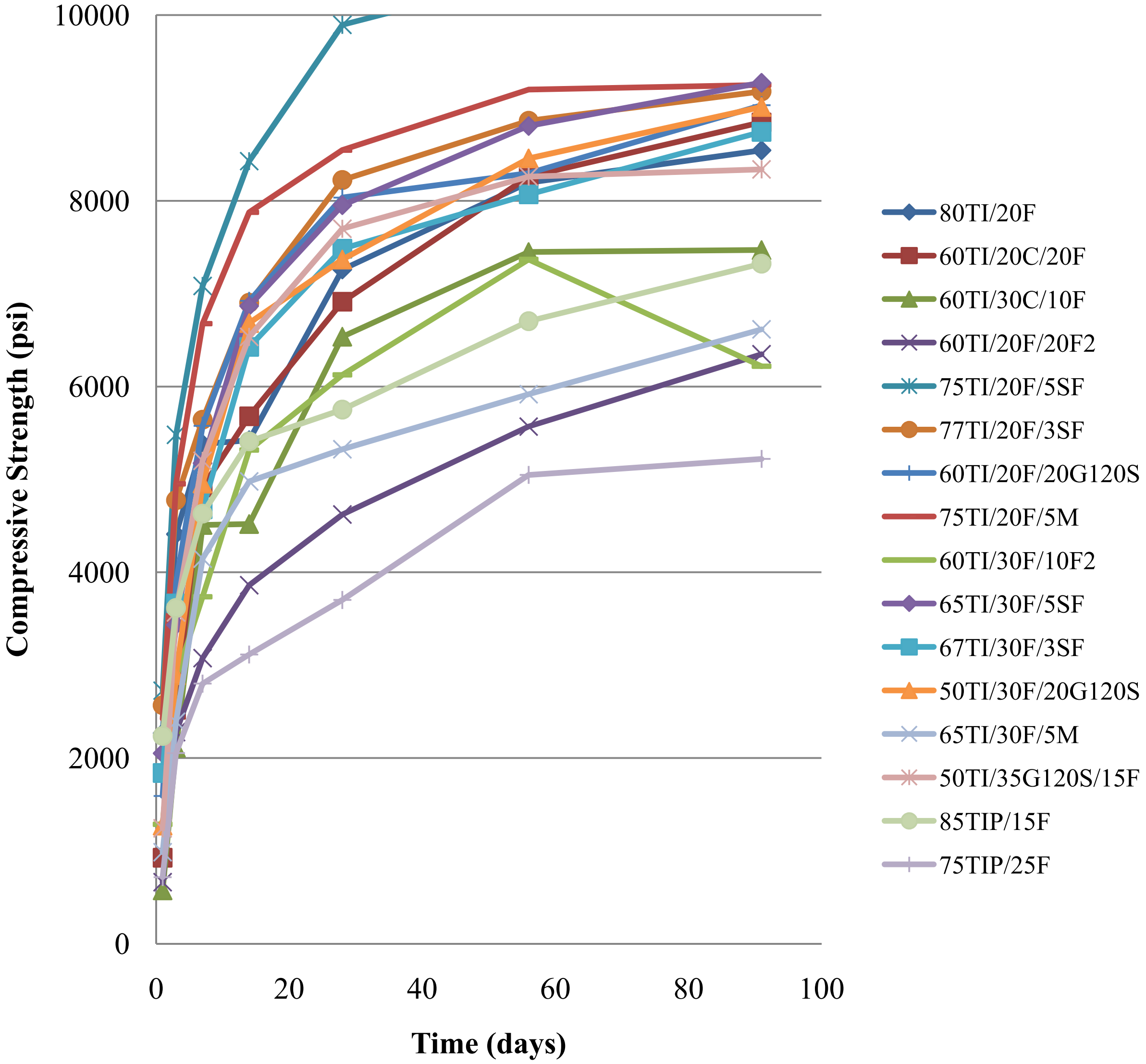

Figure 79. ASTM C39 concrete compressive strengths of mixtures containing Class F fly ash

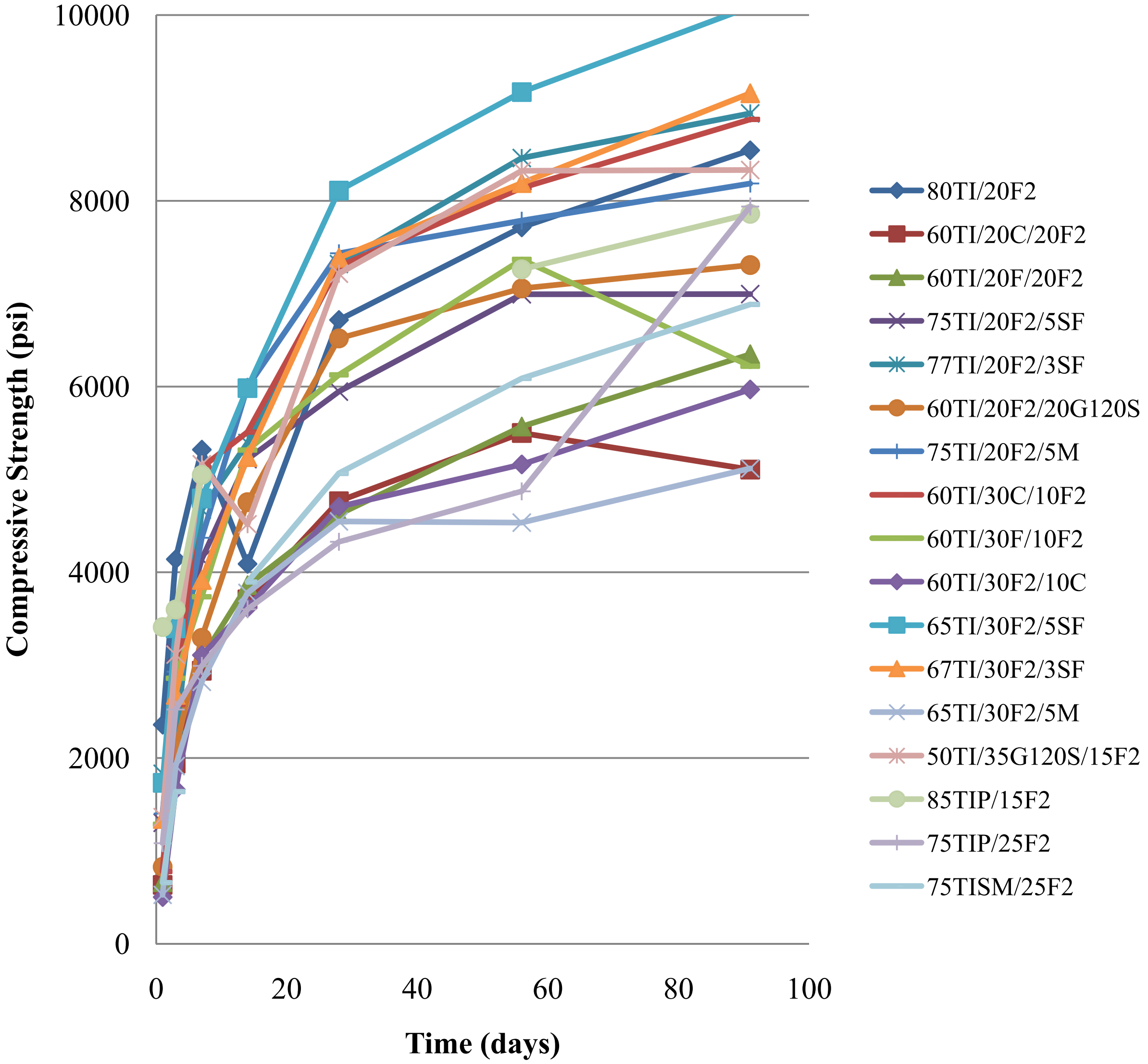

**Figure 80. ASTM C39 concrete compressive strengths of mixtures containing Class F2 fly ash**

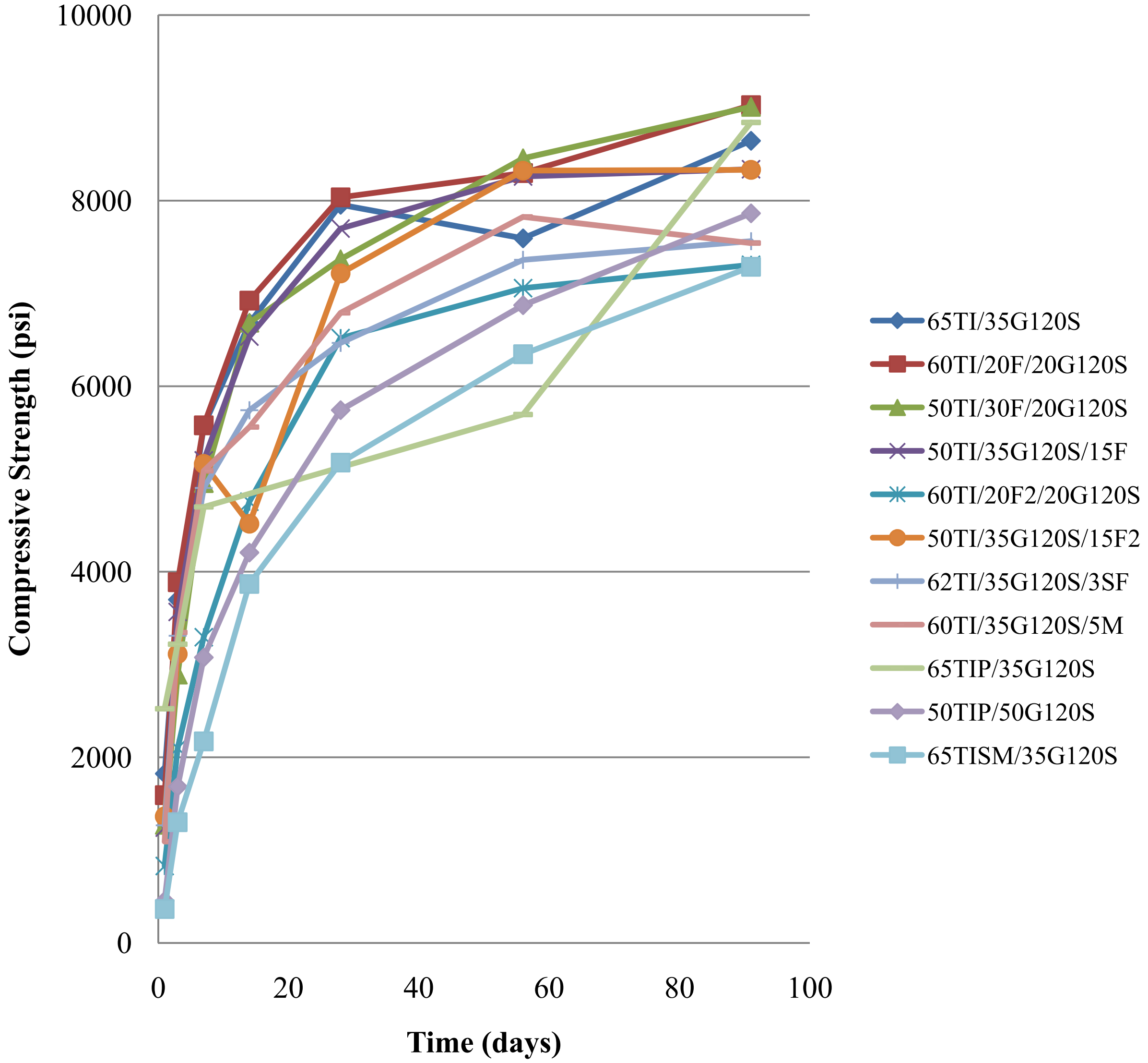

**Figure 81. ASTM C39 concrete compressive strengths of mixtures containing Grade 120 GGBFS**

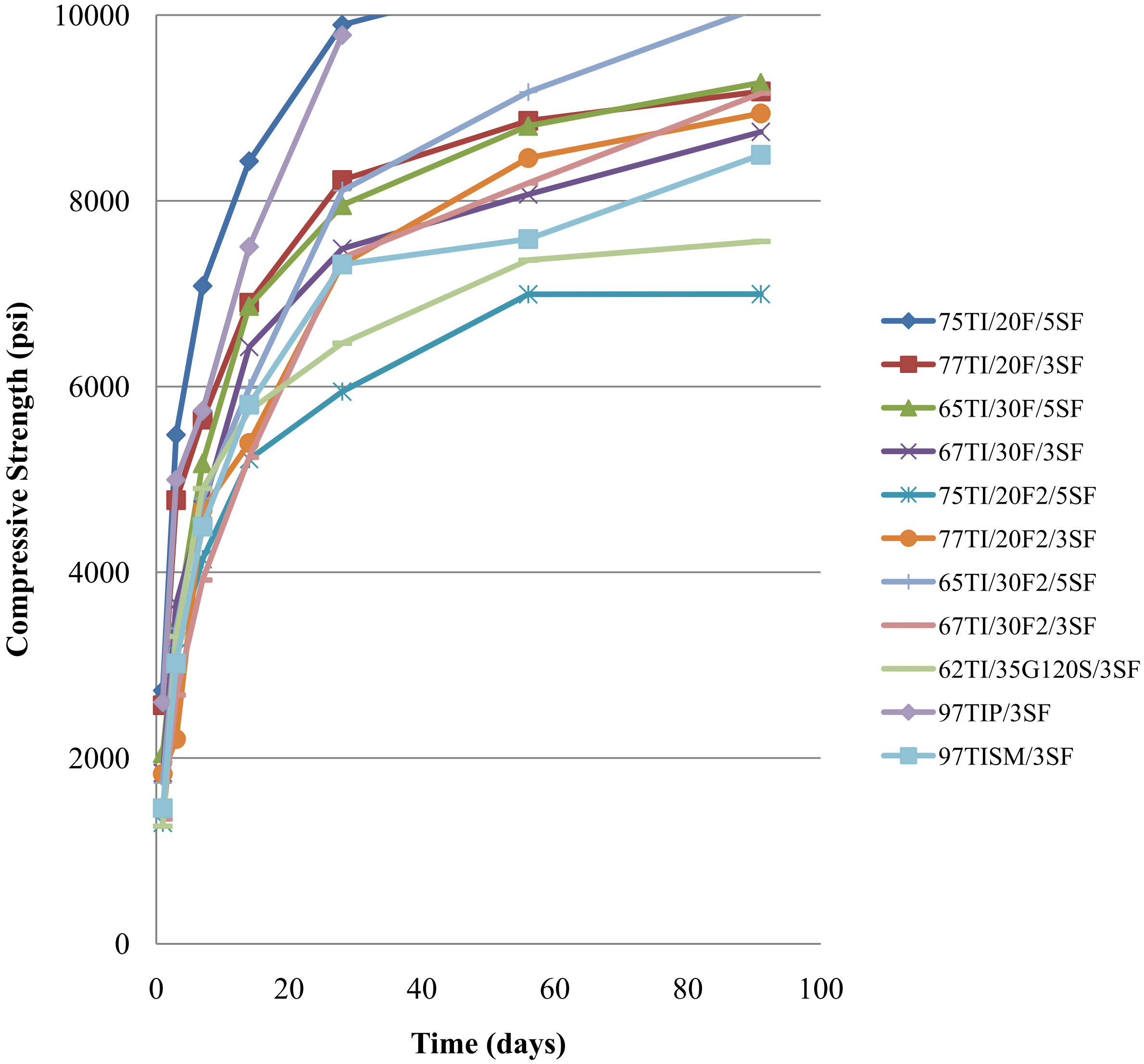

**Figure 82. ASTM C39 concrete compressive strengths of mixtures containing silica fume**

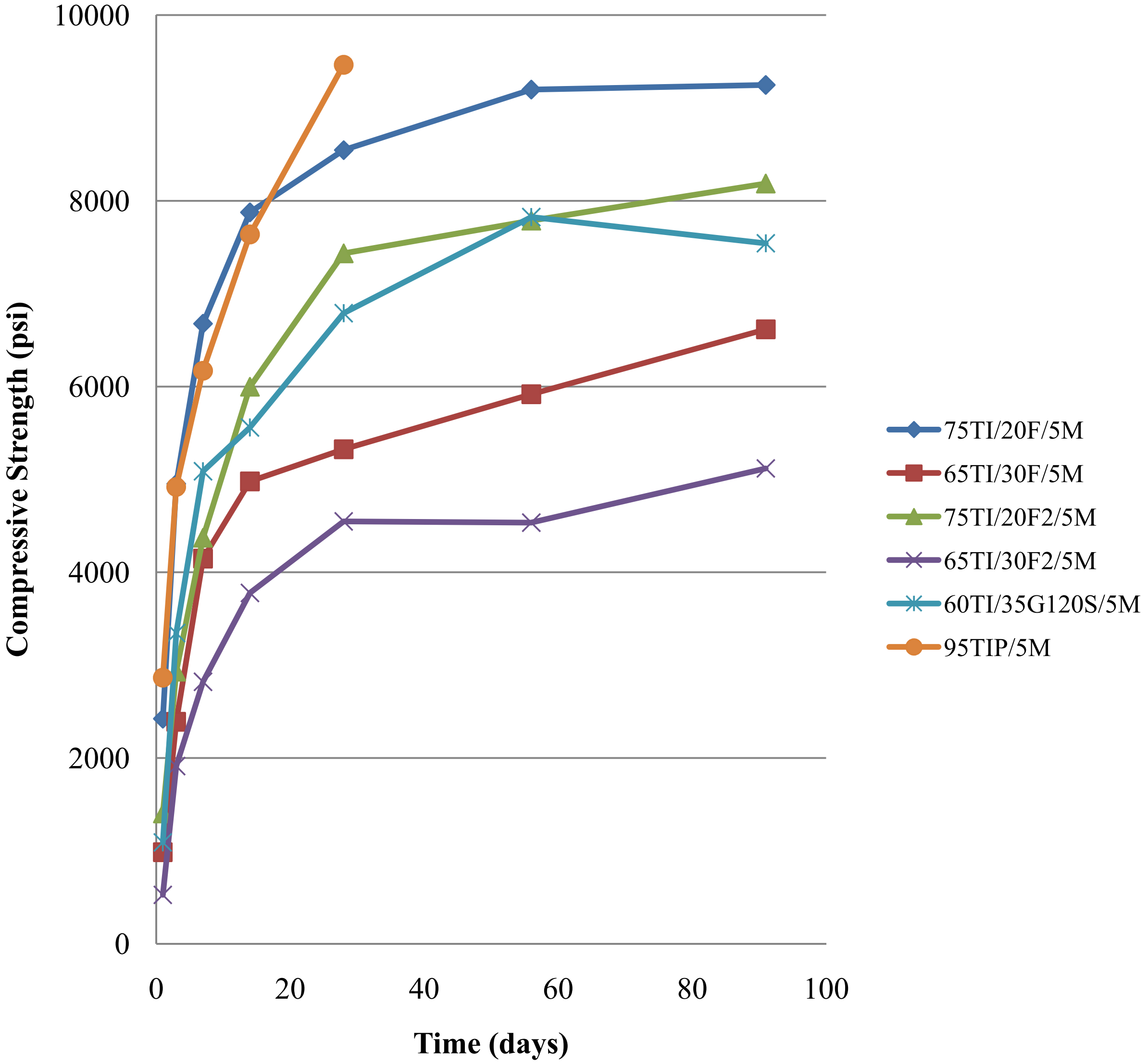

**Figure 83. ASTM C39 concrete compressive strengths of mixtures containing metakaolin**

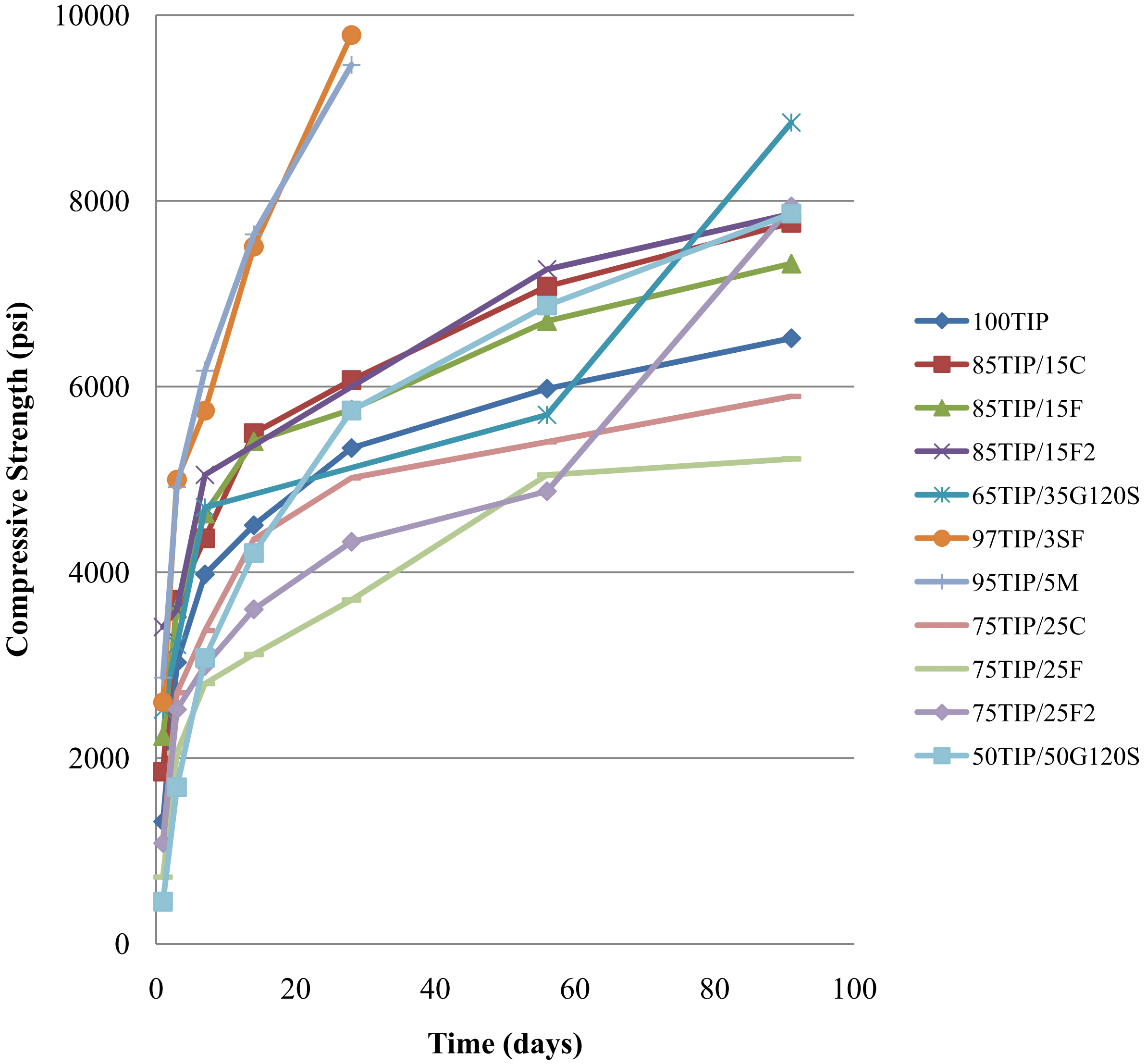

Figure 84. ASTM C39 concrete compressive strengths of mixtures containing Type IP cement

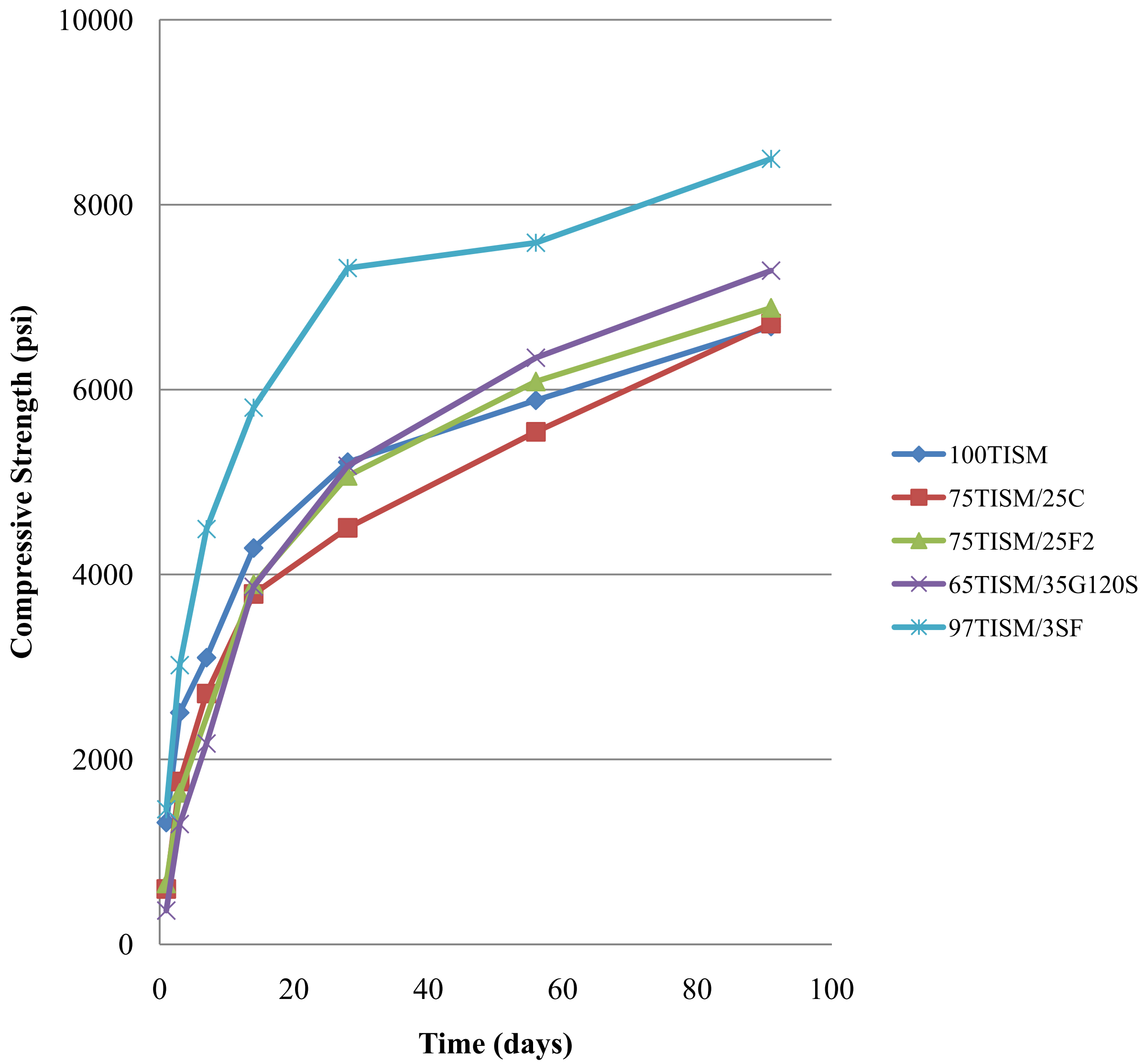

Figure 85. ASTM C39 concrete compressive strengths of mixtures containing Type IS(20) cement

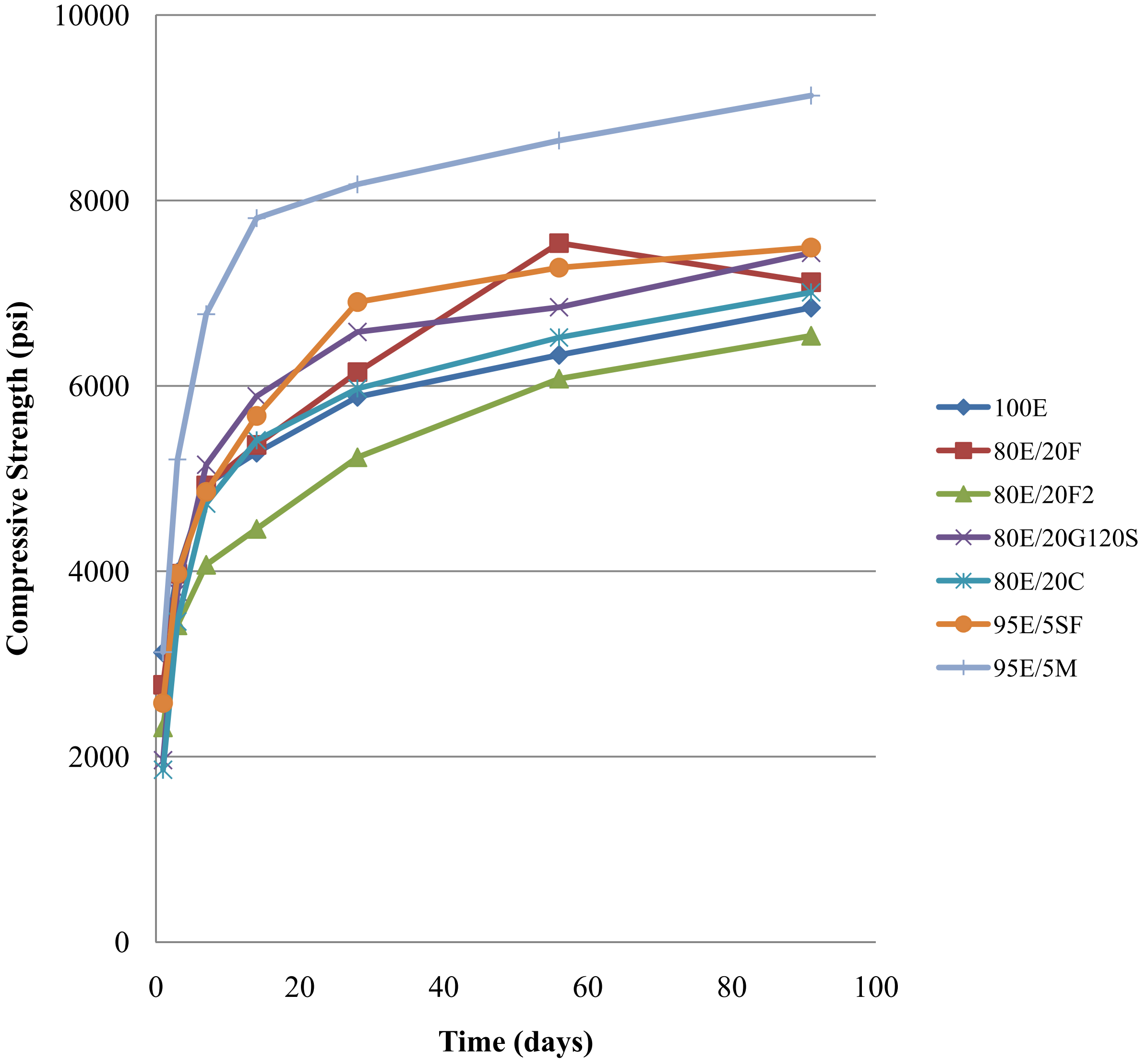

Figure 86. ASTM C39 concrete compressive strengths of mixtures containing limestone blended cement

## ASTM C157 Concrete Shrinkage Figures

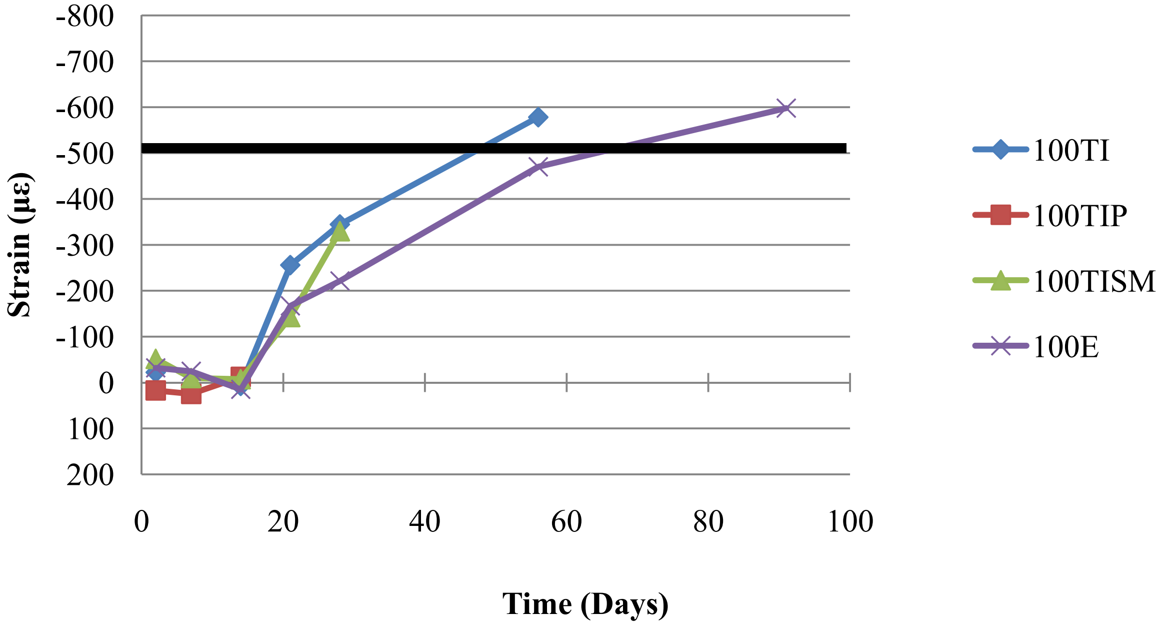

**Figure 87. ASTM C157 curing shrinkage strain for control mixtures**

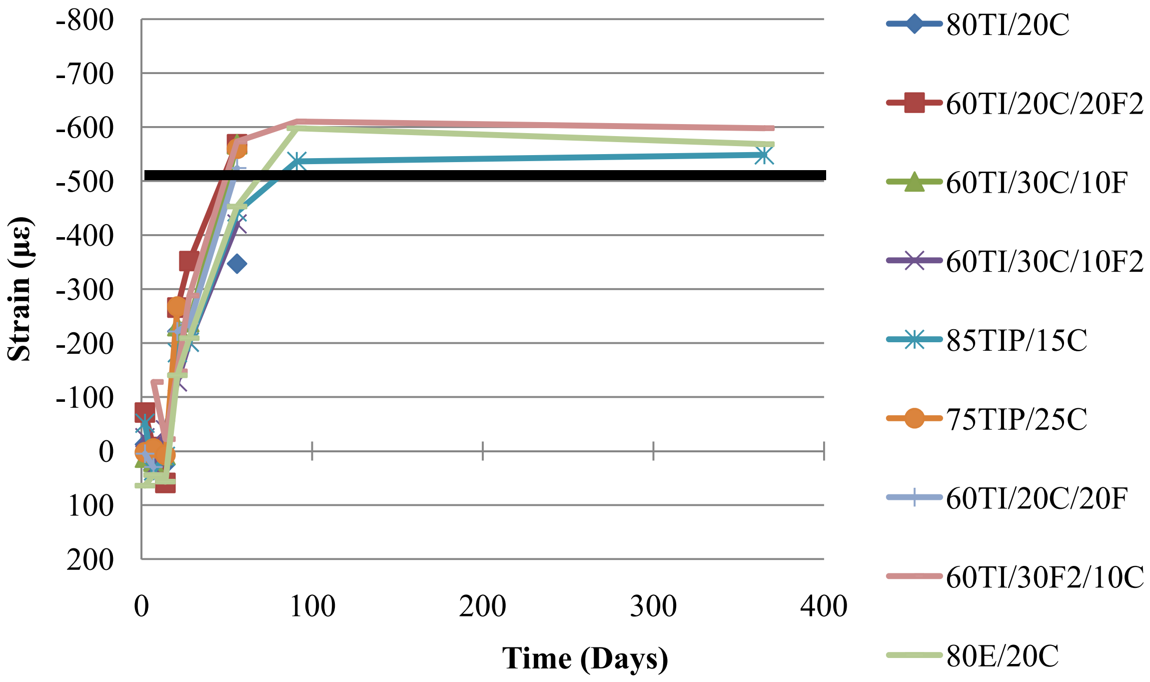

Figure 88. ASTM C157 curing shrinkage strain of mixtures containing Class C fly ash

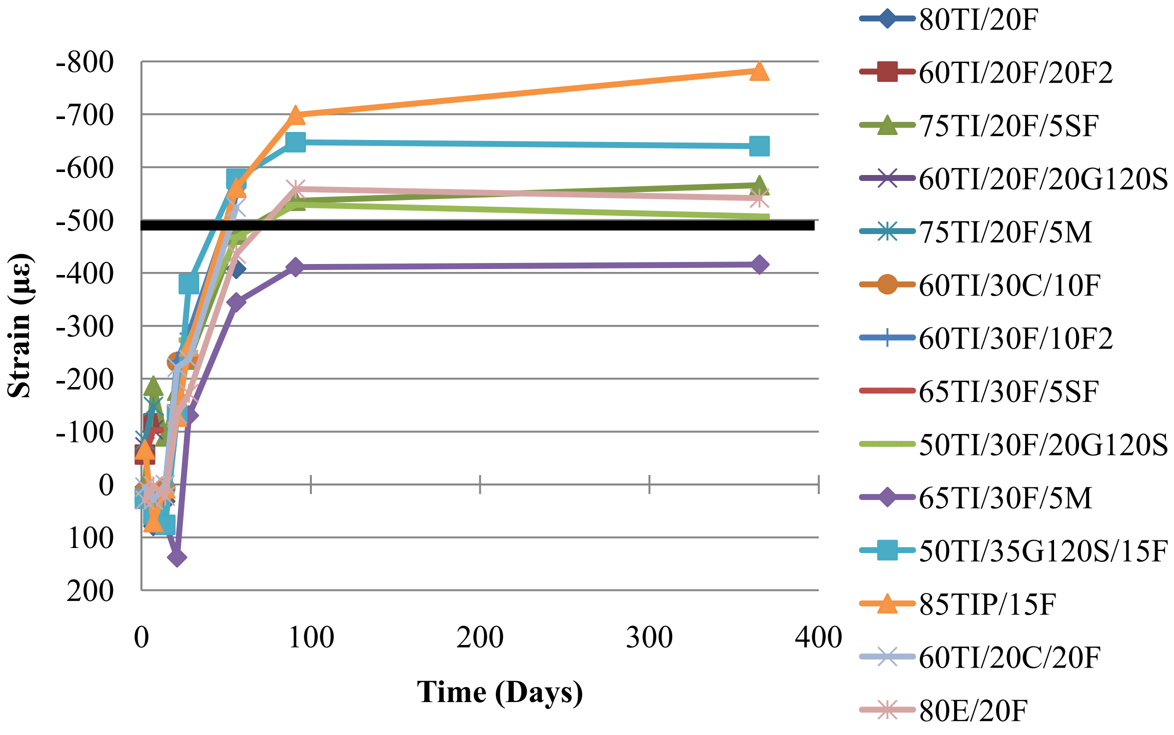

Figure 89. ASTM C157 curing shrinkage strain of mixtures containing Class F fly ash

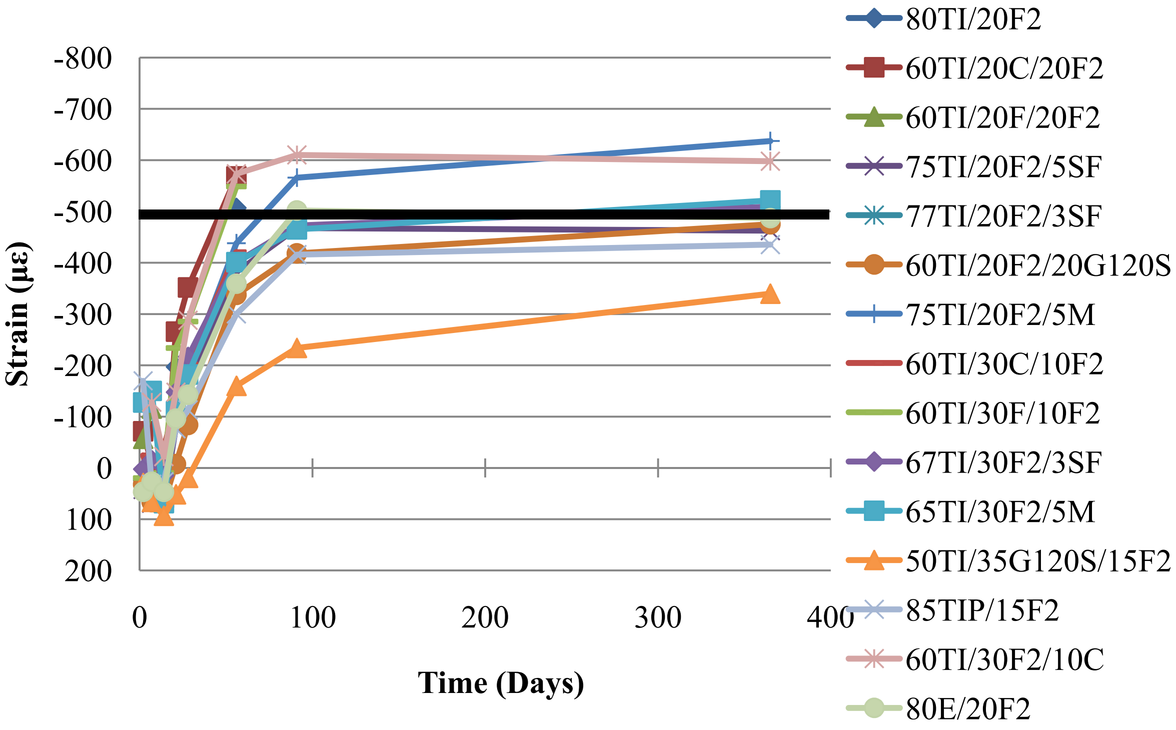

Figure 90. ASTM C157 curing shrinkage strain of mixtures containing Class F2 fly ash

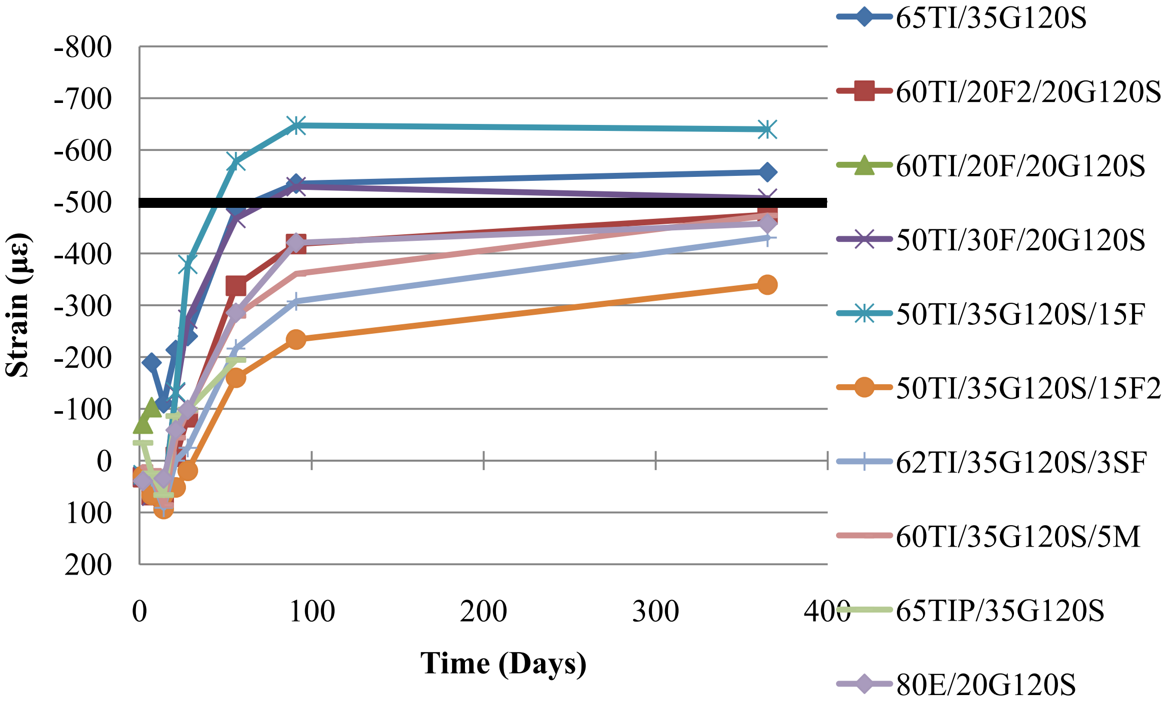

Figure 91. ASTM C157 curing shrinkage strain of mixtures containing Grade 120 GGBFS

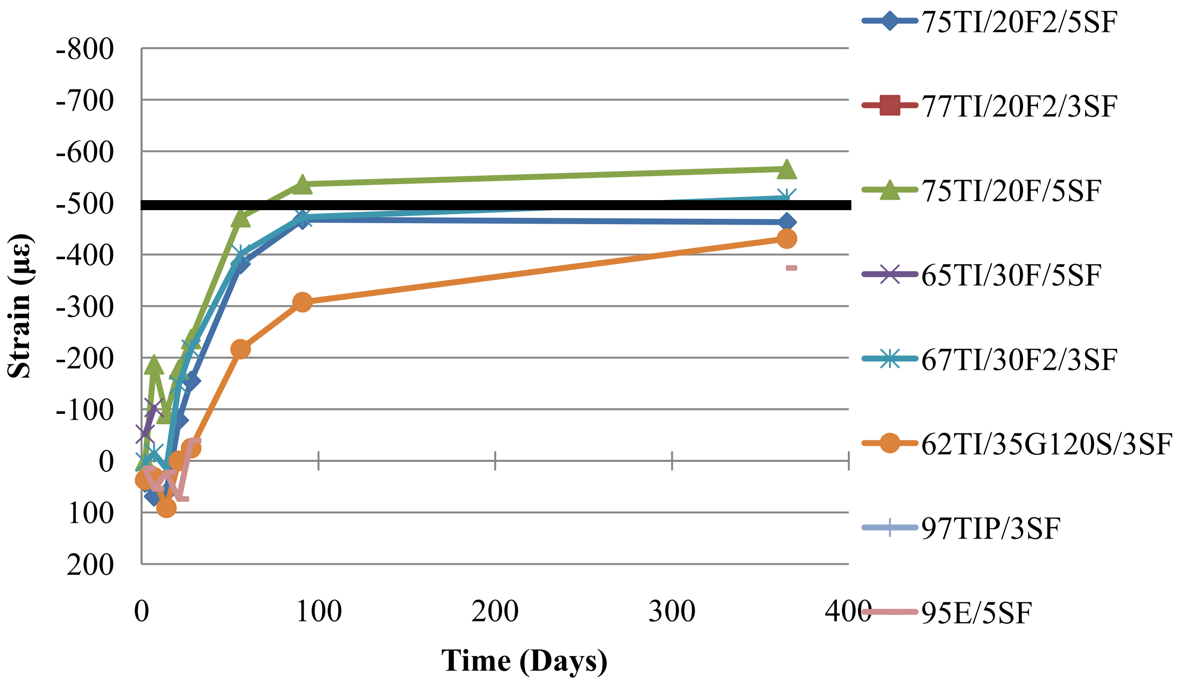

**Figure 92. ASTM C157 curing shrinkage strain of mixtures containing silica fume**

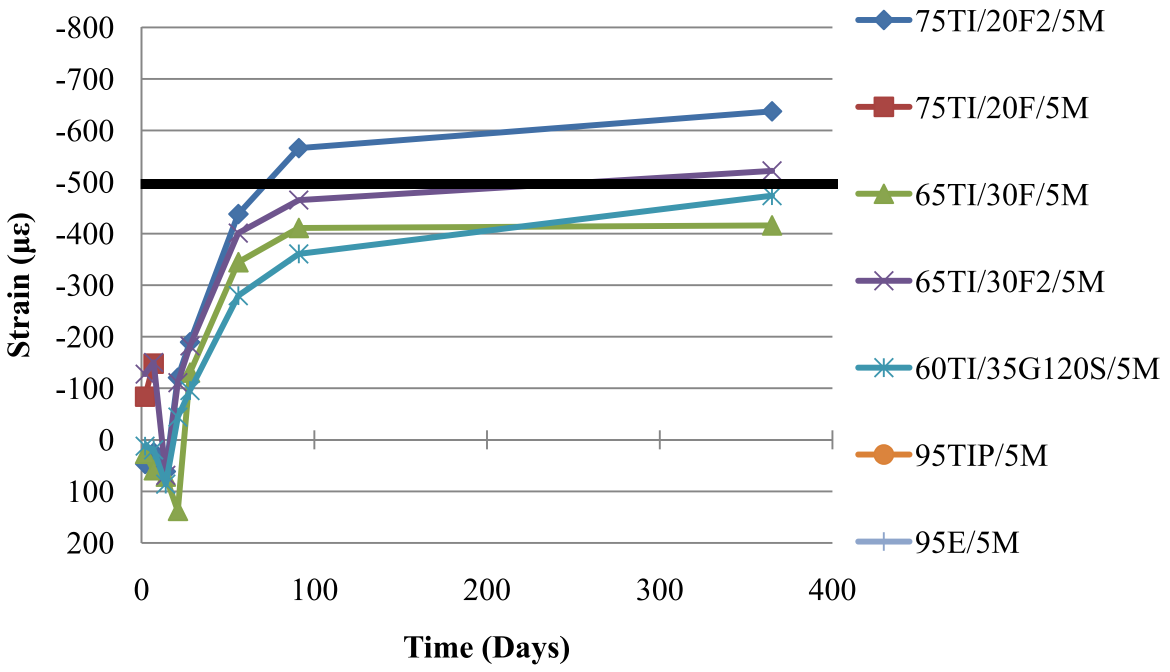

**Figure 93. ASTM C157 curing shrinkage strain of mixtures containing metakaolin**

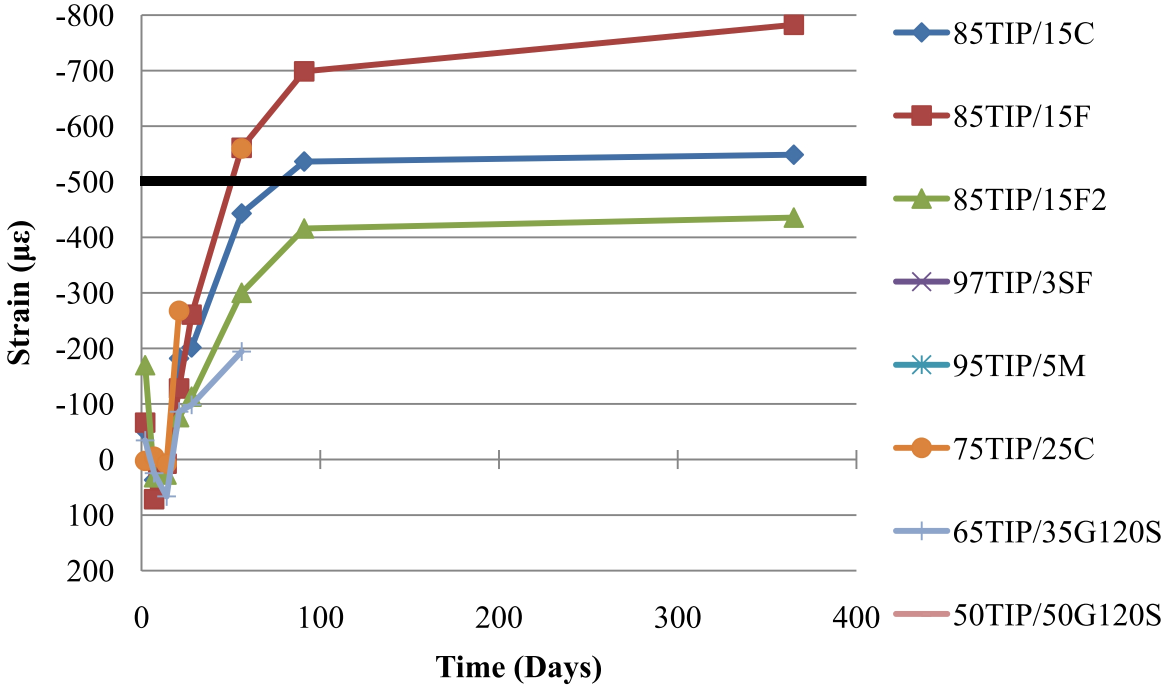

Figure 94. ASTM C157 curing shrinkage strain of mixtures containing Type IP cement

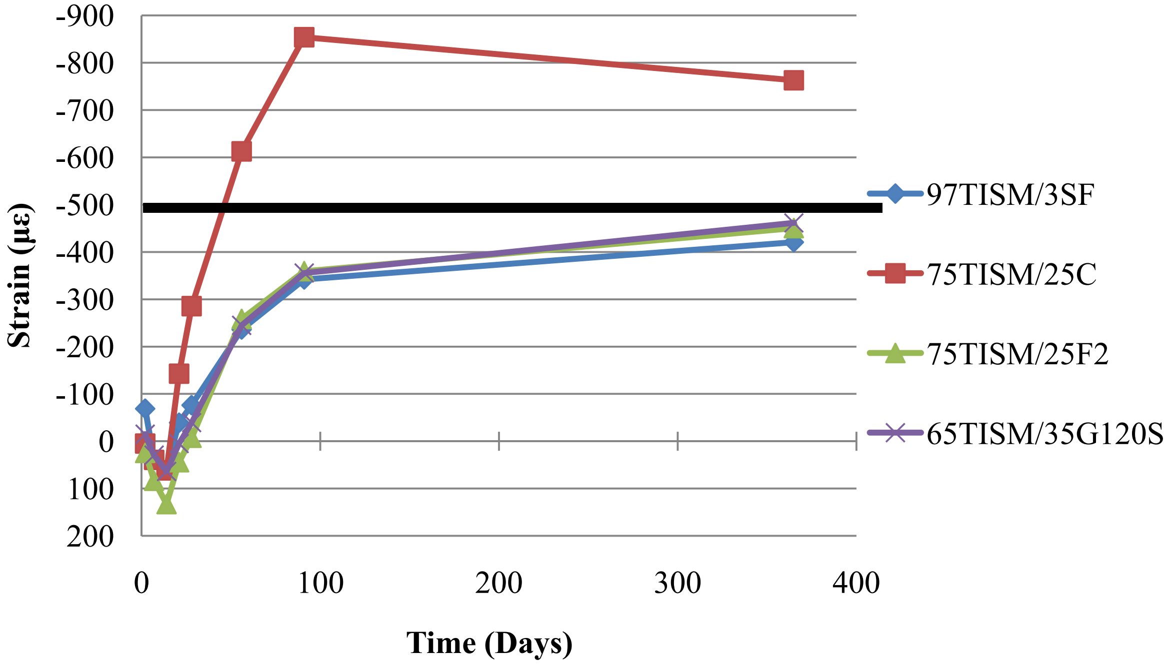

Figure 95. ASTM C157 curing shrinkage strain of mixtures containing Type IS(20) cement

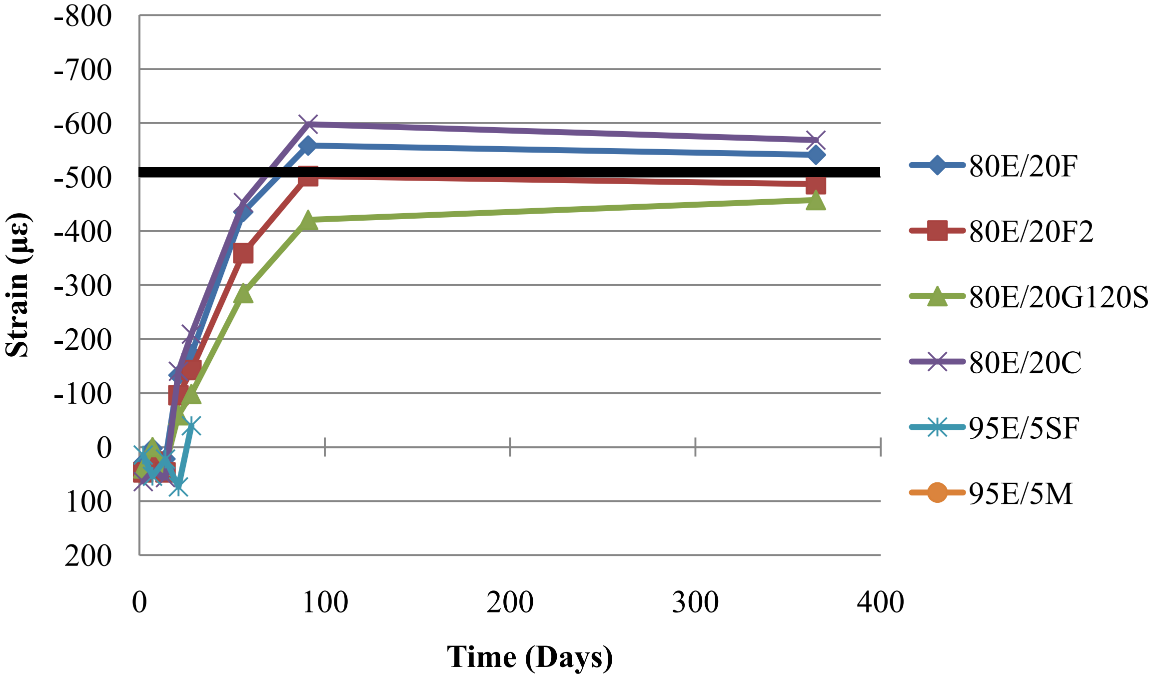

**Figure 96. ASTM C157 curing shrinkage strain of mixtures containing limestone blended cement**