UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

ANALYSIS AND COMPARISON OF CEMENT SELECTION IN ULTRA-HIGH-PERFORMANCE CONCRETE

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

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Norman, Oklahoma

2022

ANALYIS AND COMPARISON OF CEMENT SELECTION IN ULTRA-HIGH-PERFORMANCE CONCRETE

A THESIS APPROVED FOR THE

SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

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Acknowledgements

I would like to acknowledge the other members of my research team that provided encouragement, advice, and sanity checks along the way, particularly Dr. Trevor Looney and Jorge Vargas. I would also like to acknowledge Dr. Jeffery Volz, for his support throughout the research process, and John Bullock, for his broad expertise and ability to make Fears Lab feel like home. Finally, I would like to acknowledge my friends and family for supporting me and tolerating an excessive amount of concrete talk during this project.

Abstract

Ultra-high-performance concrete (UHPC) is a relatively new material that is growing in popularity and usage over recent years. The greatly increased strength and durability of UHPC compared to conventional ACI concrete makes it an attractive material for designing stronger and more efficient structural systems. However, the high costs of specialty materials needed to make UHPC have encouraged researchers to investigate methods for optimizing UHPC mixes with a balance of cost and performance in mind. Popular means of optimization include different curing conditions, particle packing methods, and the exploration of different amounts and types of materials. Materials that are commonly used and varied between different UHPC mix designs include steel fibers, silica fume, and portland cement.

The purpose of this research project was to investigate the effects of different types of cement and their properties, particularly chemical composition and heat of hydration, on the performance of a standardized UHPC mix. The methods of investigation included compressive strength testing of cube specimens at age intervals of 1 day, 3 days, 7 days, 14 days, 28 days, and 56 days, as well as calorimetry testing during the initial 3 days of hydration. Eleven different cements from six different manufacturers were investigated in this study. The collected data indicated that Type I/II portland cements performed the best overall. Investigating the individual chemical compositions showed few trends correlating individual values with higher compressive strength, though cements with higher C_3S, $C_3S+4.75*C_3A$ contents, and Blaine fineness had a slight tendency to have higher compressive strength at 56 days. Investigating the area formed under the measured calorimetry curves also yielded a positive trend between larger areas and higher compressive strengths, especially for 1 and 3 day strength.

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1 Introduction

1.1 Background and Justification

Ultra-high-performance concrete (UHPC) is a relatively new and developing material that has significant advantages over conventional normal weight concrete, including significant improvement in durability, tensile strength, and compressive strength. Researchers are exploring the use of alternative material constituents, mixing procedures, and casting procedures to develop and refine different properties of the material, with the primary purpose of optimizing a balance between cost and performance. Specialized materials are expensive and can often be limited to just a few manufacturing locations, so identifying effective local and alternative material constituents can reduce costs and increase the usage of UHPC in structural applications.

UHPC is commonly composed of a combination of portland cement, fine sand, silica fume, water, and high-range water reducer (HRWR), as well as either ground-granulated blast-furnace slag (GGBFS) or ground quartz. Portland cement is a primary staple of concrete and is segmented into different types in ASTM C150 according to intended use and specified limits on the cement properties. These properties include chemical compound compositions, particle fineness, and mortar compressive strength. Some types of cement are good at entraining air, while others are best used when higher early strength is needed. The most commonly used type of portland cement is Type I/II, due to wide availability and moderate sulfate resistance. A common way researchers are working to optimize the performance and cost of UHPC is through experimentation with various supplementary cementitious materials (SCMs) and different types of portland cement besides the commonplace Type I/II.

The optimization of UHPC is often done through the testing of many different combinations of SCMs, aggregates, cement, chemical admixtures, and steel fiber reinforcement composition. An issue presented by optimization studies is the difficulty of reproducing results due to variations in material availability. Analysis of UHPC testing that focuses on the properties of the cements themselves rather than the specific samples from certain, likely local, manufacturers may provide insight that is more widely applicable in other studies.

1.2 Project Scope

This research project aims to develop a standardized, baseline UHPC mix design that allows the various cement properties to have greater, more noticeable effects on the fresh and hardened properties of the test mixes. This research seeks to use compressive strength testing and calorimetry testing to identify the cement properties that correlate to improved UHPC performance.

1.3 Goals and Objectives

1.3.1 Goals

The goal of this research is to determine the cement properties best suited for use in optimizing UHPC formulations.

1.3.2 Objectives

The objectives necessary to reach this research goal are as follows:

- Compare the effects of different cement types, classes, and chemical compositions on the fresh properties of a standardized UHPC mix design

- Determine the relationship between strength gain and heat generation for different cement types, classes, and chemical compositions used in a standardized UHPC mix design
- Determine the impact of cement type, class, and composition on the response and behavior of a standardized UHPC mix design

1.4 Outline

This thesis consists of seven chapters and an appendix. Chapter 1 contains a brief background and justification for this research project, as well as an outline of the project scope, goals, and objectives. Chapter 2 reviews literature relevant to the project, including the topics of cement composition, cement reactivity and heat of hydration, mixing/curing temperature, fluidity, and UHPC mix optimization approaches. Chapter 3 details the development of the baseline UHPC mix used throughout the project. Chapter 4 summarizes the compressive strength testing performed on the UHPC specimens. Chapter 5 details the calorimetry testing that was performed. Chapter 6 contains the analysis done on the data gathered in Chapters 4 and 5, including analyses based on cement type/class, cement composition, and thermal profile. Chapter 7 summarizes the findings, conclusions, and recommendations of the research project. The appendix contains the mill certification reports of the different cements used in the study, as well as the raw data collected during compressive strength and calorimetry testing.

2 Literature Review

2.1 Introduction

Ultra-high-performance concrete (UHPC) is a fairly recent development in structural materials. The Federal Highway Administration defines UHPC as “a cementitious composite material composed of an optimized gradation of granular constituents, a water-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement” (Graybeal, 2011). Along with these qualities, the FHWA specifies UHPC as having a compressive strength greater than 21.7 ksi (150 MPa) and sustained postcracking tensile strength greater than 0.72 ksi (5 MPa). The improved strength and durability of UHPC creates opportunities for applications and designs that would not otherwise be possible or efficient. UHPC first became commercially available in the United States beginning in 2000, and it is increasingly being considered for use by state transportation departments in highway infrastructure applications.

This chapter contains a review of the literature related to the fresh properties, hardened properties, and optimization of UHPC. UHPC, and concrete as a whole, is known to be affected by temperature during both the mixing and curing process. In addition to high strength, UHPC is notable for its high fluidity, prompting researchers to explore different factors that affect mix fluidity. The high price of UHPC relative to normal strength concrete has created the imperative to optimize the balance of cost and performance. This optimization has been attempted through research involving combinations of supplementary cementitious materials (SCMs) in varying quantities, different cements, and different chemical admixtures that all influence the fresh and hardened properties of the UHPC.

2.2 Cement Chemical Composition Reactivity and Impact on Strength

Several different chemical compounds make up portland cements and contribute to its cementitious properties. Some of the most notable of these compounds are Tricalcium silicate (Ca_3SiO_4, or C_3S), Dicalcium silicate (Ca_2SiO_5, or C_2S), Tricalcium aluminate ($Ca_3Al_2O_6$, or C_3A), and Tetracalcium aluminoferrite ($Ca_4Al_2Fe_2O_{10}$, or C_4AF) (Mindess et al., 2003). These compounds are commonly referred to in their shorthand notation, and their composition restrictions in the different types of portland and oil well cements are specified in ASTM C150. Each compound has a different rate of hydration and contribution to cement strength gain. C_3S reacts at a moderate speed and has a high contribution to cement strength. C_2S has a slower reaction speed and a lower contribution to early strength gain, with higher eventual contribution. C_3A, in combination with gypsum, has a fast reaction speed and a lower contribution to strength gain. C_4AF, also in combination with gypsum, reacts at a moderate speed and also has a low contribution to strength gain. Of these compounds, C_3S and C_2S contribute the most toward the ultimate strength developed by the cement.

2.3 Cement Hydration and Calorimetry

A key component in maximizing the ultimate strength of concrete is maximizing the hydration of the constituent cementitious materials. The hydration in cement is all exothermic, and the different chemical compounds generate different amounts of heat as a result of their hydration reactions (Mindess et al., 2003). C_3A has the highest level of heat generation, followed by C_3S, C_4AF, and C_2S. The heat of hydration for a cement is commonly reported in a cement mill certificate (mill cert), though ASTM C150 does not require its reporting for most standard types of portland cement.

Heat of hydration, as specified by ASTM C1702, is measured using isothermal conduction calorimetry. In UHPC, the heat of hydration for a particular mix can be useful information as a possible indicator of other behaviors and so any detrimental behaviors can be avoided through careful design (Graybeal, 2006). High temperature gradients that develop in massive concrete specimens can lead to cracking that ultimately reduces strength and durability, making avoidance measures beneficial (Siler et al., 2011). Supplementary cementitious materials (SCMs), like silica fume and fly ash, as replacements for ordinary portland cement (OPC) reduce the heat generated during the hydration process, resulting in less thermal cracking in massive construction. Silica fume, with its fine particles and high reactivity, has been found to accelerate early hydration reactions and improve early concrete strength.

2.4 Effects of Mixing and Curing Temperature

As UHPC is still largely unfamiliar and uncommon, researchers are singling out specific factors in the mixing and curing procedure to determine the overall effects on the performance of the mixture. In particular, researchers are interested in how UHPC performs under various field conditions, including the temperature during mixing and curing of the concrete. Normal strength concrete is already known to be sensitive to temperature conditions during mixing and curing due to the hydration reactions that give concrete its strength (Araldi et al., 2019).

A recent study by Polytechnique Montreal investigated the impact of different combinations of mixing and curing temperatures, ranging from 10-30˚C (50-86˚F) for mixing and 10-35˚C (50-95˚F) for curing (Androuet et al., 2021). The goal of the study was to emulate field conditions and evaluate fresh and hardened properties of a typical UHPC to provide insight for planning curing duration and formwork stripping. The study found that mixing temperature had only a slight positive impact on compressive strength, and even then, only when cured at a lower temperature. Curing temperature, however, was found to have a more significant impact on compressive strength, with higher curing temperatures resulting in higher compressive strengths.

2.5 Causes of Fluidity in UHPC

In that same study by Polytechnique Montreal, it was found that increasing mixing temperature from 10˚C to 30˚C (50 to 86˚F) resulted in a reduction of 15% of the UHPC slump flow with only a slight increase in compressive strength.

In addition to mixing temperature, the properties of the silica fume being used in the UHPC has a significant impact on the fluidity of the mixture. A study performed at the Harbin Institute of Technology found four silica fume properties with varying influences on fluidity (Lin et al., 2019). Lower void ratios in the silica fume increases the “plasticizing effect”, resulting in a smaller quantity of superplasticizer required to reach the same fluidity. Higher carbon content in silica fume was found to decrease the fluidity of the mixture, as carbon is porous and able to absorb superplasticizer. Related to void ratio, having a more uniform particle size distribution enhances the “plasticizing effect”, as the silica fume particles are able to fill the voids of not only cement particles but also particles of other mineral admixtures. Further related to void ratio, higher packing density of solid particles in the silica fume-cement system results in improved fluidity. The study can be summarized as concluding that the “plasticizing effect”, filling cement particle voids with smaller spherical silica fume particles rather than water, has a significant positive effect on the fluidity of the UHPC mixture.

In addition to the effects of solid particles, the liquid components of UHPC have a significant impact on the fluidity of the mixture. A study conducted at the University of Michigan found HRWR dosage to be very important for countering the greater water demand of mixes with higher packing density (Tai et al., 2020). Though small decreases in compressive strength corresponded to higher HRWR dosages, the ability of HRWR to increase fluidity and facilitate field mixing without significantly impacting the hardened properties of the UHPC enables the mixture to be adapted more readily in the field. Despite this, researchers at the University of Oklahoma have observed that HRWR does not have as strong an influence on the fluidity of a mixture as the water/cementitious material (w/cm) ratio (McDaniel, 2017). A balanced ratio of w/cm and HRWR is required to make the UHPC flowable without becoming sticky and unusable.

2.6 Optimization of UHPC Mixes

UHPC is typically optimized in one of two ways, either for cost or for performance. When optimizing for cost, mix designers frequently turn to SCMs. Higher proportions of SCMs reduce the amount of cement in the mix, which is beneficial as cement is one of the most expensive components of UHPC. Silica fume is both less expensive than cement and also beneficial for the performance of the mixture, allowing for smaller quantities of stronger UHPC to be used at a lower cost. Fly ash and ground-granulated blast-furnace slag (GGBFS) have also been included in mixes to reduce cost and to improve performance, though the combination of the two is not advised (McDaniel, 2017). Researchers at the University of Michigan recently conducted a study to reduce the overall cost of a UHPC mix without sacrificing performance (Alkaysi et al., 2015). The researchers tested combinations of different cements, silica fume contents, and silica powder contents to find which mixes maintained ultra-high-performance with a lower material cost than the baseline mix. After comparing twenty-eight mixes, it was found that a blended portland Type I/GGBFS mix was the most cost-effective, though not the strongest in compression.

When optimizing for performance, there are many different methods that can be applied. Some methods rely on curing procedures to increase compressive strength, such as oven heat curing to increase early strength gains (McDaniel, 2017). Nonstandard curing methods can be difficult to implement in the field, however, so optimizations in the mix design itself are generally more effective. Some researchers have found success in utilizing dry/wet particle packing methods to maximize the initial packing density of the UHPC mix (Du et al., 2021). As previously mentioned, using silica fume for this purpose can increase the "plasticizing effect" that can reduce the amount of HRWR in the mix. The optimal silica fume content varies from mix to mix, but success has been found with using 10-12.5% silica fume by mass (McDaniel, 2017). Additionally, mixing time can vary significantly from mix to mix, depending on material constituents and ratios.

3 Mix Design

3.1 Introduction

This chapter details the procedure by which the final mix design was selected for testing, as well as how the mixing procedure was developed. This research required a single mix that would only be altered by replacing the cement with different samples and adjusting HRWR contents to achieve acceptable mortar flow (flow). This mix would then need to be repeated for each of the different cements with as much consistency as possible, necessitating a standardized mixing procedure with established timing and parameters for what constitutes an acceptable mix for hardened testing.

3.2 Initial Mix Design

The initial mix design for this project was selected based on prior research performed at Fears Lab. Research performed by Amy McDaniel (2017) yielded a mix design, designated J3, that was determined to be optimal based on variables that included water/cementitious material (w/cm) ratio, supplementary cementitious material (SCM) content, and aggregate/cementitious material (agg/cm) ratio. This mix design is shown in Table 3.1.

Table 3.1 J3 Mix Design Proportions

Silica Fume	0.1
GGBFS	0.3
Type I Cement	0.6
w/cm	0.2
agg/cm	1:1
HRWR (oz./cwt)	18.7
Steel Fibers (% by volume)	2

Though it was expected that the mix design would have to be altered to meet the goals of this project, the consistent performance of J3 in various projects at Fears Lab made it a suitable starting point.

3.3 Mix Proportion Optimization

With an initial baseline mix design selected, optimizations were required to tailor the mix design to this particular project. Because this project aimed to compare the effects of different cement types, it was determined that multiple components would need to be omitted from the mix design. Steel fiber reinforcement and GGBFS were omitted to reduce the number of components that would impact the fresh and hardened properties of the test mixes.

The removal of GGBFS required a rebalancing of proportions for the remaining components. GGBFS composes 30% of the cementitious material in J3, so silica fume and cement content would have to be increased to compensate. These increases were accompanied by an increase in w/cm ratio from 0.20 to 0.25 to ensure hydration of the cement and improve flow. In order to develop an optimal mix with regards to flow and compressive strength, adjustments were divided into three categories: agg/cm ratio, silica fume content, and HRWR dosage.

3.3.1 Agg/cm Ratio

Initial test mixes were prepared to determine the effects and viability of increasing the agg/cm ratio with larger quantities of fine masonry sand. The proportions of these initial mixes and their resulting flows are shown in Table 3.2.

Table 3.2 Increased Agg/cm Ratio Test Mixes

Test Mix	Silica Fume Content	Portland Cement Content	agg/cm	Initial HRWR Dosage (oz/cwt)	Total HRWR Dosage (oz/cwt)	Flow (in)
1	0.25	0.75	1.5:1	16.0	28.0	Thixotropic
2	0.20	0.80	1.25:1	18.0	20.6	Thixotropic
3	0.20	0.80	1:1	18.0	18.0	6.88

Despite additional HRWR being added at 3 stages, Test Mix 1 was found to be thixotropic (flowable only with applied agitation) and unsuitable for further testing. Test Mix 2 was prepared with a lower agg/cm ratio, lower silica fume content, and higher initial HRWR dosage to improve the flow. Visual inspection of Test Mix 2 deemed it an improvement over Test Mix 1, but the flow remained thixotropic. For Test Mix 3, agg/cm ratio was reduced to initial J3 levels and the result was a mix that did flow of its own volition. Based on the relative success of Test Mix 3, an agg/cm ratio of 1:1 was selected for further test mixes.

3.3.2 Silica Fume Content and HRWR Dosage

The adjustments to silica fume content and HRWR dosage were combined due to how interrelated their effects are on flow. Two silica fume contents, 0.20 and 0.25, were selected to be tested and HRWR dosages were adjusted for each to determine ranges of dosages that were most likely to result in a flow value within the parameters of an acceptable mix. Test mixes 4-19 are shown in Table 3.3 and all had an agg/cm ratio of 1:1 and a w/cm ratio of 0.25. Table 3.4 is an alternative version of Table 3.3 with the same data organized by ascending silica fume content and HRWR dosage. Test mixes labeled with an asterisk were mixed prior to the relocation of mixing equipment.

Table 3.3 Silica Fume Content and HRWR Dosage Test Mixes

Test Mix	Silica Fume Content	Portland Cement Content	HRWR Dosage (oz/cwt)	Flow (in)	Temperature (˚F)	Relative Humidity (%)
4*	0.20	0.80	21.0	8.50		
5*	0.20	0.80	22.0	Over 10		
6*	0.20	0.80	21.0	9.50*		
7	0.20	0.80	21.0			
8	0.20	0.80	21.0	6.00	73.9	45
9	0.20	0.80	24.0	11.44	72.9	65
10	0.20	0.80	22.7	8.38	74.3	66
11	0.25	0.75	22.7	Thixotropic	72.5	68
12	0.25	0.75	25.0	8.13	75.2	67
13	0.25	0.75	25.3	8.00	73.6	71
14	0.25	0.75	25.8	8.81	74.1	72
15	0.20	0.80	23.3	9.50	76.1	77
16	0.20	0.80	23.0	10.00	72.3	51
17	0.20	0.80	22.5	8.31	75.6	59
18	0.25	0.75	23.0	Thixotropic	79.7	61
19	0.25	0.75	25.8	8.00	84.2	67

Table 3.4 Alternative Organization of Table 3.3

Test Mix	Silica Fume Content	Portland Cement Content	HRWR Dosage (oz/cwt)	Flow (in)	Temperature (˚F)	Relative Humidity (%)
4*	0.2	0.8	21	8.5		
6*	0.2	0.8	21	9.50*		
7	0.2	0.8	21			
8	0.2	0.8	21	6	73.9	45
5*	0.2	0.8	22	Over 10		
17	0.2	0.8	22.5	8.31	75.6	59
10	0.2	0.8	22.7	8.38	74.3	66
16	0.2	0.8	23	10	72.3	51
15	0.2	0.8	23.3	9.5	76.1	77
9	0.2	0.8	24	11.44	72.9	65
11	0.25	0.75	22.7	Thixotropic	72.5	68
18	0.25	0.75	23	Thixotropic	79.7	61
12	0.25	0.75	25	8.13	75.2	67
13	0.25	0.75	25.3	8	73.6	71
14	0.25	0.75	25.8	8.81	74.1	72
19	0.25	0.75	25.8	8	84.2	67

During the process of preparing these test mixes, it was observed that the flow was sensitive to environmental conditions, particularly temperature and relative humidity. Identical mixes, like Test Mixes 4, 6, and 8, were prepared in different environmental conditions and had significantly different flow results. To account for this sensitivity and reduce the fluctuations in temperature and relative humidity, the mixer and batching materials were moved to an enclosed space to provide more consistent control over conditions. Test mixes beginning with Test Mix 8 were prepared in this controlled space. More details on adjustments to mixing conditions and procedures are discussed in Section 3.4.

After relocating the batching and mixing equipment and materials, six test mixes each were prepared for silica fume contents of 0.20 and 0.25. It was difficult to consistently match a HRWR dosage to silica fume content and environmental conditions and obtain a flow that was within acceptable mix parameters. Test mixes that did have a flow within acceptable parameters were placed in 2 in. cube specimens for heat curing. After 24 hours of curing at 72°F, cube specimens were placed in an environmental chamber for heat curing over a period of 48 hours at 194˚F (90˚C) and 95% relative humidity. After the 48 hours, the chamber and specimens were allowed to cool for 24 hours before specimens were removed. After heat curing, each set was tested to find their approximate 28-day compressive strength. These values are shown in Table 3.4.

Table 3.5 Compressive Strength for Acceptable Test Mixes

Test Mix	**Silica Fume Content**	**HRWR Dosage (oz/cwt)**	**Flow (in)**	**Average Compressive Strength (psi)**
14	0.25	25.8	8.81	15,020
15	0.20	23.3	9.50	15,900
17	0.20	22.5	8.31	16,020
19	0.25	25.8	8.00	16,470

While the different silica fume contents resulted in similar compressive strengths, it was decided that a silica fume content of 0.20 would be used for further mixes. Silica fume tends to result in "stickier" mixes, thus a lower amount generally improves overall workability. The average compressive strength for mixes with a silica fume content of 0.20 was 15,960 psi compared to an average of 15,745 psi for 0.25. Further, mixes with a content of 0.20 required lower dosages of HRWR to achieve acceptable flow values, making them easier to work with.

3.3.3 Final Mix Design Considerations

Having experimented with proportions for agg/cm ratio, silica fume content, and HRWR dosage, a final mix was deemed optimal for this project. The proportions for that final mix are shown in Table 3.5.

Table 3.6 Final Mix Design Proportions

Silica Fume	0.20
Cement	0.80
w/cm	0.20
agg/cm	1:1
Base/Initial HRWR (oz./cwt)	23.3

While this final mix design sacrifices compressive strength by omitting GGBFS and steel fiber reinforcement, it was believed that this rebalanced mix would allow the different cements to have a larger, more significant impact on the compressive strength of each mix. It is worth noting that the alterations from the base mix J3 rendered the test mixes unable to meet the FHWA definition of UHPC. The removal of steel fiber reinforcement and the increased w/cm of 0.25 disqualified the test mixes based on composition. Further, the removal of components like steel fiber reinforcement and GGBFS resulted in a significant negative impact on the compressive strength of the hardened UHPC, making test mixes incapable of reaching the FHWA threshold of 21.7 ksi (McDaniel 2017). For the purposes of this project, test mixes are still referred to as UHPC despite this shortcoming.

3.4 Development of Mixing Procedure

In developing the finalized mixing procedure, the baseline was selected from the same source as the mix design; previous research at Fears Lab involving the UHPC mix J3. The following is the mixing procedure, which is also based on similar research (Graybeal, 2006; McDaniel, 2017):

1. 0:00 – 0:10: blend dry constituents at low speed
2. 0:10 – 0:12: add water mixed with half of the HRWR dosage, gradually, at low speed
3. 0:12 – 0:13: run at low speed
    a. Suspend mixing and scrape bowl
4. 0:13 – 0:14: add second half of the HRWR dosage, at low speed
5. 0:14 – 0:17: run at low speed
    a. Suspend mixing and scrape bowl
6. 0:17 – 0:19: run at medium speed
7. Establish if additional mixing time is required
8. Conduct mortar flow test
9. Place in molds

This initial procedure served as a useful starting point, and remained largely unchanged through the finalized procedure. Steps 3a and 5a were especially important in preventing the buildup of dry or stiff material at the bottom of the mixing bowl, which could alter the homogeneity of the mix. Increasing the batch size from 0.10 cu. ft to 0.12 cu. ft further reduced this buildup significantly, though these steps were retained as a precaution and point of consistency.

As test mixes were prepared, adjustments were made to address potential complications and opportunities for reducing inconsistencies that arose. The low batch quantities made it difficult to add the water and HRWR in Steps 2 and 4 over the full allotted times, so the allotments were shortened in half and kept constant throughout all test mixes. Step 4 was modified again by using a syringe to add the HRWR at a slow, constant pace for the full thirty seconds. The syringe allowed for better control and accuracy in this stage. A further simplification was made to maintain the same low speed throughout the mixing process without increasing the speed in Step 6.

An additional step was added beginning with Mix 5, which was a check to determine if additional HRWR would be necessary to achieve an acceptable flow. Prior to adding this step, adjustments to dosage were only made before mixing began, which limited the amount of control over the final results. The inclusion of this step reduced the number of batches required to meet acceptable parameters and thus reduced material waste.

Finally, Step 7 was removed and Step 6 was modified to have the mixer run until a total mixing time of 25 minutes had passed. Early test mixes relied on operator judgement for determining if the mix was ready or if it needed additional mixing time. Selecting 25 minutes as the set total time for every mix removed operator judgement as a factor and ensured every mix was prepared with the same procedure. The final mixing procedure was as follows:

1. 0:00 – 0:10: blend dry constituents at low speed
2. 0:10 – 0:11: add water mixed with half of the HRWR dosage, gradually, at low speed
3. 0:11 – 0:13: run at low speed
    a. Suspend mixing and scrape bowl along sides and bottom
4. 0:13 – 0:14: add second half of the HRWR dosage using a syringe, at low speed
5. 0:14 – 0:17: run at low speed
    a. Suspend mixing and scrape bowl along sides and bottom
6. 0:17 – 0:20: run at low speed
7. At 0:20: decide if mix requires additional small dosage of HRWR to meet flow requirements. If it does, add HRWR and record the additional dosage
8. 0:20-0:25: run at low speed
9. Conduct mortar flow test
10. Place in molds if flow is within acceptable parameters

Establishing the final mixing procedure required more than just adjusting the steps of the mixing itself. The issue of unpredictable and inconsistent environmental conditions in the lab had to be addressed, as flow was found to be sensitive to ambient temperature and relative humidity. The flows of identical mixes prepared on different days varied by almost 2 in. because of differences in the lab environment. To address this issue, mixing and flow testing equipment was moved to an enclosed, environmentally-controlled room that was not as severely affected by outside conditions. Batching materials were also moved to this space to protect them from environmental fluctuations. This enclosed space had its own air conditioning unit to monitor and adjust the temperature and humidity, as well as an additional dehumidifier unit to further control humidity. The space was maintained at or around 72˚F and 50% relative humidity throughout the curing process. Relocating to this alternative mixing space resulted in a noticeable and significant improvement in the predictability of mix behavior.

Other complications arose during testing with regards to testing the flow of a mix. The standard flow table was incapable of measuring flows greater than 10 in., and mixes with flows approaching 9.5 in. or greater ran the risk of not being perfectly centered and flowing off the table slightly, skewing the results and rendering them inaccurate. Accurate flow measurements were crucial, not only for reporting purposes and for fitting within acceptable parameters, but also for adjusting HRWR dosages for subsequent mixes. A flow that fell outside of acceptable parameters could still be used to improve future mixes through the use of linear interpolation to predict a HRWR dosage that would be likely to fall within acceptable parameters. This method of prediction required accurate flow measurements, so accommodations were made to ensure accurate measurements could be taken. To this end, a larger flow table, conforming to ASTM C230 specifications, was acquired and implemented to allow for flow measurements of up to 12 in. This larger flow table removed the issue of UHPC flowing over the sides and skewing the measurements results, and it proved to be successful throughout the entirety of its use in this project.

After addressing the issues and sources of potential inconsistencies discovered throughout the initial phase of test mixes, testing could proceed with confidence that each mix would have a high degree of consistency.

3.4.1 Acceptable Mix Parameters

Throughout the initial phase of test mixes, the parameters that determined what constituted an acceptable mix were subject to discovery and alteration when necessary. Some parameters, like homogeneity and workability, were straightforward and clear from the onset. Others, like a lack of significant buildup of dry, unmixed material were made obvious during these test mixes and were added to consideration once they had made themselves known. While this particular issue was largely addressed by increasing the batch size and scraping the bowl thoroughly at two stages of mixing, the parameter remained for quality control purposes.

One parameter that had to be adjusted over the course of the initial phase of mixing was the range of acceptable flow values for a test mix. The initial range for acceptable values was set at 9 ± 0.5 in., and this was believed to be a realistic and reasonable range to target. Test Mixes 1-19 proved otherwise, however, as only 3-4 mixes fell within this range in spite of best efforts. After consideration, the range for acceptable flow values was increased to 9 ± 1 in., as this was believed to be significantly more attainable while still keeping mixes within a tight enough range to be comparable.

3.4.1.1 Special Exception to Parameter Requirements

Through the use of multiple trial mixes and HRWR dosages, the majority of mixes were adjusted to meet the parameters for an acceptable mix. The singular exception to this was Mix 12, which was prepared using a Class H oil well cement. Trial mixes with this cement demonstrated that excessively high dosages of HRWR were required to meet the acceptable flow requirements, to the degree that the mix was overdosed. It was clear the mix was unacceptable at the 24 hour demolding stage. Figures 3.1 and 3.2 show the specimens before and after demolding.

Figure 3.1 Overdosed Cube Specimens in Molds

Figure 3.2 Overdosed Cube Specimens Demolded

After demolding the overdosed cube specimens and wiping away the excess liquid, it was confirmed that the cubes were unacceptable for compressive strength testing. The specimens were noticeably soft, a generally undesirable quality for UHPC, and could be scratched by a fingernail with light pressure after 24 hours of curing. It was decided the mix would be redone with the maximum allowable dosage that would not result in such unusable test specimens.

After further trials, the maximum allowable dosage of HRWR resulted in a mix with a flow of just 4.91 in., well below the minimum acceptable flow of 8 in. Ultimately, the base mix design would have to be altered for this cement to be capable of meeting flow requirements. Since this was not an acceptable option at this stage, this mix, Mix 12, was still placed in the cube molds and given additional effort and time dedicated to consolidating the UHPC within the molds. It was decided that, if the cured specimens were fully consolidated, they would still be tested for compressive strength with the understanding that they fell outside of acceptable parameters. Figures 3.3 and 3.4 show Mix 12 specimens before and after demolding at 24 hours.

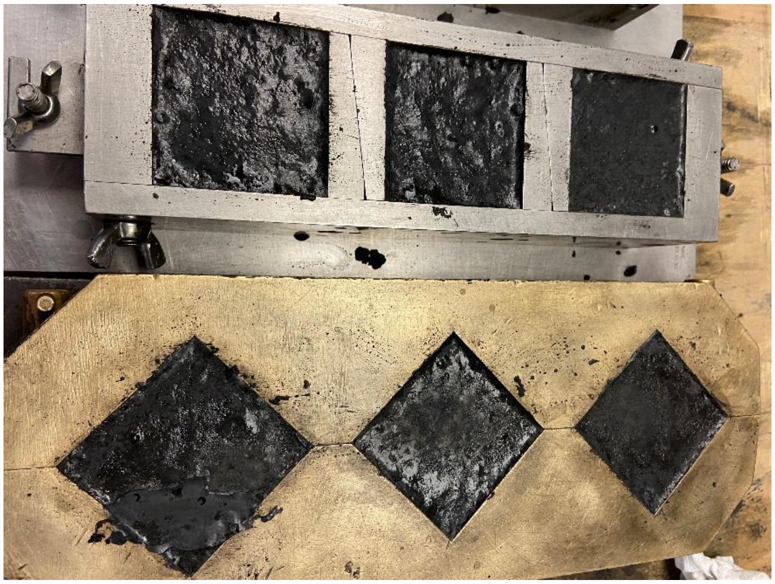


Figure 3.3 Mix 12 Cube Specimens in Molds

Figure 3.4 Mix 12 Cube Specimens Demolded

Upon demolding, it was determined that the cube specimens were fully consolidated and acceptable for testing. The results of the compressive strength testing for Mix 12 can be found in more detail in Chapter 4.

3.5 Blended Cement Testing

The exception made for Mix 12 prompted a truncated experiment to determine if a blended cement consisting of equal parts Type I/II and Class H oil well cements would perform more similarly to other, more typical mixes. Though this mix was not used for full comparison like the others, the results would determine if future research into the effects of blending cements in UHPC are warranted.

3.6 Sample Cement Material Acquisition

The collection of sample cement materials was a crucial aspect of this project, as a wide array of types and manufacturers was required to allow the project to provide any insight on the effects of different cement types and chemical compositions. In order to gather these materials, samples were requested and acquired from various manufacturers, primarily American Concrete Institute (ACI) members. In addition to these, samples that had been collected for previous research at Fears Lab were also gathered for this project. Requested materials included any official type of portland cement as well as oil well cements, with the requirement that any sample be accompanied by a verified cement mill certificate (mill cert). Without the mill cert, a cement sample could not be meaningfully compared to others used in this project. At the beginning of this project, it was established that a minimum of 10 samples was required to meet the needs of this project. This goal was met with a collection of 11 different samples from 6 manufacturers and plant locations in 8 states.

3.7 Cement Mill Certs

A cement mill cert is a standard document, conforming to ASTM C150 specifications, that contains a plethora of useful information for comparing different cements. A mill cert specifies the type designation of the cement and displays an array of chemical and physical properties alongside the ASTM C150 specified limits for each property, when applicable. Properties that are of particular interest for this project include C_3S content, C_2S content, C_3A content, and Blaine fineness. The collected cement mill certs and the information on them was used to identify patterns and, if possible, draw conclusions regarding the effects different cement types and compositions have on UHPC mix performance. The mill certs are included in Appendix C.

4 Compressive Strength Testing

4.1 Introduction

This chapter describes the procedure and results from compressive strength testing performed on cube specimens. The cube specimens were tested according to ASTM C109, which pertains to hydraulic cement mortars, as the concrete test mixes lack coarse aggregate and internal fiber reinforcement. Thirteen total batches of cubes, each from a different mix, were prepared and tested for compressive strength at testing ages of 24 hours, 3 days, 7 days, 14 days, 28 days, and 56 days.

4.2 Procedure

All sets of cube specimens were prepared for testing using the mixing procedure detailed in Chapter 3. This mixing procedure allowed for a high level of overall consistency between test batches, though some anomalies did present themselves. These anomalies are detailed in Section 4.2.3, along with the measures taken to adjust for these anomalies.

4.2.1 Specimen Preparation

All cube specimens were prepared using the same 6 sets of 2 in. cube molds, each set capable of producing 3 cubes. Prior to the time of mixing, each mold was disassembled, cleaned, coated in a thin layer of form release agent, and reassembled. If a prepared test batch of UHPC met the parameters for an acceptable mix, it was placed in the cube molds. The molds were tapped firmly and repeatedly to assist in consolidation and the top surface was struck off with a flat scraper. After specimens had been fully prepared, they were covered with a sheet of plastic to preserve moisture during the initial stage of curing.

In keeping with ASTM C109 procedures, all cube specimens were demolded at 24 ± 0.5 hours and further prepared for testing. Specimens were labeled with the mix label and date of mixing. Proper labeling was crucial for preventing confusion later on that might interfere with test results. Cube specimens also had their edges scraped with a scraper to remove raised areas and sharp edges. Bearing surfaces received a light scraping as well to ensure that they were fully smooth. This edge and bearing surface preparation was determined in prior research to lead to slightly better testing results from cube specimens (McDaniel, 2017).

After cube specimens had been labeled and scraped, a single set of 3 cubes was set aside for the 24 hour testing while the others were placed in a lime water bath for curing. Cubes were left in the lime bath for the full duration leading up to the time of testing. Prior to testing, each set of cube specimens was measured with dial calipers to maximize the accuracy of test results. Dimensions were recorded to the nearest 0.001 in. to account for variations formed during placement and any shrinkage or expansion that may have occurred during curing. While the differences in dimensions between specimens were small, these recorded dimensions were used to calculate compressive strength rather than the assumed 4 in.^{2}.

4.2.2 Testing

Minor modifications were required to adjust the compressive strength testing procedure to UHPC, as the ASTM considers standard cement mortar specimens instead. The applied load rate was standardized as 600 lb/s (150 psi/s) for a 4 in.^{2} bearing surface. Additionally, permissible tolerance ranges for specimen test ages of 14 days and 56 days are not specified, so linear interpolation was used to fill in the blanks. Based on those provided, a permissible tolerance of ±6 hours was chosen for 14 day specimens and ±24 hours for 56 day specimens. Initially, expected compressive strength was not easily estimated, so a preload of 8,000 lb (2,000 psi) was selected to avoid exceeding 50% of total load at failure. After multiple mixes had undergone testing at different ages, estimates for load at failure could be improved and the preload was adjusted accordingly to testing age while still avoiding exceeding 50% of total load at failure.

4.2.3 Testing Anomalies

Over the course of testing, different anomalies were encountered. The first to present itself was the Mix 7 Day 1 set, which had the first specimen fail at 8,410 lb (2,110 psi), almost immediately following the preload of 8,000 lb (2,000 psi). After reducing the preload to 1,000 lb (250 psi), the second specimen failed at just 2,750 lb (690 psi), roughly a quarter of the first specimen. This second specimen did not fail in the same pattern typical for a Day 1 break, visible in Figure 4.1, and instead appeared to only partially fail. To test this theory, the specimen was tested a second time, this time failing at 17,900 lb (4,480 psi). While this result would still be considered invalid, it did indicate that the set was capable of reaching strengths more comparable to the average measured so far. The third specimen failed at a load of 19,320 lb (4,810 psi), far exceeding the first two specimens. Based on these results, it is believed that the issues were likely due to faulty specimens from errors made during specimen preparation/placement. As a result, it was decided that Mix 7 would be redone with Mix 8, though testing with Mix 7 did continue to determine if the same issues would persist at later testing ages.

The next testing anomaly was encountered with two different mixes and sets. Mix 3 Day 56 and Mix 9 Day 28 experienced the same issue where a cube specimen failed during preload, despite the preload being below 50% of the average for the two remaining cubes in each set. To avoid causing premature failure in other specimens, the maximum preload for testing was set at 18,000 lb (4,500 psi) and the issue was not encountered again after the change. It is unknown what the cause of this premature failure was.

The final anomaly was encountered with Mix 12, the details of which are discussed in Chapter 3. Mix 12 did not meet the parameters for an acceptable mix, and it was determined that it would not be possible to adjust the HRWR dosage to meet the parameters without also altering the base mix. Though Mix 12 required additional effort and time to consolidate fully in the cube molds, it was deemed acceptable for testing. The cube specimens at early ages were found to have significantly lower compressive strength than other mixes, but results became reasonably comparable to others at a test age of 14 days and beyond.

4.3 Summary of Results

4.3.1 Typical Cube Failure Mode

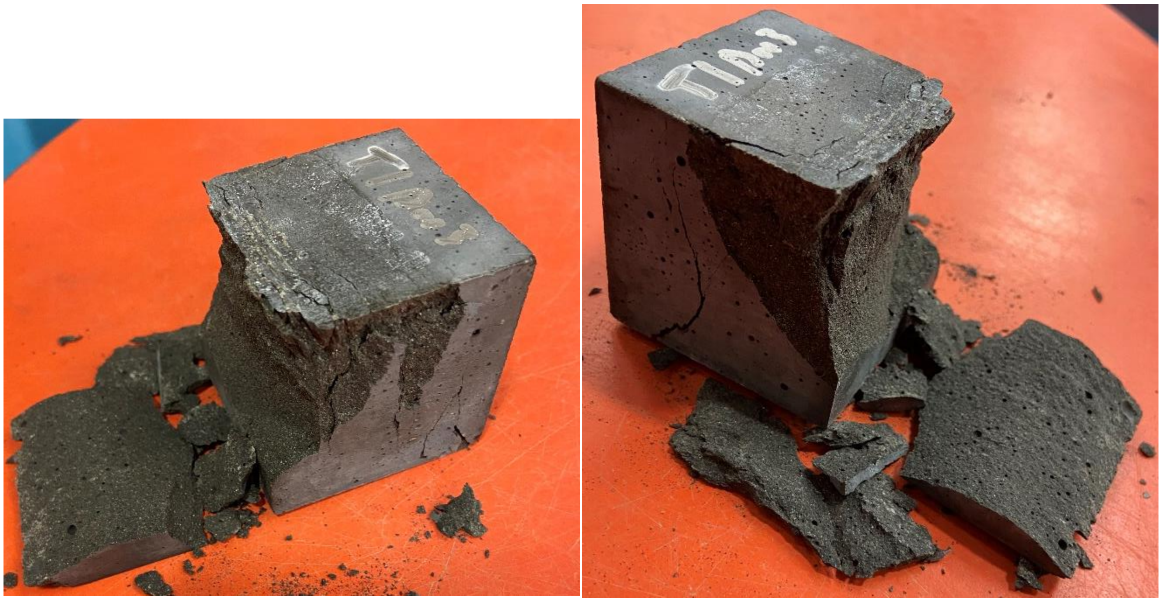
Outliers and inconsistencies are not unexpected due to the variable nature of concrete and specimen preparation/placement. Despite the anomalies observed during testing, most of the cube specimens performed consistently. Cube specimens were found to generally follow a predictable pattern of failure based on specimen maturity. A typical example of a 1 day cube break is shown in Figure 4.1.

(a) *(b)*

Figure 4.1 Typical 1 Day Break Failure Morphology

A typical 1 day cube had cracks along some of the top edges and along the edges of the cube face that was the exposed top face during casting. These specimens sometimes showed signs of crushing and remained mostly intact, even after failure. Most 1 day specimens failed along this pattern, though some approached a cross between a 1 day and a 3 day fracture pattern with a singular face breaking off.

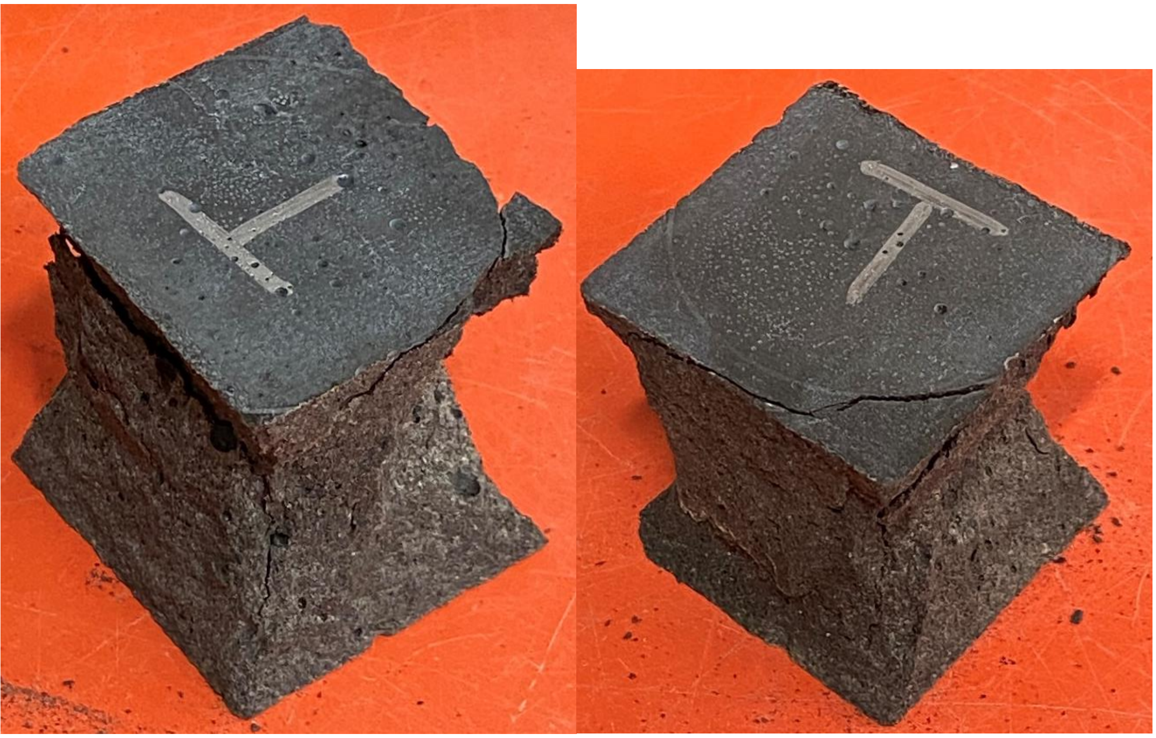
A typical 3 day cube specimen had a more developed failure mode than a 1 day specimen, usually with the exposed top face breaking off completely from the failed specimen and parts of other faces flaking off as well. The angle of the failure began to approach 45˚ from the corners of the cube toward the center, and this angle became more pronounced as specimens advanced in maturity. Most 3 day specimens followed this failure pattern with some exceptions that had more vertical fracture lines. An example of a typical broken 3 day cube specimen is shown in Figure 4.2.



(a) *(b)*

Figure 4.2 Typical 3 Day Break Failure Morphology

A typical 7 day cube specimen failure continued the pattern as a more developed form of a 3 day break. The four non-bearing surface faces of the cube typically fractured off or could be pulled apart without any effort. The angle of the failure from the corners of the cube were closer to 45˚ than earlier specimens, and the failed specimens appeared reminiscent of a Type 1 fracture pattern as defined by ASTM C39. Typical examples of 7 day cube failures are shown in Figure 4.3.



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(a) *(b)*

Figure 4.3 Typical 7 Day Break Failure Morphology

Cube specimens aged 14 days and beyond typically broke similarly, with a more developed fracture compared to a 7 day break. At 14 days, the failed specimens could be pulled apart into two roughly pyramidal pieces. Variations of this pattern were similar but the two main pieces each fractured into several more pieces held together by friction and geometric interlock. The 28 day and 56 day specimens typically followed this same 14 day pattern but fractured more completely into several smaller pieces. Examples of 14, 28, and 56 day specimen failures are shown in Figures 4.4, 4.5, and 4.6.

Figure 4.4 Typical 14 Day Break Failure Morphology

Figure 4.5 Typical 28 Day Break Failure Morphology

Figure 4.6 Typical 56 Day Break Failure Morphology

4.3.2 Raw Compressive Strength Testing Data

The raw compressive strength testing data is shown in Tables 4.1 and 4.2. The only adjustments made to the data in these tables is the conversion of the failure load (lb) to stress at failure (psi) using the dimension measurements with the dial caliper prior to testing. Failure loads and cube specimen dimensions can be found in Appendix A.

Table 4.1 Raw Compressive Strength Data, Mixes 1-6

		Compressive Strength (psi)					
		1 Day	**3 Day**	**7 Day**	**14 Day**	**28 Day**	**56 Day**
Mix 1	**Cube 1**	6,578	6,266	10,941	11,944	15,350	14,718
	Cube 2	6,132	10,324	11,428	13,266	14,220	14,544
	Cube 3	5,761	9,890	12,121	13,843	13,619	14,619
	Average	**6,157**	**8,827**	**11,497**	**13,017**	**14,396**	**14,627**
Mix 2	**Cube 1**	7,241	9,805	13,755	12,636	13,967	17,664
	Cube 2	7,409	11,544	13,306	12,719	12,291	17,165
	Cube 3	6,880	11,476	13,918	13,663	13,963	17,020
	Average	**7,177**	**10,942**	**13,660**	**13,006**	**13,407**	**17,283**
Mix 3	**Cube 1**	6,380	10,665	12,405	13,032	16,002	15,517
	Cube 2	6,332	10,427	12,121	12,753	15,801	16,261
	Cube 3		10,371	12,557	11,013	15,860	6,068
	Average	**6,356**	**10,488**	**12,361**	**12,266**	**15,888**	**12,615**
Mix 4	**Cube 1**	6,809	8,313	9,276	12,654	15,374	15,913
	Cube 2	6,835	9,253	10,234	13,284	15,191	15,273
	Cube 3	6,720	9,804	10,881	13,051	14,035	16,892
	Average	**6,788**	**9,123**	**10,130**	**12,996**	**14,867**	**16,026**
Mix 5	**Cube 1**	7,208	8,753	4,602	10,372	14,206	16,373
	Cube 2	7,211	8,467	10,963	10,786	15,324	15,840
	Cube 3	7,139	6,975	11,665	9,918	15,813	16,565
	Average	**7,186**	**8,065**	**9,077**	**10,359**	**15,114**	**16,260**
Mix 6	**Cube 1**	4,864	5,652	11,546	13,119	13,862	16,944
	Cube 2	4,942	5,461	11,605	14,449	13,435	16,856
	Cube 3	4,574	5,604	10,491	14,727	14,295	16,428
	Average	**4,794**	**5,572**	**11,214**	**14,098**	**13,864**	**16,743**

Table 4.2 Raw Compressive Strength Data, Mixes 7-13

		Compressive Strength (psi)					
		1 Day	**3 Day**	**7 Day**	**14 Day**	**28 Day**	**56 Day**
Mix 7	**Cube 1**	2,108	7,421	10,912	14,580	14,523	17,175
	Cube 2	4,478	5,730	11,762	12,171	13,274	17,090
	Cube 3	4,808	4,418	10,897	15,645	13,978	18,459
	Average	**3,798**	**5,856**	**11,190**	**14,132**	**13,925**	**17,575**
Mix 8	**Cube 1**	8,784	10,427	12,751	13,522	13,172	17,462
	Cube 2	8,344	9,561	13,006	14,495	13,459	15,285
	Cube 3	8,801	9,430	10,979	14,369	11,190	15,999
	Average	**8,643**	**9,806**	**12,245**	**14,129**	**12,607**	**16,249**
Mix 9	**Cube 1**	8,068	9,203	12,806	13,627	5,436	11,384
	Cube 2	7,593	9,345	12,314	13,530	16,328	12,107
	Cube 3	6,504	9,545	12,878	12,620	15,431	9,212
	Average	**7,388**	**9,364**	**12,666**	**13,259**	**12,398**	**10,901**
Mix 10	**Cube 1**	5,331	8,312	12,826	13,511	13,004	14,752
	Cube 2	5,489	9,567	12,563	12,037	11,126	15,518
	Cube 3	5,386	9,760	12,767	11,747	11,503	15,657
	Average	**5,402**	**9,213**	**12,719**	**12,432**	**11,878**	**15,309**
Mix 11	**Cube 1**	5,814	9,669	6,784	12,807	10,029	10,954
	Cube 2	5,957	9,375	7,553	13,222	7,519	11,637
	Cube 3	5,846	9,719	7,588	12,244	8,200	11,979
	Average	**5,872**	**9,588**	**7,308**	**12,758**	**8,583**	**11,524**
Mix 12	**Cube 1**	1,101	6,135	9,870	5,636	14,835	14,852
	Cube 2	1,098	6,129	9,232	12,133	14,488	13,618
	Cube 3	1,043	6,564	9,195	11,930	13,684	14,733
	Average	**1,081**	**6,276**	**9,432**	**9,900**	**14,336**	**14,401**
Mix 13	**Cube 1**	3,103	8,655	12,268			
	Cube 2	3,159	8,721	12,388			
	Cube 3	3,067	8,633	11,902			
	Average	**3,110**	**8,670**	**12,186**			

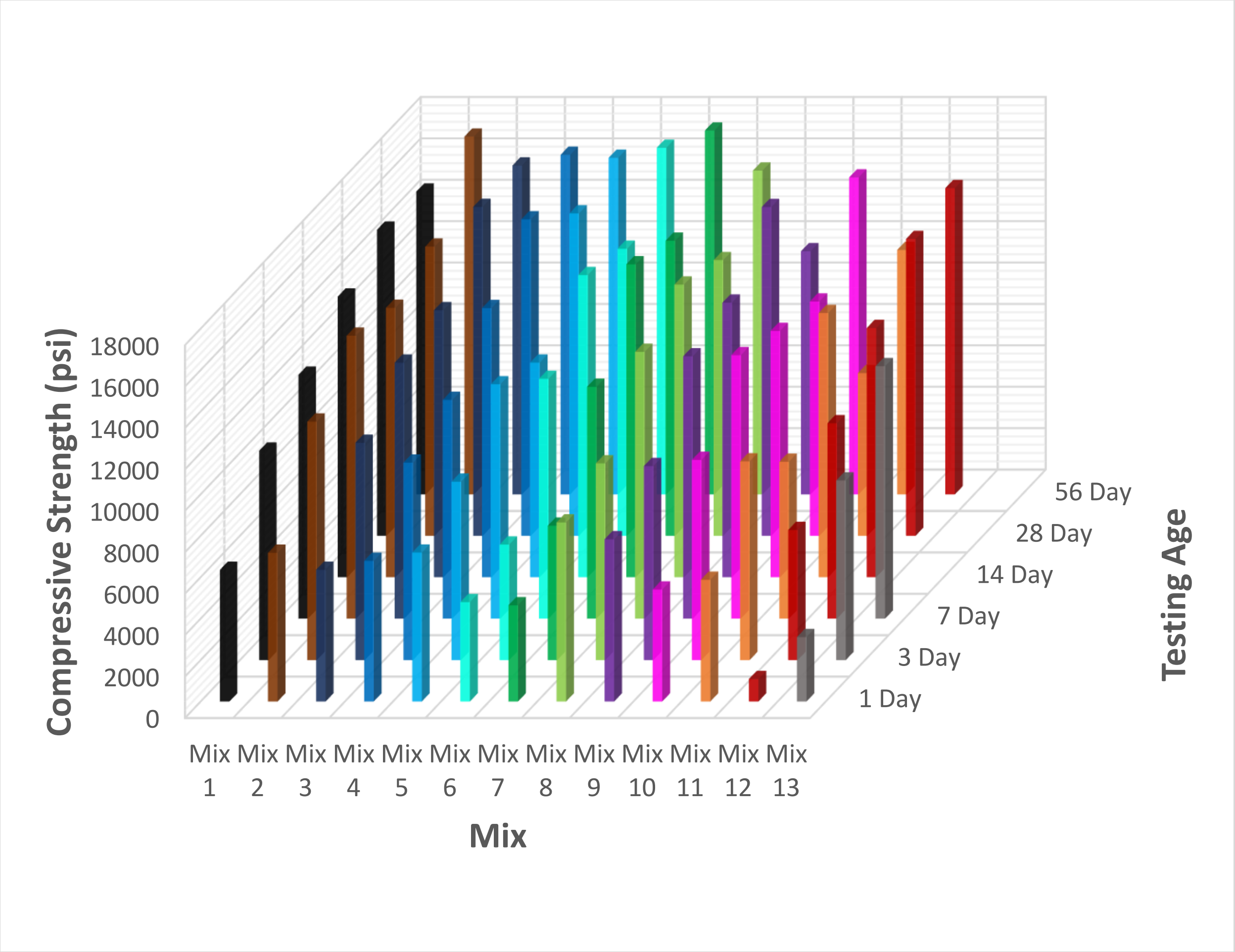


Figure 4.7 Adjusted Compressive Strength Data Comparison

As expected, most mixes followed a general trend of positive strength gain over time, reaching their maximum or near maximum measured strength at 28 days. Some mixes, like Mixes 2, 6, and 10 gained significant strength from 28 to 56 days. Other mixes had sets with strengths that measured lower than sets from the same mix at an earlier age. As predicted during mix design development, no set achieved a compressive strength high enough to meet the FHWA definition for UHPC (21.7 ksi) (Graybeal, 2011).

5 Calorimetry Testing

5.1 Introduction

This chapter describes the procedure and results from calorimetry testing performed on cylindrical test specimens of the same thirteen test mixes that underwent compressive strength testing. Calorimetry is the process of measuring the amount of heat released or absorbed during a chemical reaction. For cementitious materials, this process is exothermic in that heat is released during curing which can be used as a measure of the hydration reaction of a particular mixture. The calorimetry testing was performed with the guidance of ASTM C1753, and the equipment used conformed to that standard.

5.2 Procedure

The equipment used to perform the testing was an F-Cal 4000 semi-adiabatic calorimeter (F-Cal) and is shown in Figure 5.1. In the semi-adiabatic process, there is no transfer of heat towards or from the specimen, which is housed in a highly insulated testing environment. In the isothermal process, there is a transfer of heat towards or from the specimen to maintain the overall temperature of the specimen constant.

Figure 5.1 F-Cal 4000 Calorimeter

Cement hydration is traditionally measured through the semi-adiabatic process. The F-Cal used a proprietary data logging and reporting software referred to as CalCommander. This calorimeter was designed to be left on for extended periods of time, allowing for multiple test specimens to be placed in the calorimeter without the need to wait for ongoing tests to conclude. Data was recorded to the nearest 0.01˚F in one minute intervals, allowing for detailed data curves to be obtained over the course of testing, a sample of which is shown in Figure 5.2.

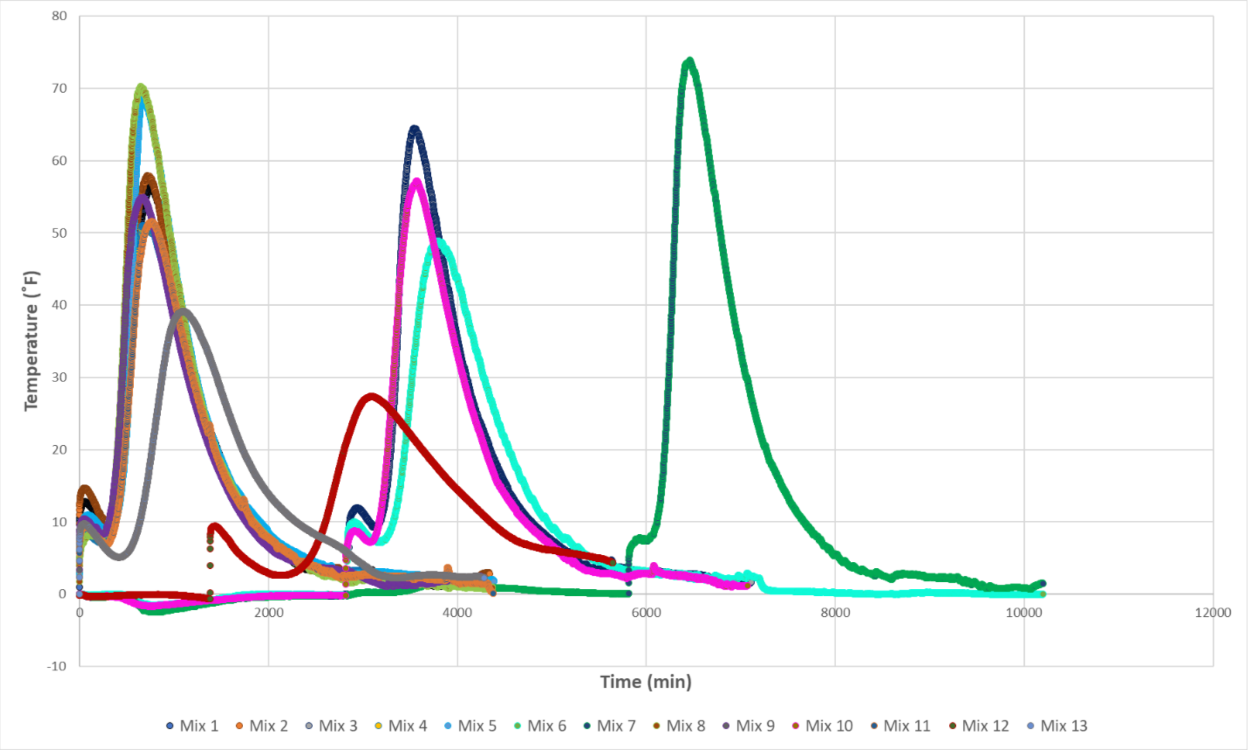


Figure 5.2 Example Calorimetry Data Curves

The calorimeter was initially placed in an enclosed, air-conditioned room that was separate from the mixing area. When space had been made available and no tests were ongoing, the calorimeter was relocated to a different room with its own air conditioning unit. This was intended as a precaution to reduce the possibility of fluctuations in environmental conditions, but this relocation was later reversed after a series of wild fluctuations were measured during a later test. Only one test specimen was affected by these wild fluctuations, and the mix was not used for compressive strength testing, but the calorimeter was moved back to its original location and no significant fluctuations were measured there.

The procedure for calorimetry testing was fairly straightforward, requiring minimal preparation ahead of testing. The time at which the mixing water was added to the dry cementitious materials was recorded for the adjustment of log data in the CalCommander software. One 4 in. by 8 in.

cylindrical specimen was cast at the same time as each set of companion compressive strength cube specimens. Immediately following the casting of the cube and cylindrical test specimens, the cylindrical specimens were placed in the calorimeter and the data logger was switched on. Data logging for each specimen was halted to coincide with the 3 day compressive strength testing of the corresponding mix's cube specimens, which had a testing interval of 3 days ± 1 hr. Based on the project mixing schedule, there were occasionally multiple cylindrical specimens being tested at the same time. When this was the case, the data logger was not shut off when a specimen was removed, and careful note was taken to ensure the correct data was linked to each specimen. The collected data for each specimen required correction, which is discussed further in Section 5.3.

5.3 Data Correction

To determine the heat generated by each cylindrical specimen, the measured specimen data had to be corrected using data from a reference cell. An open testing cell was always kept unused and open to the room environment to be used as this reference cell, and, for consistency, the same reference cell was used for all data correction. Data correction for the test specimens was required to allow the data sets to be compared equally to each other, as well as to remove or reduce the effects of environmental noise on the data.

To perform the initial correction, the raw data for each specimen had to be separated to include only the test specimen data and the reference data. The remainder of this step consisted of subtracting the reference cell data from the test specimen cell data, which helped reduce the effect of environmental noise and translated the data to represent the heat gained during curing. Examples of what this correction looks like are shown in Figures 5.3 and 5.4.

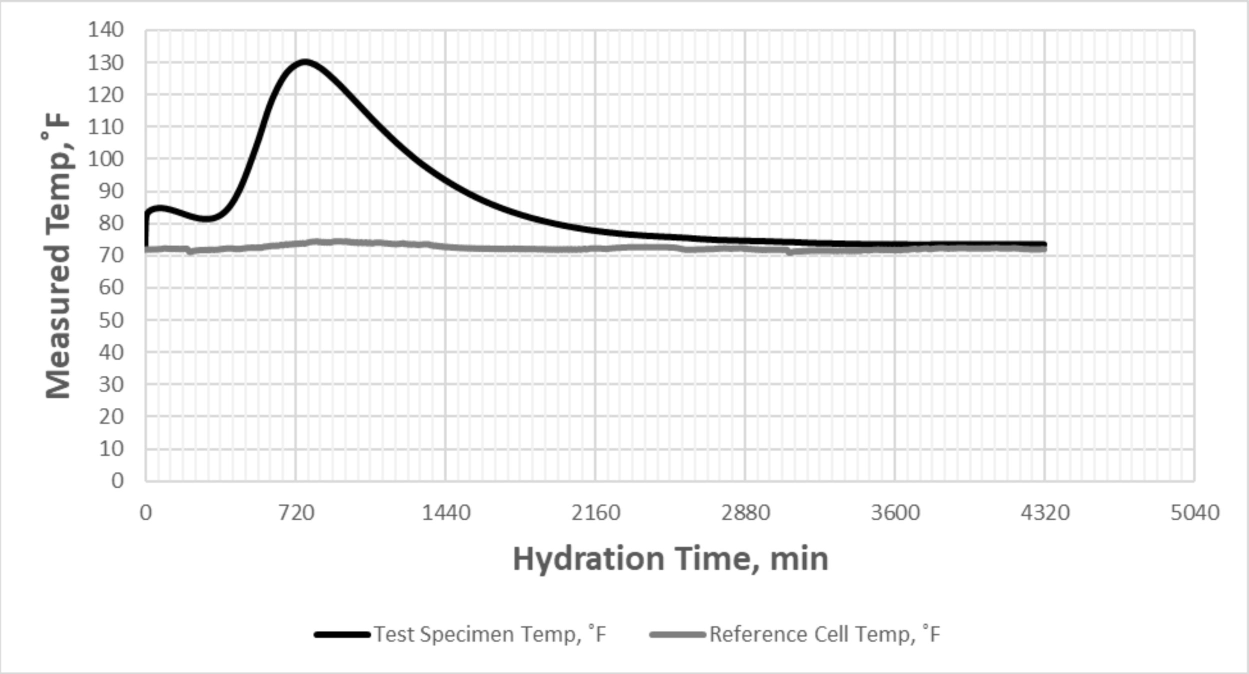


Figure 5.3 Mix 1 Data Before Correction

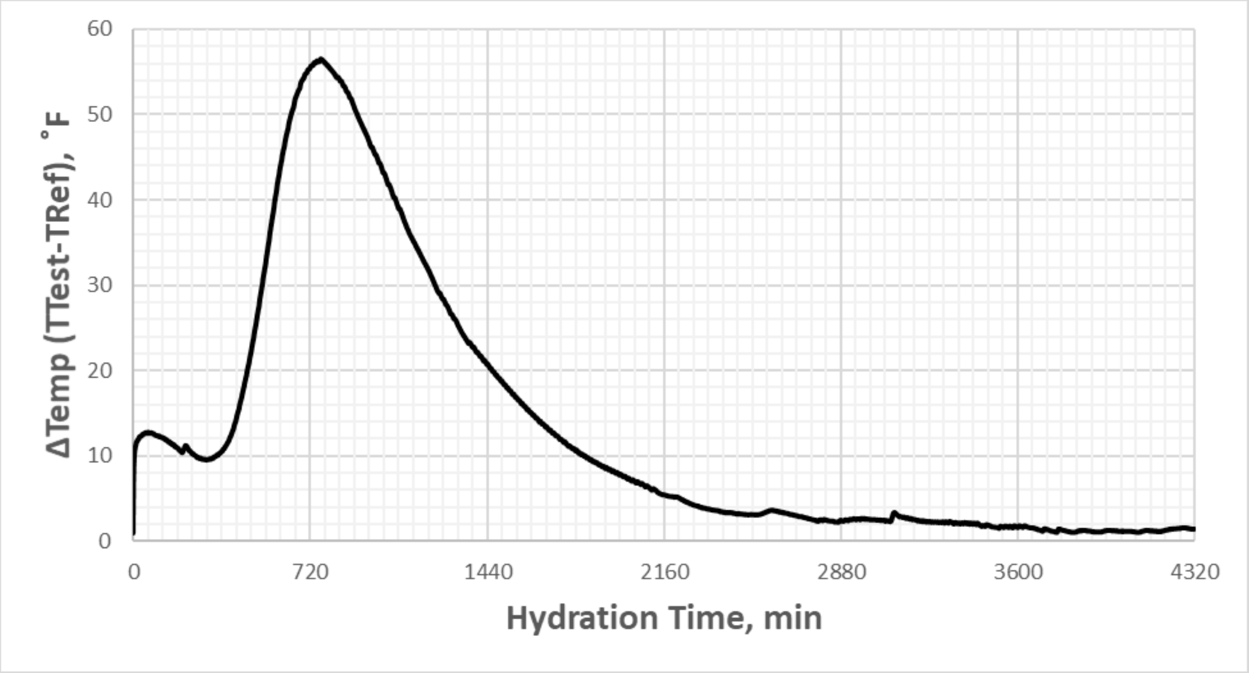


Figure 5.4 Mix 1 Data After Correction

Slight variations in logger start time and end time, as well as occasions with multiple specimens being tested simultaneously but with staggered start times, required some of the data to be trimmed. Removing the data logged before the specimen was placed in the logger was accomplished by identifying the earliest data point that begins a positive trend and setting this data point as the new beginning of the series, discarding the data before this point. The other half of this stage of the data correction was terminating the series at 4320 minutes, representing 3 days of data collection. Examples of the trimming stage of data correction are shown in Figures 5.5 and 5.6. The raw data used for these corrections is contained in Appendix B.

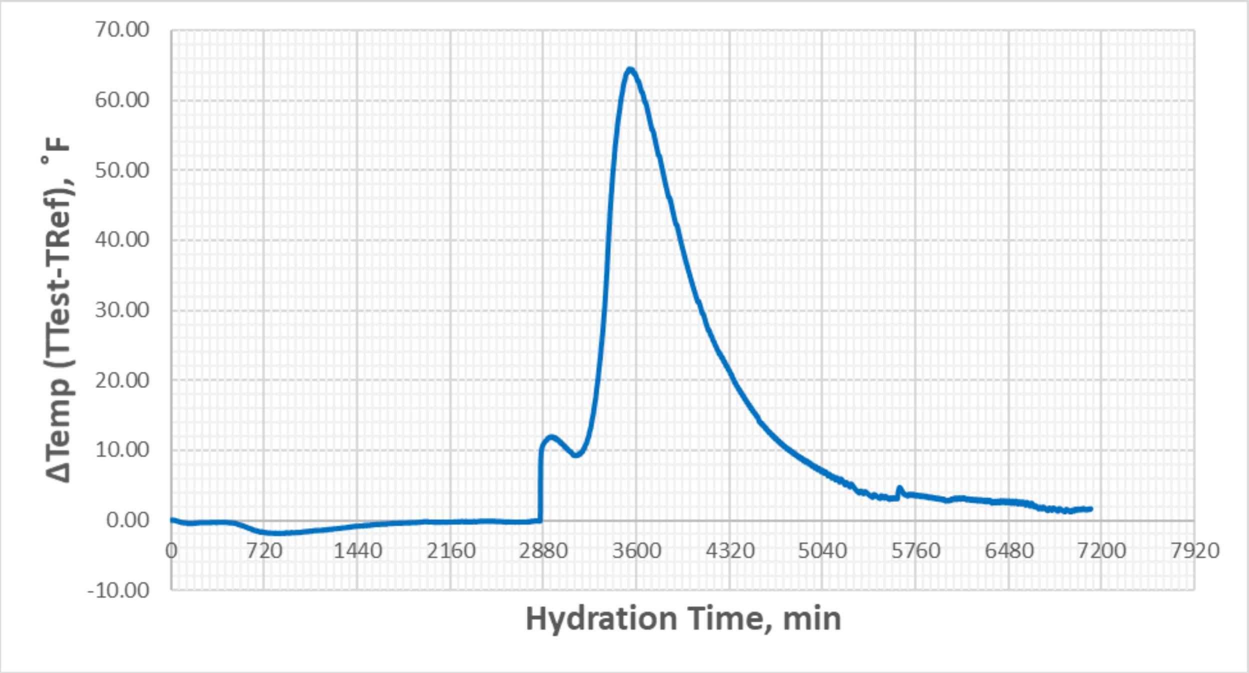


Figure 5.5 Mix 3 Untrimmed Corrected Data

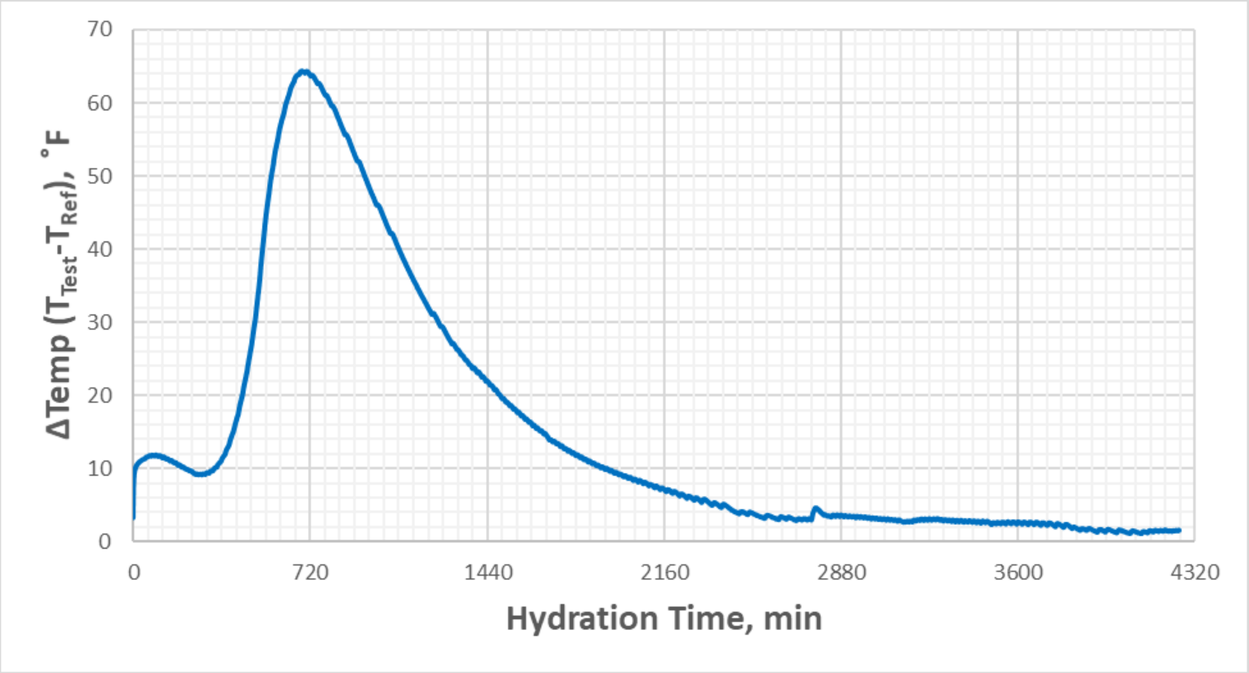


Figure 5.6 Mix 3 Trimmed Corrected Data

5.4 Summary of Results

The plots of the individual corrected test mix data sets are shown in Figures 5.7-5.19, and an overall comparison of all of the data sets is shown in Figure 5.20.

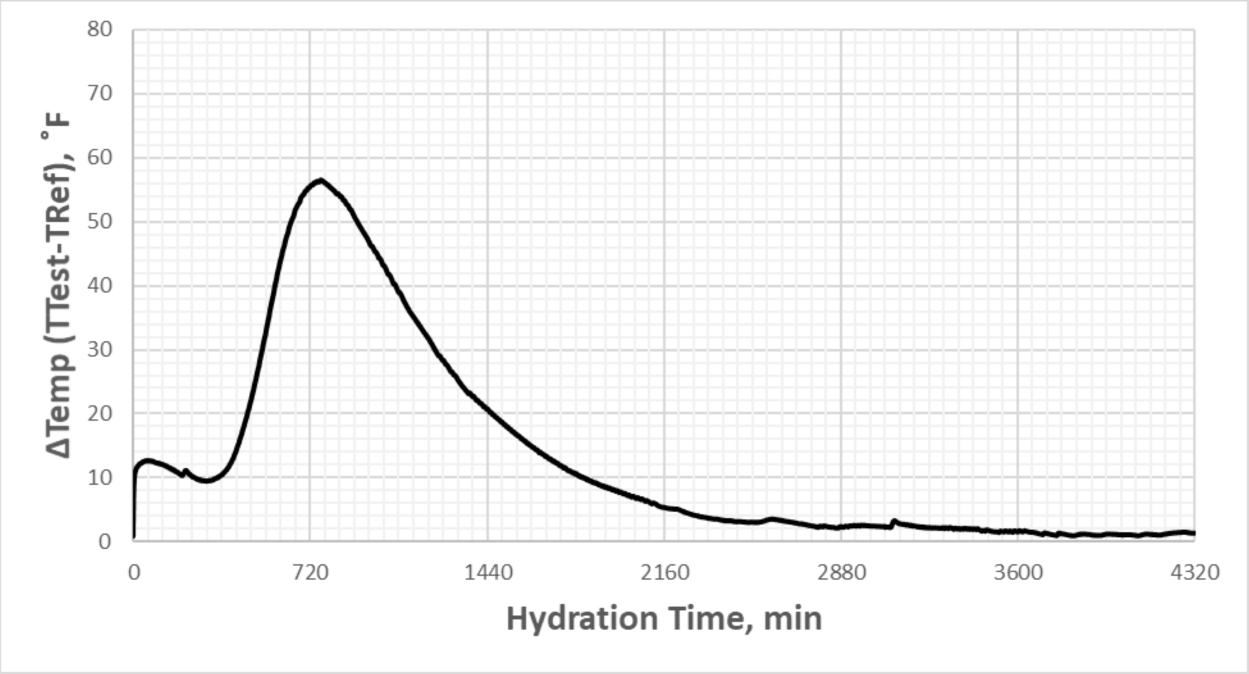


Figure 5.7 Test Mix 1 Corrected Calorimetry Data

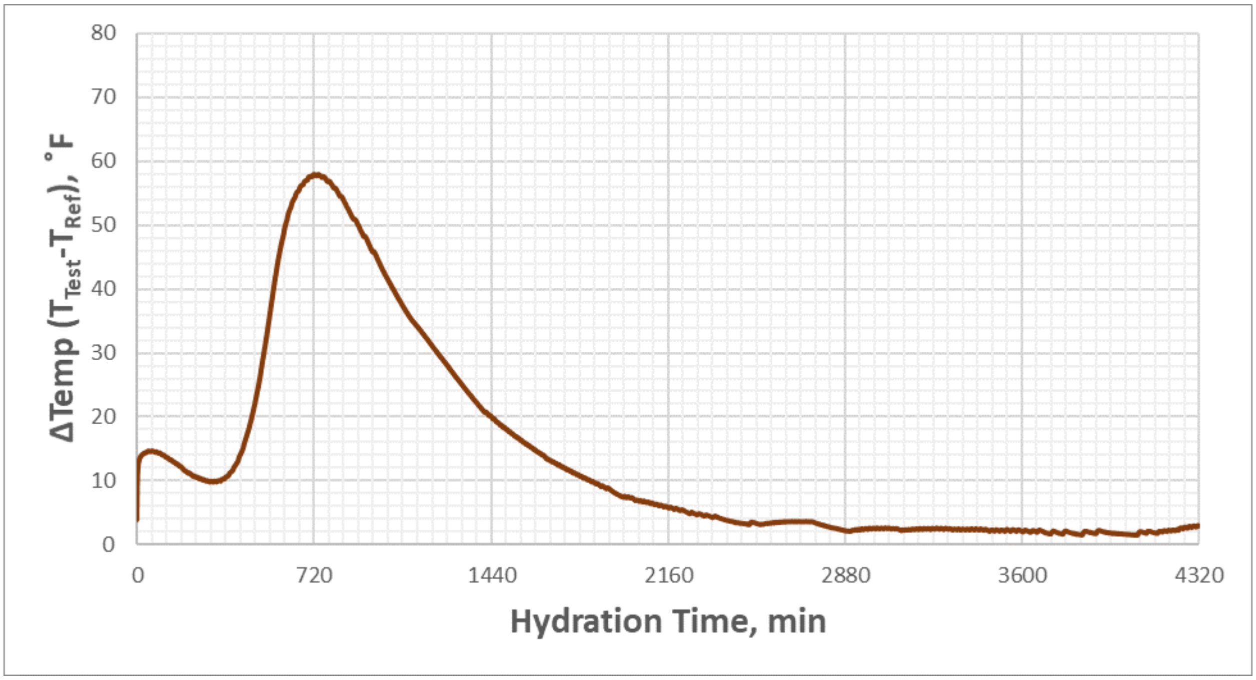


Figure 5.8 Test Mix 2 Corrected Calorimetry Data

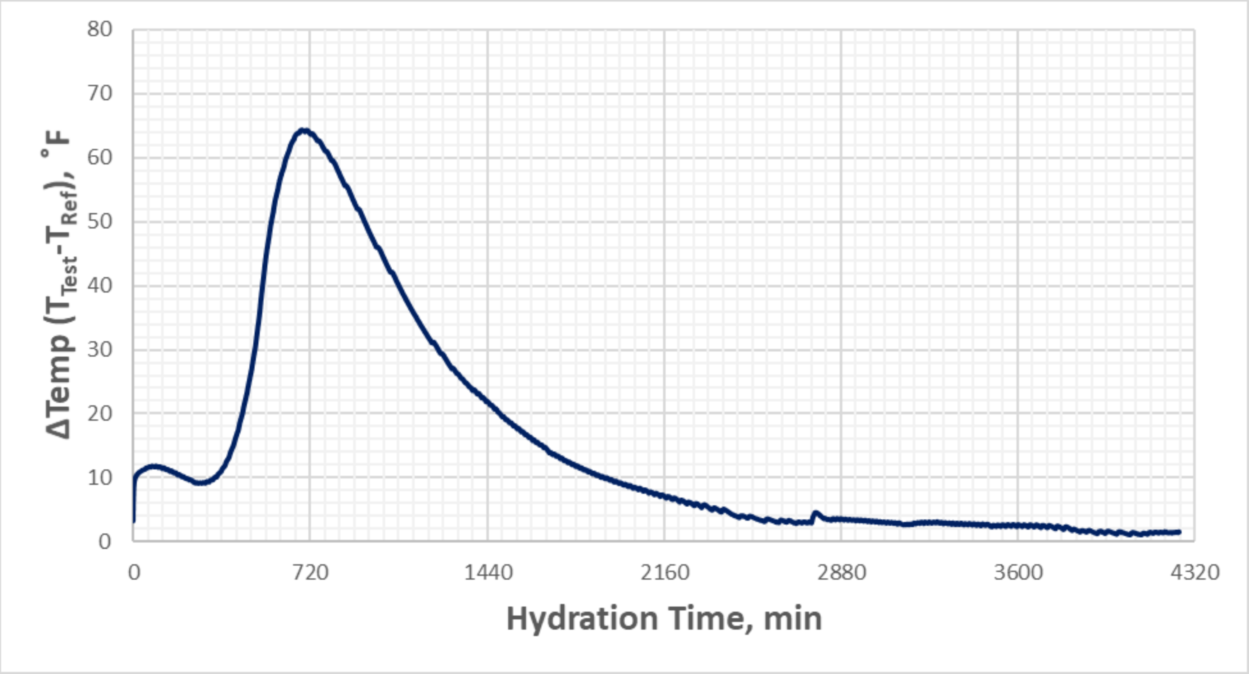


Figure 5.9 Test Mix 3 Corrected Calorimetry Data

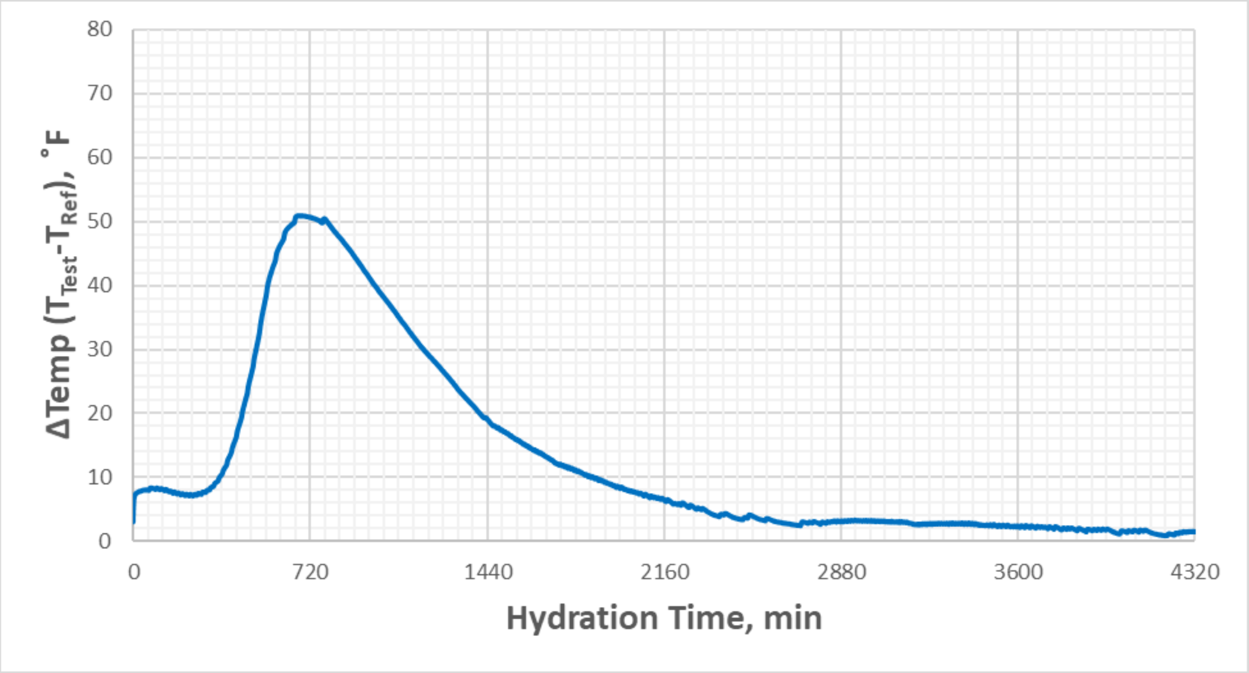


Figure 5.10 Test Mix 4 Corrected Calorimetry Data

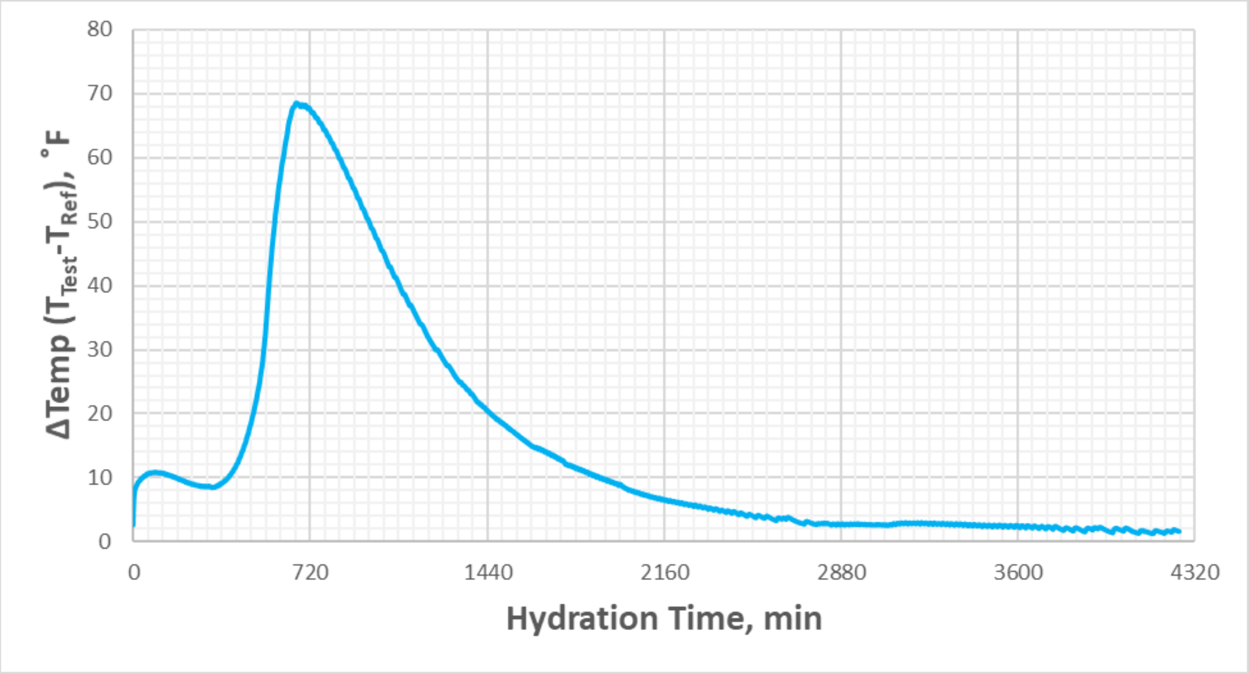


Figure 5.11 Test Mix 5 Corrected Calorimetry Data

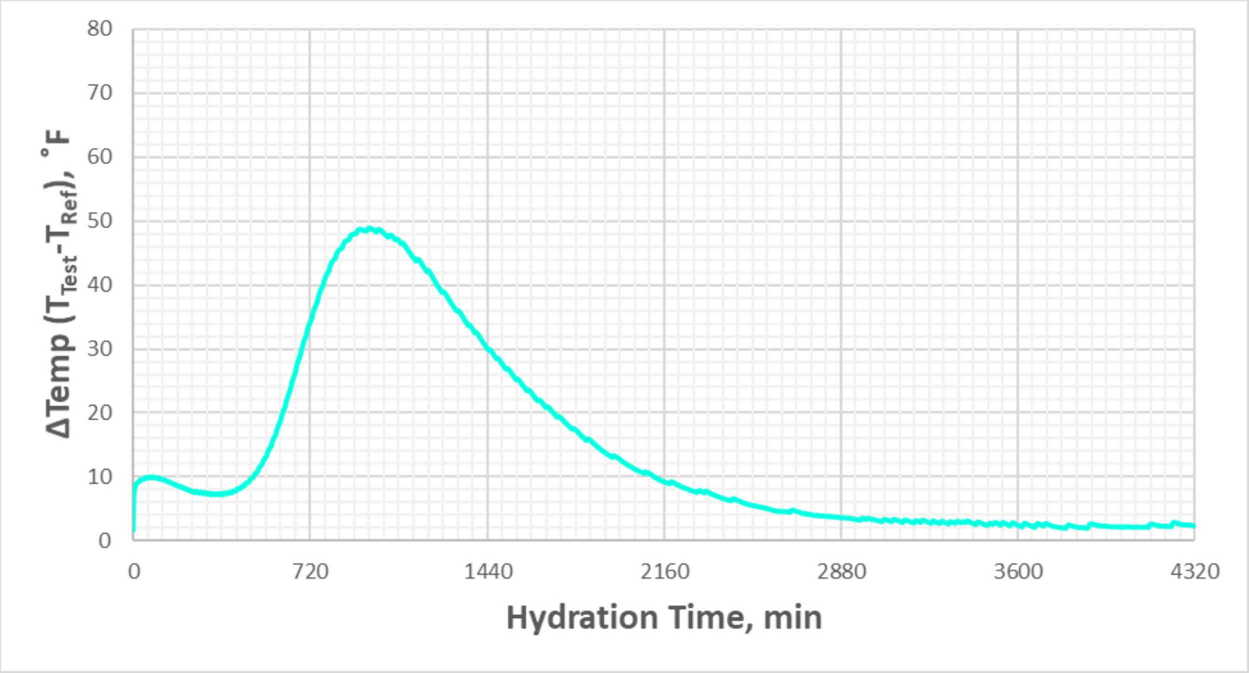


Figure 5.12 Test Mix 6 Corrected Calorimetry Data

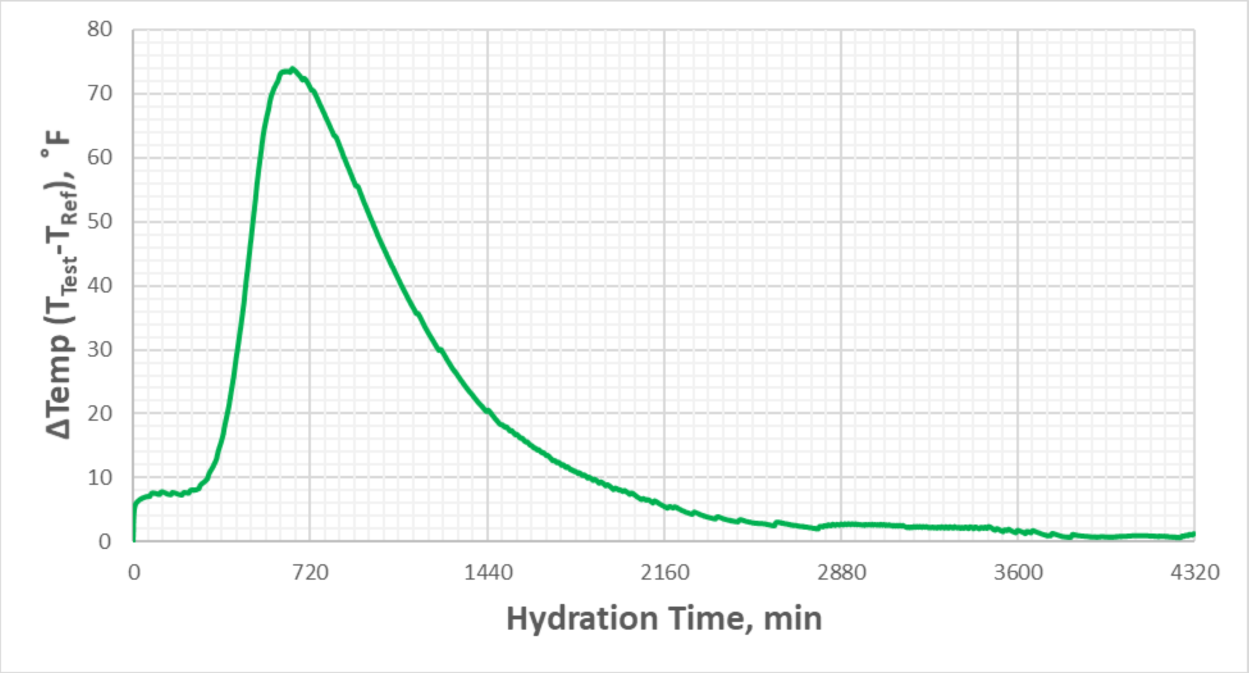


Figure 5.13 Test Mix 7 Corrected Calorimetry Data

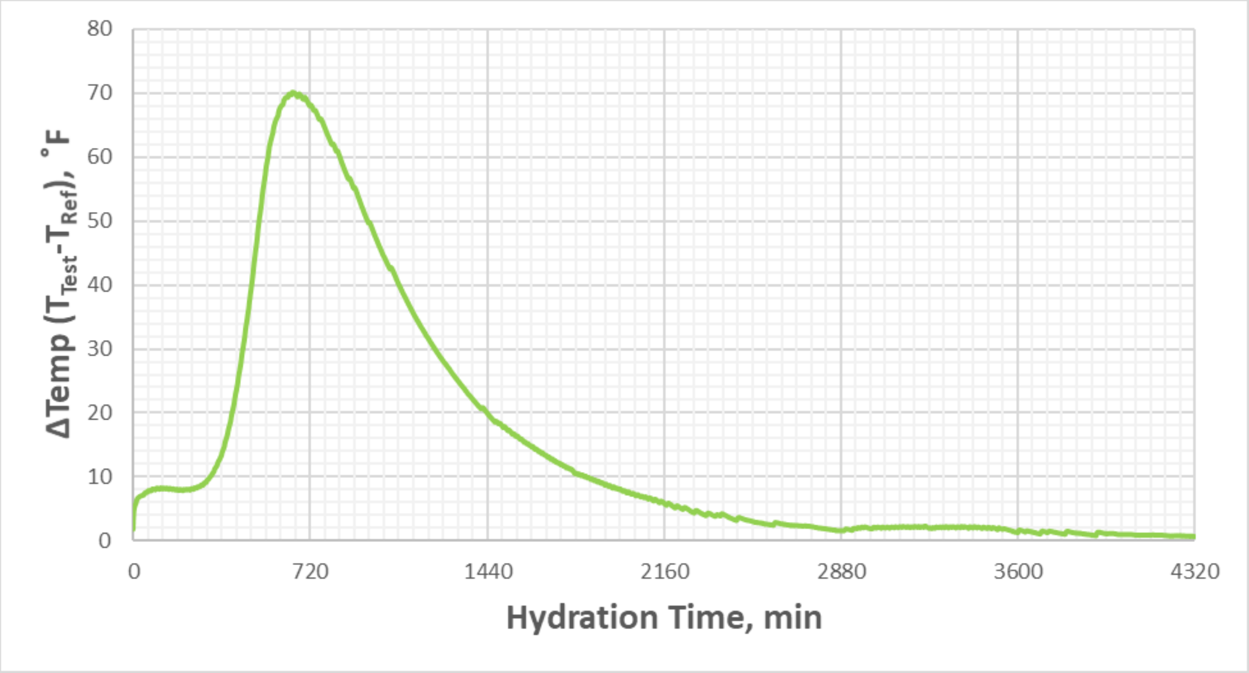


Figure 5.14 Test Mix 8 Corrected Calorimetry Data

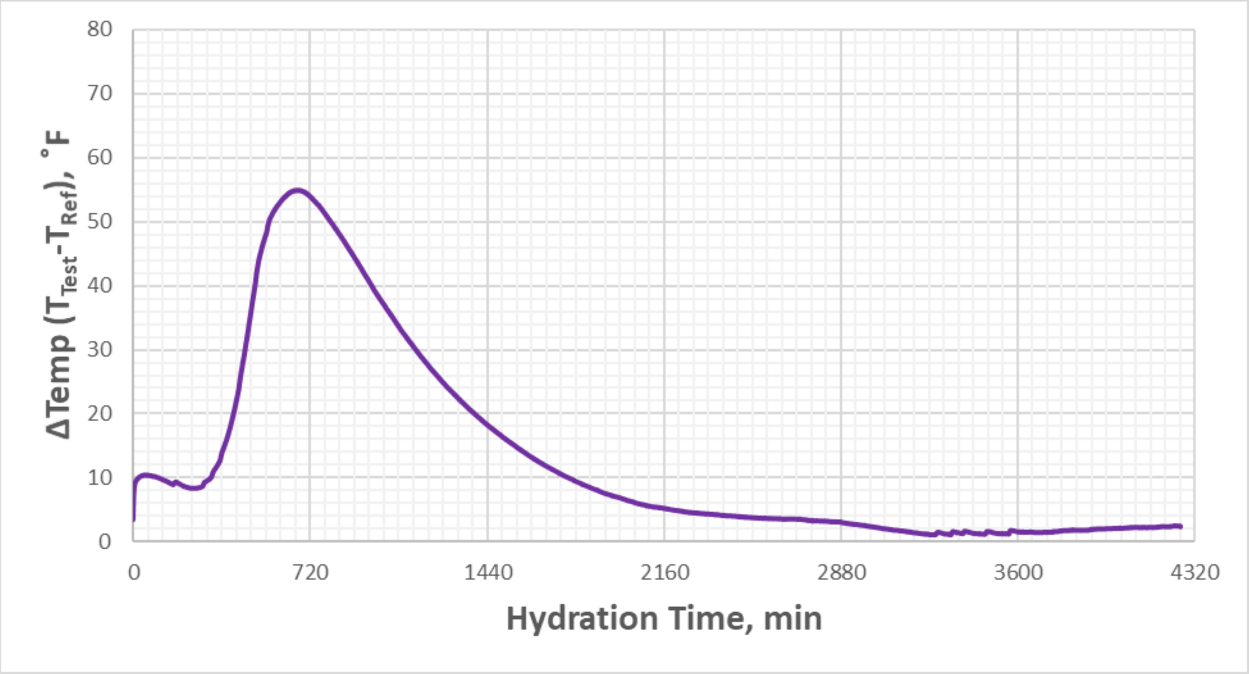


Figure 5.15 Test Mix 9 Corrected Calorimetry Data

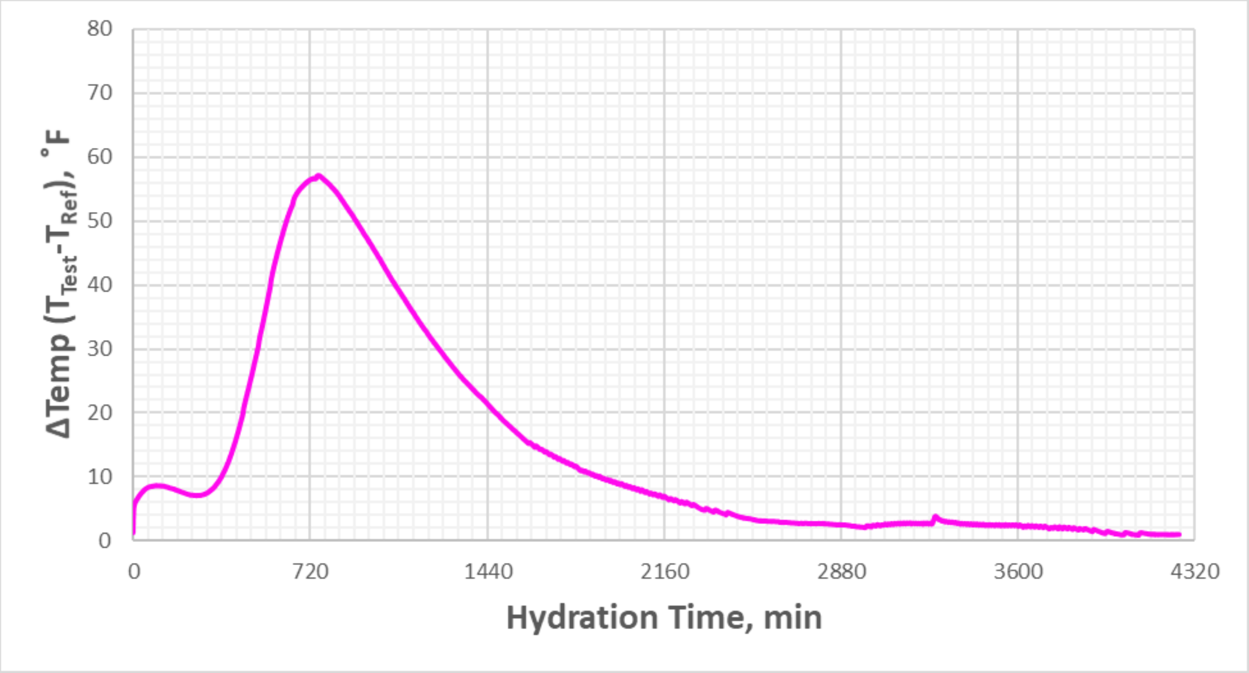


Figure 5.16 Test Mix 10 Corrected Calorimetry Data

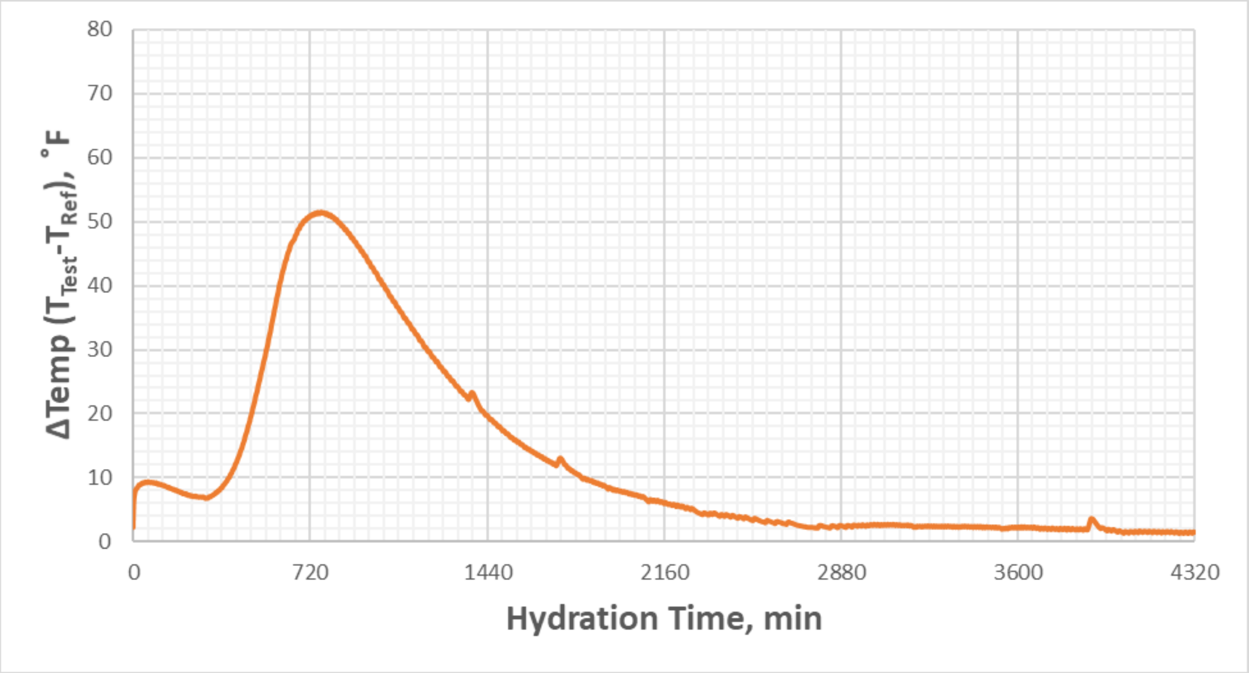


Figure 5.17 Test Mix 11 Corrected Calorimetry Data

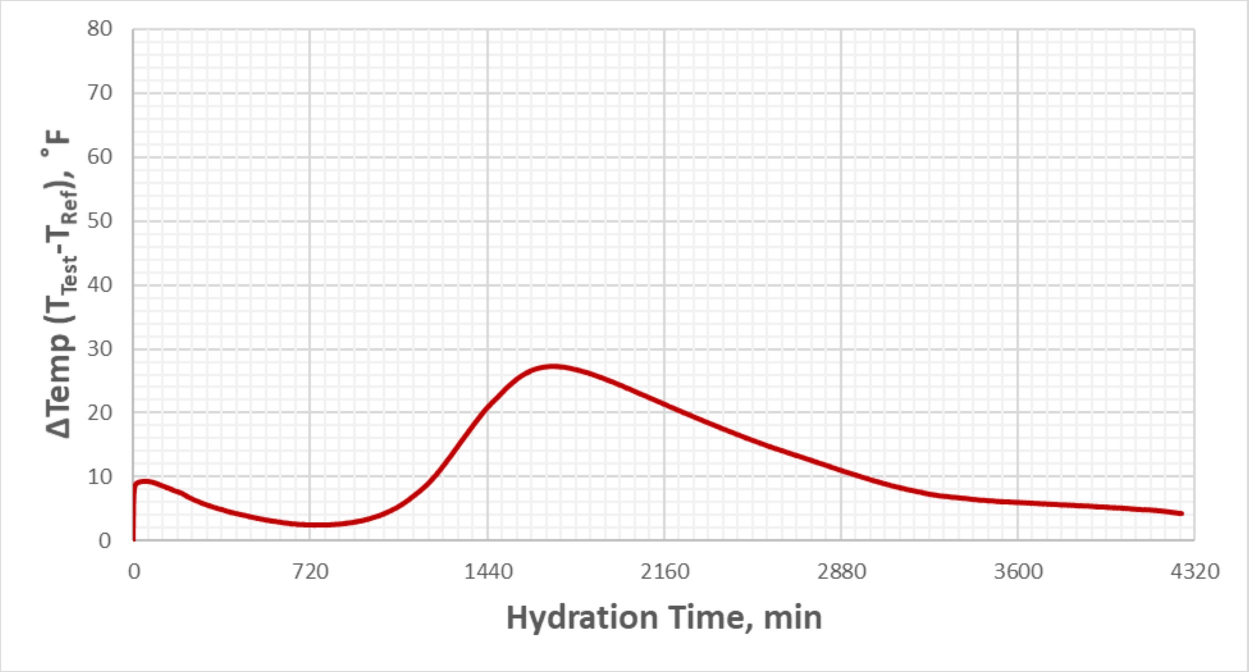


Figure 5.18 Test Mix 12 Corrected Calorimetry Data

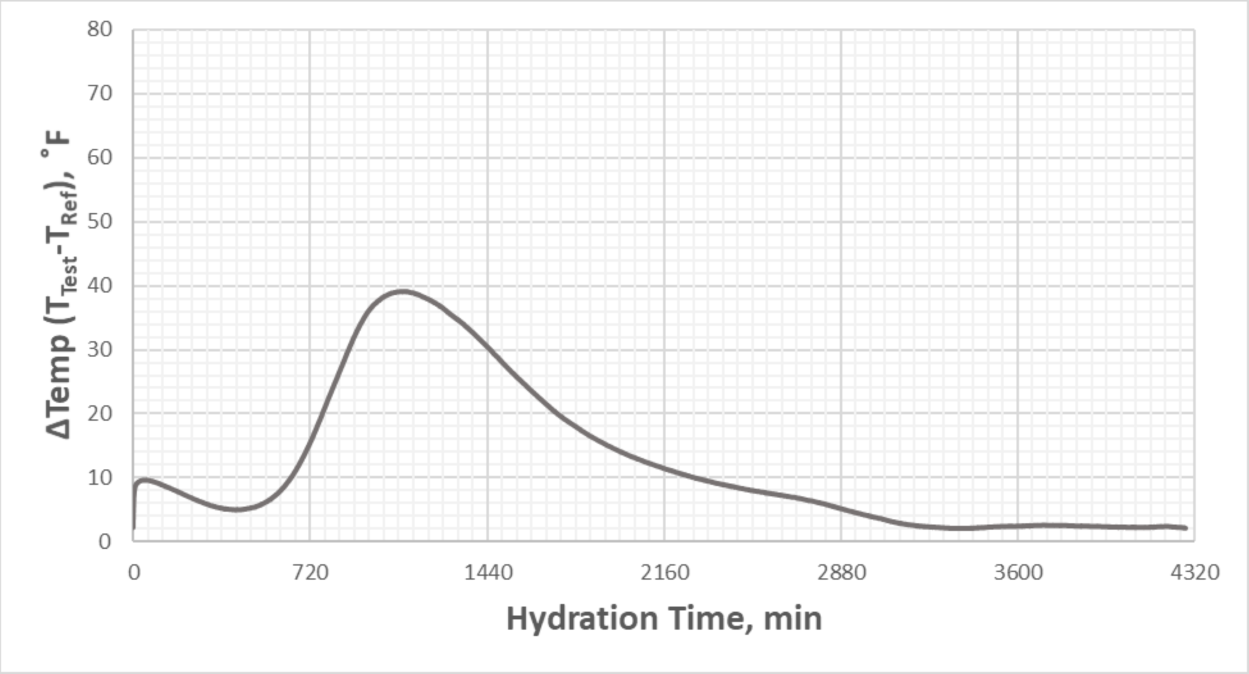


Figure 5.19 Test Mix 13 Corrected Calorimetry Data

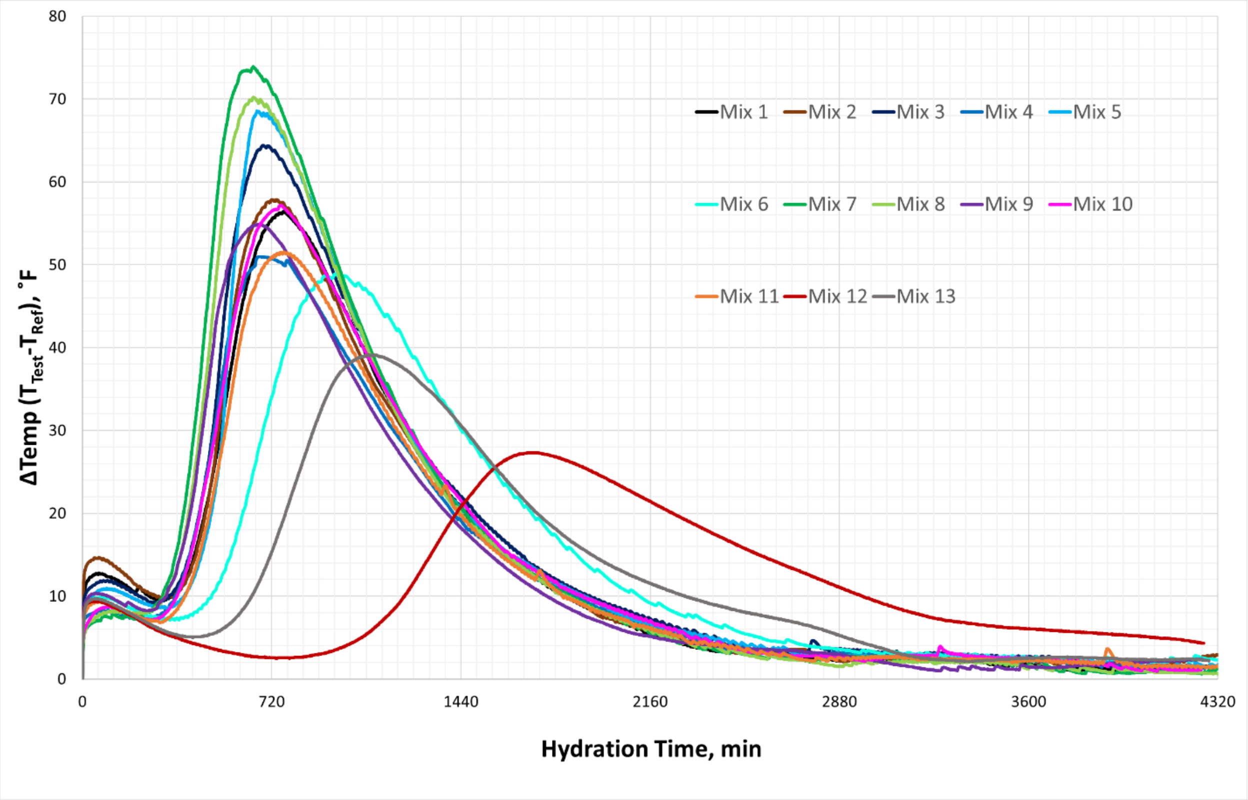


Figure 5.20 Compiled Corrected Calorimetry Data

Comparing the trimmed, corrected data shows most of the test mixes followed a very similar pattern: a rapid rise in temperature, a dormancy period, another rapid rise in temperature, and then a more gradual decrease that approaches an asymptote at room temperature. Additionally, data regarding the peak of each curve, the lowest temperature of each dormancy period, and the difference between these data points is shown in Table 5.1.

Table 5.1 Thermal Profile Comparison

	Time of Peak ΔTemp, min	**Peak ΔTemp, ˚F**	**Time of Lowest Point of Dormancy Period, min**	**Lowest Temp of Dormancy Period, ˚F**	**(Peak-Lowest), ˚F**	**Time Between Lowest and Peak, min**
Mix 1	764	56.46	299	9.50	46.96	465
Mix 2	720	57.86	312	9.77	48.09	408
Mix 3	689	64.41	268	9.19	55.22	421
Mix 4	680	50.99	245	7.03	43.96	435
Mix 5	664	68.54	323	8.50	60.04	341
Mix 6	964	48.86	351	7.12	41.74	613
Mix 7	649	73.90	198	7.26	66.64	451
Mix 8	650	70.20	202	7.79	62.41	448
Mix 9	678	54.87	246	8.25	46.62	432
Mix 10	754	57.17	260	7.11	50.06	494
Mix 11	767	51.54	295	6.78	44.76	472
Mix 12	1,712	27.32	787	2.52	24.8	925
Mix 13	1,094	39.11	421	5.02	34.09	673

The average peak ΔTemp was 55.48˚F, occurring at the 830 minute mark. The average lowest temperature of the dormancy period was 7.37˚F, occurring at the 324 minute mark. The average difference between the peak ΔTemp and lowest temperature of the dormancy period was 48.11˚F, with a difference of 506 minutes between these points. These results are altered due to the inclusion of some more divergent mixes. Of all thirteen mixes, the ones with the most divergent results were Mix 6, Mix 12, and Mix 13. These three mixes had the most drawn-out periods of hydration, taking above average lengths of time to progress through their dormancy periods, reach their peak ΔTemp, and to return to ambient temperature.

6 Analysis of Test Results and Data

6.1 Introduction

With the collected data from compressive strength and calorimetry testing, comparisons were drawn between the thirteen mixes and their different specifications. A comparison based on the standard classification of each portland and oil well cement, according to ASTM C150 and API Specification 10A respectively, was the initial baseline of analysis. An extension of this analysis was performed for the 50/50 cement blend used in Mix 13 compared to the pure usage of the two constituent cements. More granular analyses were performed to determine trends in performance based on many of the individual specifications found in the corresponding mill certs. Finally, the calorimetry data was analyzed to identify trends based on heat evolution during this testing.

6.2 Analysis Based on Cement Type Specification

An overall analysis of all thirteen mixes was performed based on the cement type specification of each of the cements used. The cement type and average compressive strength of each mix at each of the six testing ages, as well as the average for all mixes at each testing age, is shown in Table 6.1.

Table 6.1 Average Compressive Strength Data, All Testing Ages

		Compressive Strength (psi)					
	Cement Type/Class	**1 Day**	**3 Day**	**7 Day**	**14 Day**	**28 Day**	**56 Day**
Mix 1	I/II	6,350	10,110	11,780	13,550	14,790	14,630
Mix 2	I/II	7,180	11,510	13,660	13,010	13,970	17,280
Mix 3	I/II	6,360	10,490	12,360	12,890	15,890	15,890
Mix 4	I/II	6,790	9,530	10,560	13,000	15,280	16,400
Mix 5	I	7,190	8,610	11,310	10,360	15,570	16,260
Mix 6	II/V	4,800	5,570	11,580	14,590	13,860	16,740
Mix 7	III	4,640	6,490	11,190	15,110	14,250	17,580
Mix 8	III	8,640	9,500	12,880	14,130	13,320	15,640
Mix 9	1L	7,830	9,360	12,670	13,260	15,880	11,740
Mix 10	1L	5,400	9,660	12,720	11,890	11,320	15,310
Mix 11	C	5,880	9,590	7,570	12,760	7,860	11,810
Mix 12	H	1,080	6,280	9,430	12,030	14,340	14,790
Mix 13	I/II and H	3,110	8,670	12,190			
	Average	**5,790**	**8,870**	**11,530**	**13,050**	**13,860**	**15,340**

Mixes 1-4, utilizing Type 1/II cements, all performed close to or above average for all six testing ages, with the exception of Mix 4 at 970 psi below average at 7 days. Mix 5, utilizing Type I cement, performed similarly consistently, with the exception of its poor performance at 14 days. The reason for Mix 5's underperformance at 14 days is unclear, and none of the three cube specimens tested at that time stood out as outliers within the set. Mixes 9 and 10, utilizing Type 1L cements, performed comparably well to the other Type I and Type I/IIs at earlier test ages, but with more inconsistent performance at 28 and 56 days.

Mix 6, which utilized Type II/V cement, underperformed at early ages but performed at or above average at 7 days or more. Mix 7, utilizing a Type III cement, displayed unexpected underperformance at early ages, which was surprising due to the tendency of Type III cements to achieve higher early strengths than other cements. As mentioned in Chapter 4, Mix 7 was redone as Mix 8 to determine if the early testing failure anomalies would persist at later testing ages. The performance of Mix 8, as well as the performance of Mix 7 at testing ages of 7 days and later, confirms that the mixes were capable of strength gain comparable to and above average for the complete data set, particularly at testing ages of 14 days and later.

Mix 11, which used a Class C oil well cement, was predicted to behave similarly to Mixes 7 and 8, since its intended use is for construction requiring high early strength like Type III (API Specification 10A, 2002). Counter to this prediction, Mix 11 vastly underperformed at most testing ages and was only above average at 3 days. Mix 12, which utilized a Class H oil well cement, performed the worst of all thirteen mixes. Mix 12 is discussed further in Section 6.2.1, along with Mix 13 which used a blended cement.

As an alternate means of comparison, Mixes 1-12 have also been organized by the ranking of their compressive strengths at each testing age, as shown in Table 6.2. These rankings – scored sequentially from highest strength as 1 to lowest strength as 12 – present an additional visual for evaluating relative performance of each mix at each testing age. Mix 13 was omitted from these tables because it only underwent testing up to 7 days of age, making the rankings slightly more difficult to compare across testing ages and overall.

Table 6.2 Mixes Ranked by Compressive Strength

		Compressive Strength Ranking						
	Cement Type/Class	**1 Day**	**3 Day**	**7 Day**	**14 Day**	**28 Day**	**56 Day**	**Average Ranking**
Mix 1	I/II	7	3	6	4	5	10	5.83
Mix 2	I/II	4	1	1	6	8	2	3.67
Mix 3	I/II	6	2	5	8	1	6	4.67
Mix 4	I/II	5	6	10	7	4	4	6.00
Mix 5	I	3	9	8	12	3	5	6.67
Mix 6	II/V	10	12	7	2	9	3	7.17
Mix 7	III	11	10	9	1	7	1	6.50
Mix 8	III	1	7	2	3	10	7	5.00
Mix 9	1L	2	8	4	5	2	12	5.50
Mix 10	1L	9	4	3	11	11	8	7.67
Mix 11	C	8	5	12	9	12	11	9.50
Mix 12	H	12	11	11	10	6	9	9.83

The rankings in Table 6.2 paint a picture that was more difficult to see with just the compressive strength values in Table 6.1. Mix 2 is shown to have performed very well and well above average, with only a single testing age ranked below average. (A value of 6.50 represents the average for a 1 through 12 sequential ranking.) Mix 3 also performed well and above average, though results at more of the testing ages ranked closer to average and one was also below average. Mix 8 ranked above average overall but displayed more inconsistency throughout testing. Three of its testing ages performed very well while the other three ranked below average. Mix 9 also performed above average overall, though weaker performances at 3 days and 56 days brought its overall score down. Mixes 1 and 4 performed very similarly overall, with rankings that all generally trend toward the middle. Interestingly, Mix 7 earned an average ranking of 6.50, which represents perfectly the average for a data set of twelve mixes. Mixes 5 and 6 performed below average overall, with Mixes 10-12 at the bottom of the overall performance ranking.

While the rankings in Table 6.2 are useful for individual comparison, they do not fully depict the overall performance of each cement as a type or class. To remedy this, each cement type and class was evaluated as a group and given a ranking based on the total average of all mixes within each group. Additional statistical values, specifically regarding the standard deviations and coefficients of variation of each type or class, were calculated as well. These rankings and statistical values are shown in Table 6.3, with the data organized in order of cement type.

Table 6.3 Extended Analysis of Cement Type/Class Rankings

	Cement Type/Class	Average Ranking	Overall Average Ranking	Standard Deviation	COV	Deviations From Average
Mix 5	I	6.67	6.67	0.00	0.0%	0.00
Mix 9	1L	5.50	6.58	1.08	16.5%	-1.00
Mix 10	1L	7.67				1.00
Mix 1	I/II	5.83	5.04	0.95	18.8%	0.84
Mix 2	I/II	3.67				-1.45
Mix 3	I/II	4.67				-0.40
Mix 4	I/II	6.00				1.01
Mix 6	II/V	7.17	7.17	0.00	0.0%	0.00
Mix 7	III	6.50	5.75	0.75	13.0%	1.00
Mix 8	III	5.00				-1.00
Mix 11	C	9.50	9.50	0.00	0.0%	0.00
Mix 12	H	9.83	9.83	0.00	0.0%	0.00

Table 6.3 confirms the trend of strong performance for the mixes that used Type I/II cements, with an overall average ranking of 5.04/12. All four of the Type I/II cements represented in this group performed above average, with the lowest ranked 6.00 overall. Type III, with just one

cement but two mixes, also performed well and above average with an overall average ranking of 5.75/12. The Type 1L cements performed just slightly below average overall, as did Type I. Type II/V performed solidly below average with a ranking of 7.17/12. The Class C and Class H oil well cements performed very poorly overall, with rankings of 9.50/12 and 9.83/12, respectively.

The testing ages of 28 days and 56 days are the ones most commonly used for compressive strength analysis. To focus more specifically on these testing ages, Table 6.4 presents the twelve non-blended cement mixes in ascending order of compressive strength. Both testing ages had two mixes with compressive strengths significantly below the next highest value. To better understand visually how the higher ten, more clustered, mixes performed relative to each other, Figures 6.1 and 6.2 present the data in Table 6.4 along with average lines for both the full twelve mixes and the ten highest mixes.

Table 6.4 Mixes 1-12 Ordered by Compressive Strength, 28 and 56 Day

28 Day			56 Day		
Mix	**Cement Type/Class**	**Compressive Strength (psi)**	**Mix**	**Cement Type/Class**	**Compressive Strength (psi)**
Mix 11	C	7,860	**Mix 9**	1L	11,740
Mix 10	1L	11,320	**Mix 11**	C	11,810
Mix 8	III	13,320	**Mix 1**	I/II	14,630
Mix 6	II/V	13,860	**Mix 12**	H	14,790
Mix 2	I/II	13,970	**Mix 10**	1L	15,310
Mix 7	III	14,250	**Mix 8**	III	15,640
Mix 12	H	14,340	**Mix 3**	I/II	15,890
Mix 1	I/II	14,790	**Mix 5**	I	16,260
Mix 4	I/II	15,280	**Mix 4**	I/II	16,400
Mix 5	I	15,570	**Mix 6**	II/V	16,740
Mix 9	1L	15,880	**Mix 2**	I/II	17,280
Mix 3	I/II	15,890	**Mix 7**	III	17,580
Average of All 12 Mixes		13,860	**Average of All 12 Mixes**		15,340
Average of Highest 10 Mixes		14,720	**Average of Highest 10 Mixes**		16,050

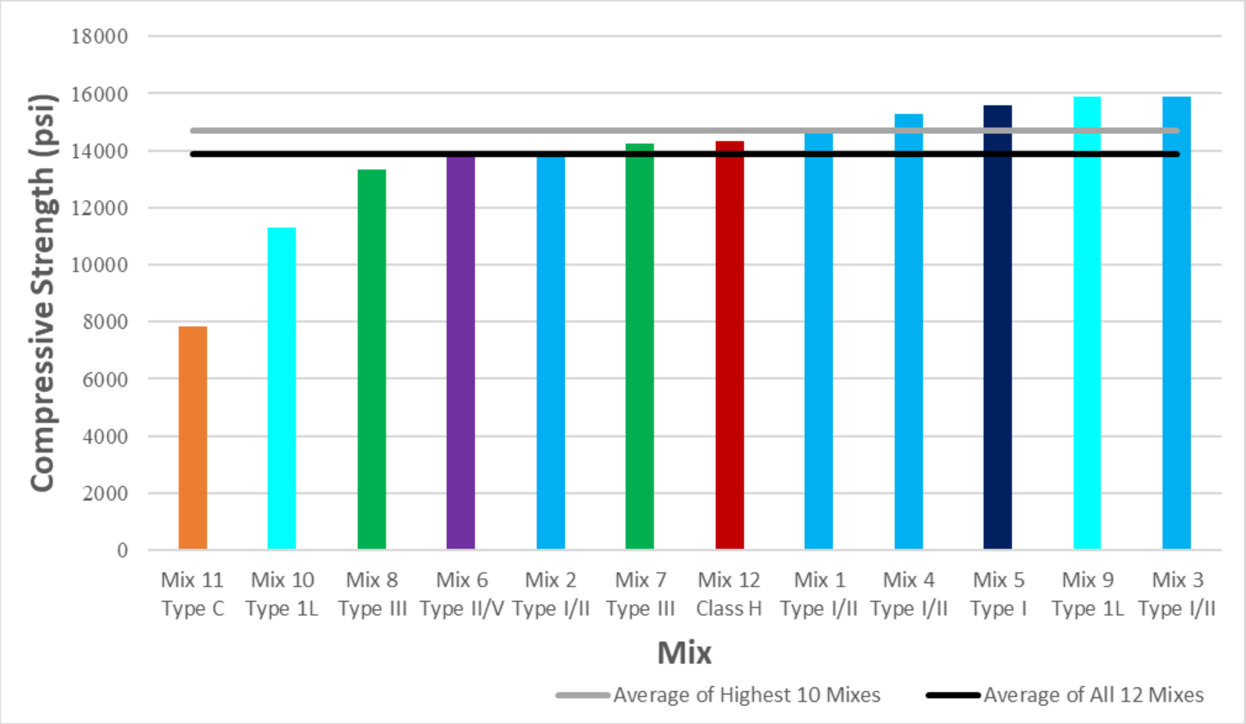


Figure 6.1 Mixes Ranked by 28 Day Compressive Strength

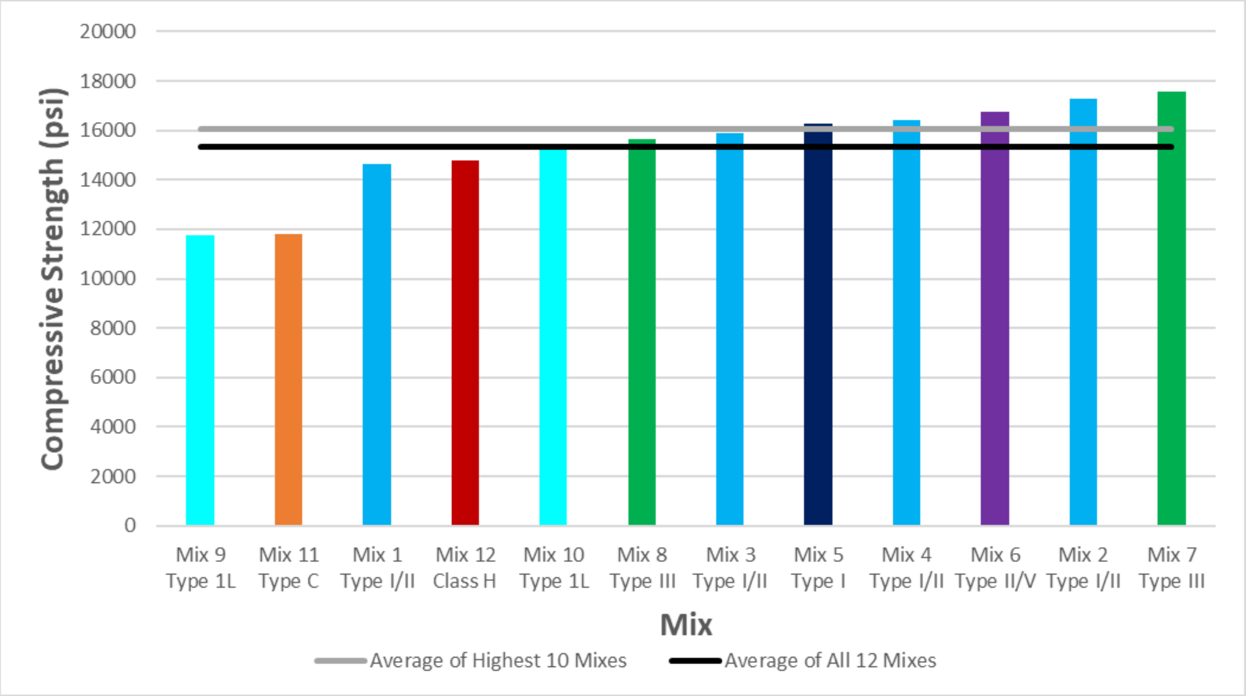


Figure 6.2 Mixes Ranked by 56 Day Compressive Strength

Figures 6.1 and 6.2 show that, while the majority of mixes are at or above average when considered as a full group, omitting the lowest two mixes presents the data set as a more average spread. At 28 days, the ten mix set has a range of 2,570 psi, with the lowest value at 9.5% below average and the highest value at 7.9% above the average of 14,720 psi. At 56 days, the ten mix set has a range of 2,950 psi, with the lowest value at 8.9% below average and the highest value at 9.5% above the average of 16,050 psi.

6.2.1 Blended Cement Analysis

Mix 13, which used a 50/50 blend of Type I/II and Class H cements, was considered separately from the other twelve mixes. The Type I/II portland cement used in Mix 13 was the same that was used in Mix 1, and the Class H oil well cement was the same that was used in Mix 12. As the intention of the blended mix was to determine if the Class H cement could be combined with a more conventional cement to create a more workable UHPC with improved early strength, the testing was performed for just the 1 day, 3 day, and 7 day testing ages. The compressive strengths at these testing ages for Mix 1, Mix 12, and Mix 13 are shown in Table 6.6.

Table 6.5 Blended Cement Compressive Strength Comparison

		Mix 1	**Mix 12**	**Mix 13**	
	Cement Type/Class	I/II	H	I/II and H	**Average**
Compressive Strength (psi)	**1 Day**	6,350	1,080	3,110	**3,510**
	3 Day	10,110	6,280	8,670	**8,350**
	7 Day	11,780	9,430	12,190	**11,130**

At 1 and 3 days, Mix 13 performed close to the average of its unblended counterparts. At 1 day, Mix 13 was above the average of Mixes 1 and 12, while at 3 days it performed below the average. Surprisingly, at 7 days, Mix 13 outperformed both its unblended counterparts.

6.3 Analysis Based on Mill Cert Specifications

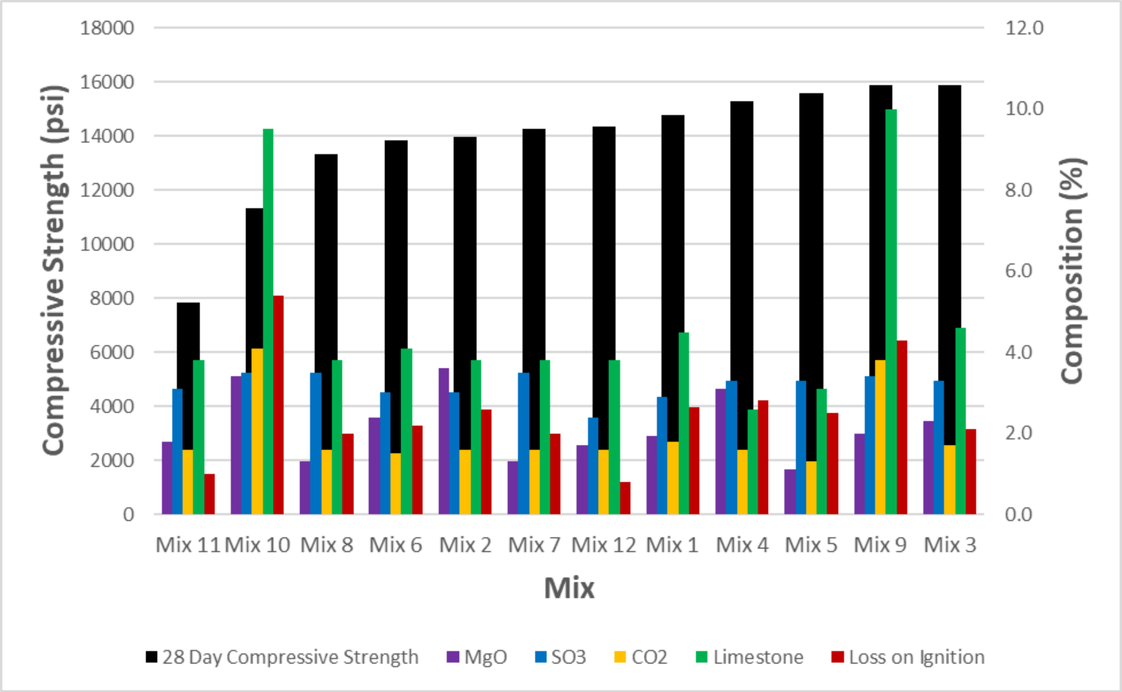
The wide range of specifications presented in cement mill certs was also analyzed to identify possible trends. These specifications were separated into groups for analysis based on close relation to other specifications and commonality of comparison. These groups were as follows: the uncategorized specifications, oxide compositions, calcium compound compositions, and Blaine fineness. The uncategorized specifications could not easily be grouped with other listed specifications and consisted of loss on ignition, MgO, SO_3, CO_2, and limestone contents. The oxide composition group consisted of SiO_2, Al_2O_3, Fe_2O_3, and the sum of these three compositions. The calcium compound composition group consisted of C_3S, C_2S, C_3A, C_4AF, and $C_3S+4.75*C_3A$ contents. Other mill cert specifications, like inorganic process addition and heat of hydration, were considered for analysis but were ultimately omitted due to the lack of data availability for the majority of cements. Mix 13 was also omitted from analysis due to the blended nature of its cement composition.

6.3.1 Uncategorized Mill Cert Specifications

The loss on ignition, MgO, SO_3, CO_2, and limestone contents of Mixes 1-12 were transferred from the provided cement mill certs and compiled in Tables 6.7 and 6.8, with the mixes placed in ascending order of 28 day and 56 day compressive strength, respectively. Mixes 7, 8, 11, and 12 were all missing the CO_2 and limestone composition values from their mill certs. To allow a modified analysis, the average CO_2 and limestone values of the other non-Type 1L cements were used as placeholder values. The Type 1L cements were exempted due to their intentionally high limestone contents and the skewing effect they would have had if included. Figures 6.3 and 6.4 present additional visuals of the comparisons.

Table 6.6 Uncategorized Specification Comparison, 28 Day Compressive Strength

	MgO (%)	**SO_3 (%)**	**CO_2 (%)**	**Limestone (%)**	**Loss on Ignition (%)**	**28 Day Compressive Strength (psi)**
Mix 11	1.8	3.1	1.6*	3.8*	1.0	7,860
Mix 10	3.4	3.5	4.1	9.5	5.4	11,320
Mix 8	1.3	3.5	1.6*	3.8*	2.0	13,320
Mix 6	2.4	3.0	1.5	4.1	2.2	13,860
Mix 2	3.6	3.0	1.6	3.8	2.6	13,970
Mix 7	1.3	3.5	1.6*	3.8*	2.0	14,250
Mix 12	1.7	2.4	1.6*	3.8*	0.8	14,340
Mix 1	1.9	2.9	1.8	4.5	2.6	14,790
Mix 4	3.1	3.3	1.6	2.6	2.8	15,280
Mix 5	1.1	3.3	1.3	3.1	2.5	15,570
Mix 9	2.0	3.4	3.8	10.0	4.3	15,880
Mix 3	2.3	3.3	1.7	4.6	2.1	15,890
* Indicates a placeholder value, actual value was not included in mill cert						



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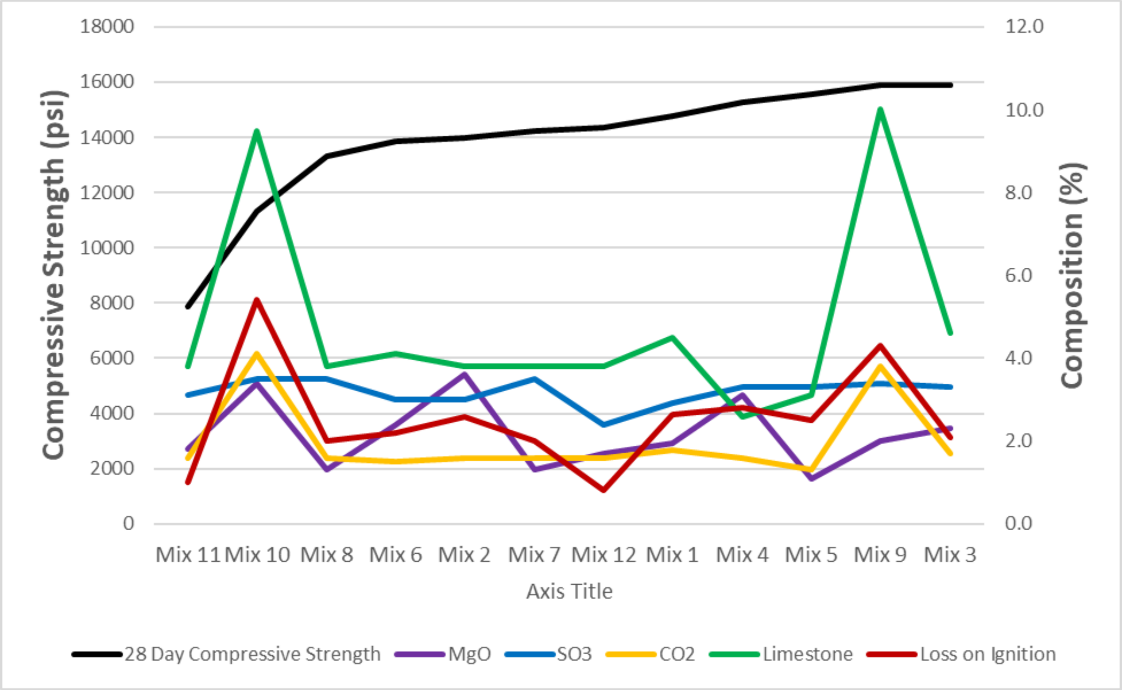

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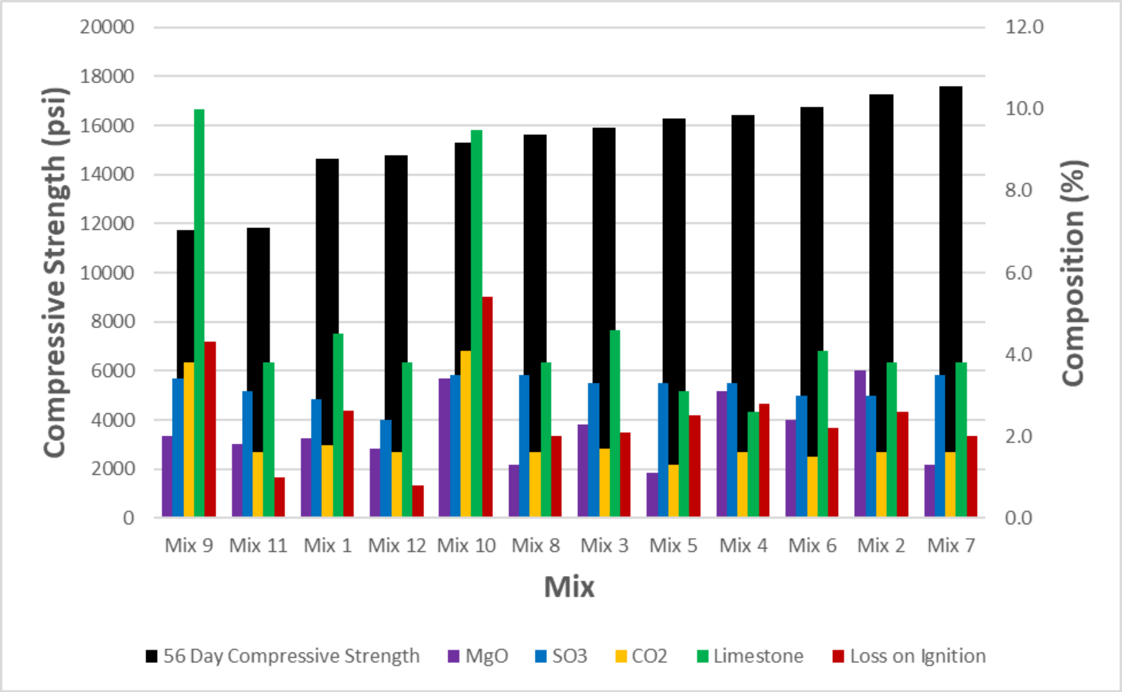
Figure 6.3 Uncategorized Specification Comparison, 28 Day Compressive Strength

Table 6.7 Uncategorized Specification Comparison, 56 Day Compressive Strength

	MgO (%)	**SO_3 (%)**	**CO_2 (%)**	**Limestone (%)**	**Loss on Ignition (%)**	**56 Day Compressive Strength (psi)**
Mix 9	2.0	3.4	3.8	10.0	4.3	11,740
Mix 11	1.8	3.1	1.6*	3.8*	1.0	11,810
Mix 1	1.9	2.9	1.8	4.5	2.6	14,630
Mix 12	1.7	2.4	1.6*	3.8*	0.8	14,790
Mix 10	3.4	3.5	4.1	9.5	5.4	15,310
Mix 8	1.3	3.5	1.6*	3.8*	2.0	15,640
Mix 3	2.3	3.3	1.7	4.6	2.1	15,890
Mix 5	1.1	3.3	1.3	3.1	2.5	16,260
Mix 4	3.1	3.3	1.6	2.6	2.8	16,400
Mix 6	2.4	3.0	1.5	4.1	2.2	16,740
Mix 2	3.6	3.0	1.6	3.8	2.6	17,280
Mix 7	1.3	3.5	1.6*	3.8*	2.0	17,580
* Indicates a placeholder value, actual value was not included in mill cert						



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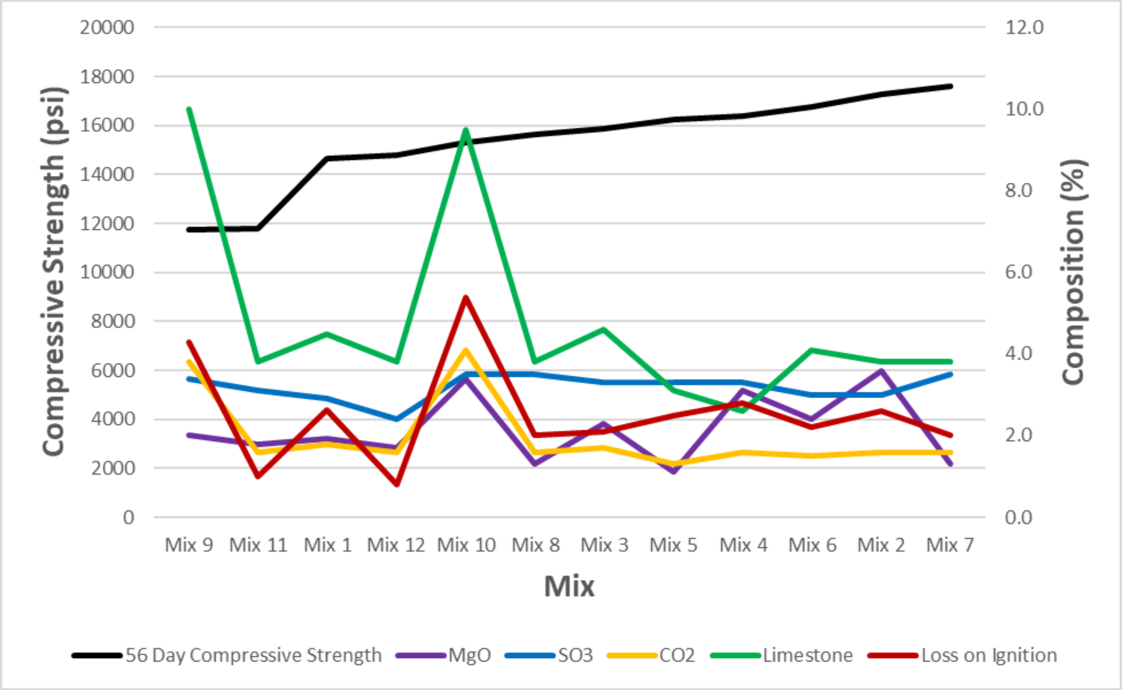

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Figure 6.4 Uncategorized Specification Comparison, 56 Day Compressive Strength

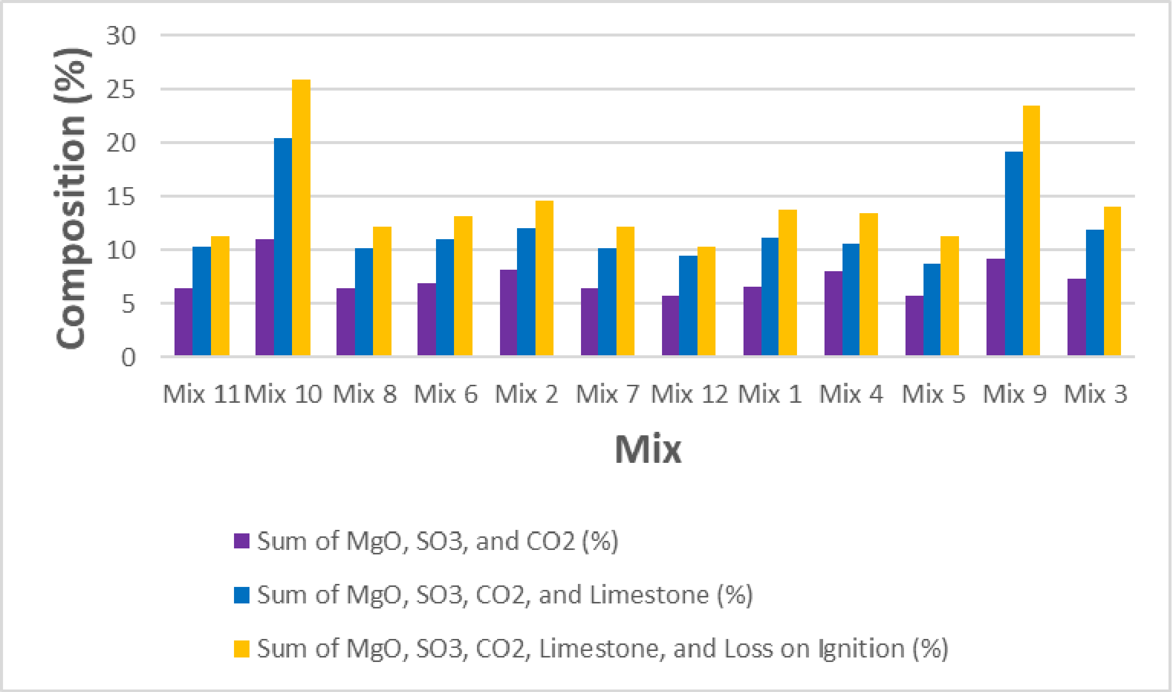
There appears to be no trend between any individual composition and higher compressive strength. However, in Figures 6.3 and 6.4, it appears that a slight trend between lower sums of the different compositions and higher compressive strength may be present. Mixes 9 and 10 appear to be exceptions to this, with their significantly higher limestone contents. To confirm if there is indeed a trend, a further analysis of the sums of these compositions was performed in Section 6.3.1.1.

6.3.1.1 Sums of Uncategorized Specification Compositions

Analysis of the possible trend tied to the sums of the compositions in the uncategorized group was performed with three approaches. Each approach looked at a different sum at both 28 days and 56 days. One approach was the sum of MgO, SO_3, and CO_2, another was the same sum plus limestone, and the third was the sum of all five values. Table 6.9 and Figure 6.5 show the data for 28 day strength, and Table 6.10 and Figure 6.6 show the data for 56 day strength.

Table 6.8 Sums of Uncategorized Specification Compositions, 28 Day Compressive Strength

	Sum of MgO, SO_3, and CO_2 (%)	**Sum of MgO, SO_3, CO_2, and Limestone (%)**	**Sum of MgO, SO_3, CO_2, Limestone, and Loss on Ignition (%)**
Mix 11	6.5	10.3	11.3
Mix 10	11	20.5	25.9
Mix 8	6.4	10.2	12.2
Mix 6	6.9	11	13.2
Mix 2	8.2	12	14.6
Mix 7	6.4	10.2	12.2
Mix 12	5.7	9.5	10.3
Mix 1	6.6	11.1	13.8
Mix 4	8	10.6	13.4
Mix 5	5.7	8.8	11.3
Mix 9	9.2	19.2	23.5
Mix 3	7.3	11.9	14



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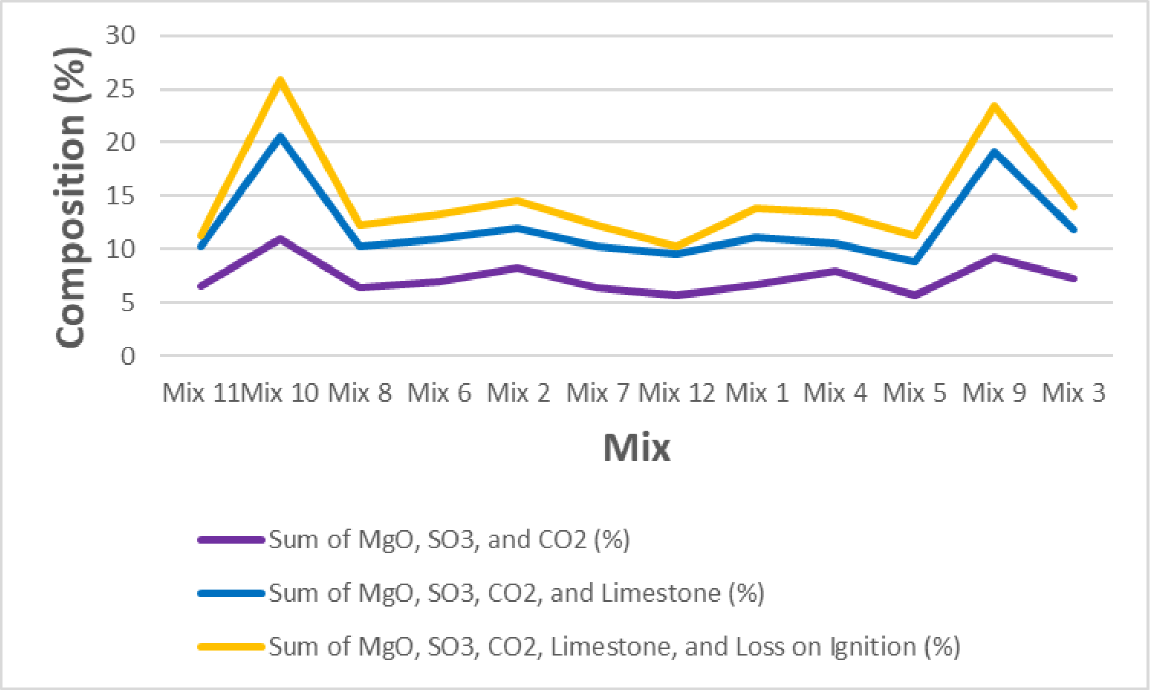

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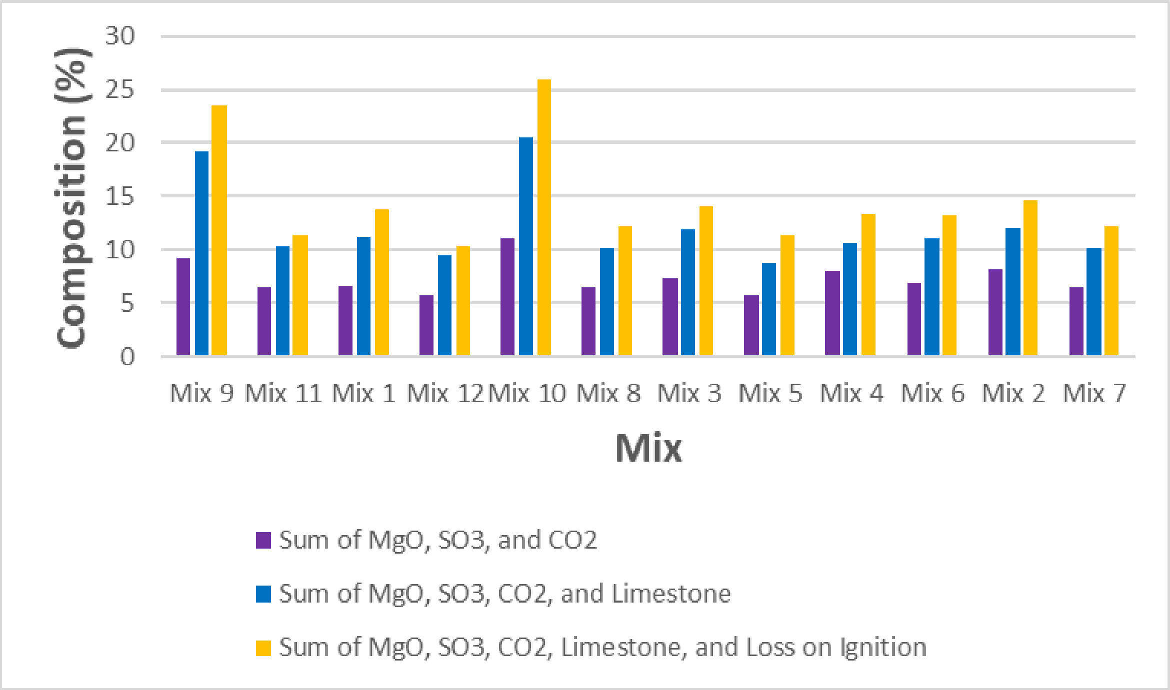
Figure 6.5 Sums of Uncategorized Specification Compositions, 28 Day Compressive Strength

Table 6.9 Sums of Uncategorized Specification Compositions, 56 Day Compressive Strength

	Sum of MgO, SO_3, and CO_2 (%)	Sum of MgO, SO_3, CO_2, and Limestone (%)	Sum of MgO, SO_3, CO_2, Limestone, and Loss on Ignition (%)
Mix 9	9.2	19.2	23.5
Mix 11	6.5	10.3	11.3
Mix 1	6.6	11.1	13.8
Mix 12	5.7	9.5	10.3
Mix 10	11	20.5	25.9
Mix 8	6.4	10.2	12.2
Mix 3	7.3	11.9	14
Mix 5	5.7	8.8	11.3
Mix 4	8	10.6	13.4
Mix 6	6.9	11	13.2
Mix 2	8.2	12	14.6
Mix 7	6.4	10.2	12.2



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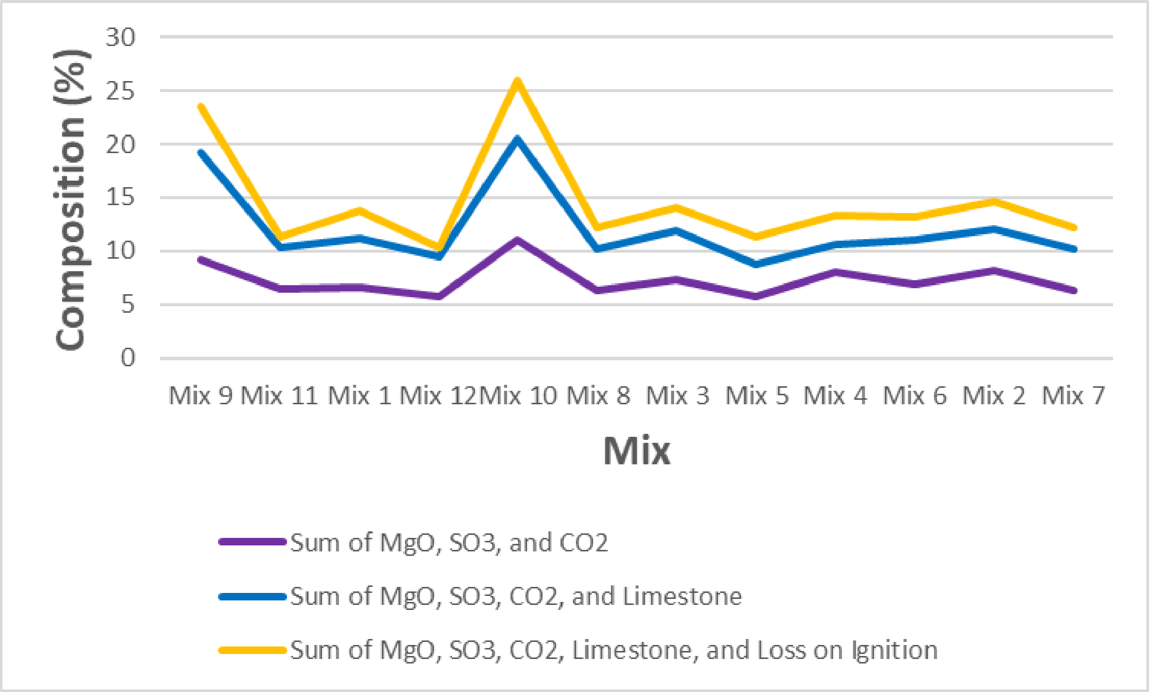

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Figure 6.6 Sums of Uncategorized Specification Compositions, 56 Day Compressive Strength

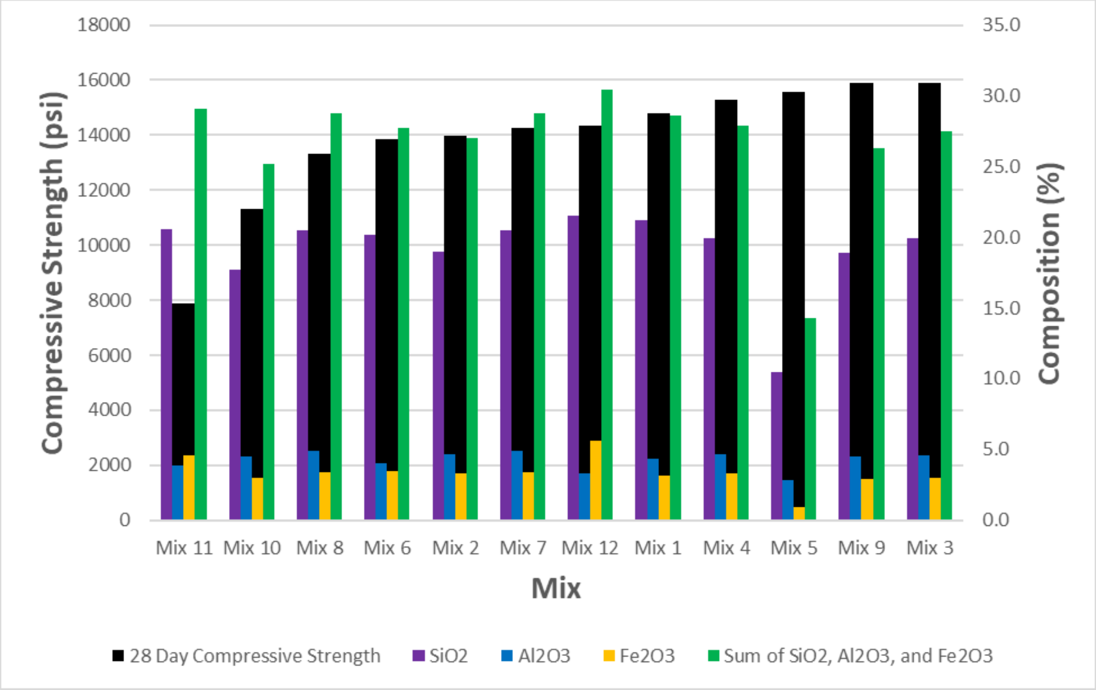
Upon further analysis of these sums at both testing ages, there appears to be no trend. The sums do appear to be fairly consistent between the twelve mixes, with the exceptions of the Type 1L cements.

6.3.2 Oxide Composition Mill Cert Specifications

Another set of mill cert specifications grouped together for analysis were oxide compositions, specifically the SiO_2, Al_2O_3, and Fe_2O_3 compositions. The sum of these three compositions was also analyzed alongside the individual values. Table 6.11 and Figure 6.7 show the data for 28 days, and Table 6.12 and Figure 6.8 show the data for 56 days.

Table 6.10 Oxide Composition Specification Comparison, 28 Day Compressive Strength

	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Sum of SiO_2, Al_2O_3, and Fe_2O_3 (%)	28 Day Compressive Strength (psi)
Mix 11	20.6	3.9	4.6	29.1	7,860
Mix 10	17.7	4.5	3.0	25.2	11,320
Mix 8	20.5	4.9	3.4	28.8	13,320
Mix 6	20.2	4.0	3.5	27.7	13,860
Mix 2	19.0	4.7	3.3	27.0	13,970
Mix 7	20.5	4.9	3.4	28.8	14,250
Mix 12	21.5	3.3	5.6	30.4	14,340
Mix 1	21.2	4.3	3.1	28.6	14,790
Mix 4	19.9	4.7	3.3	27.9	15,280
Mix 5	10.5	2.9	1.0	14.3	15,570
Mix 9	18.9	4.5	2.9	26.3	15,880
Mix 3	19.9	4.6	3.0	27.5	15,890



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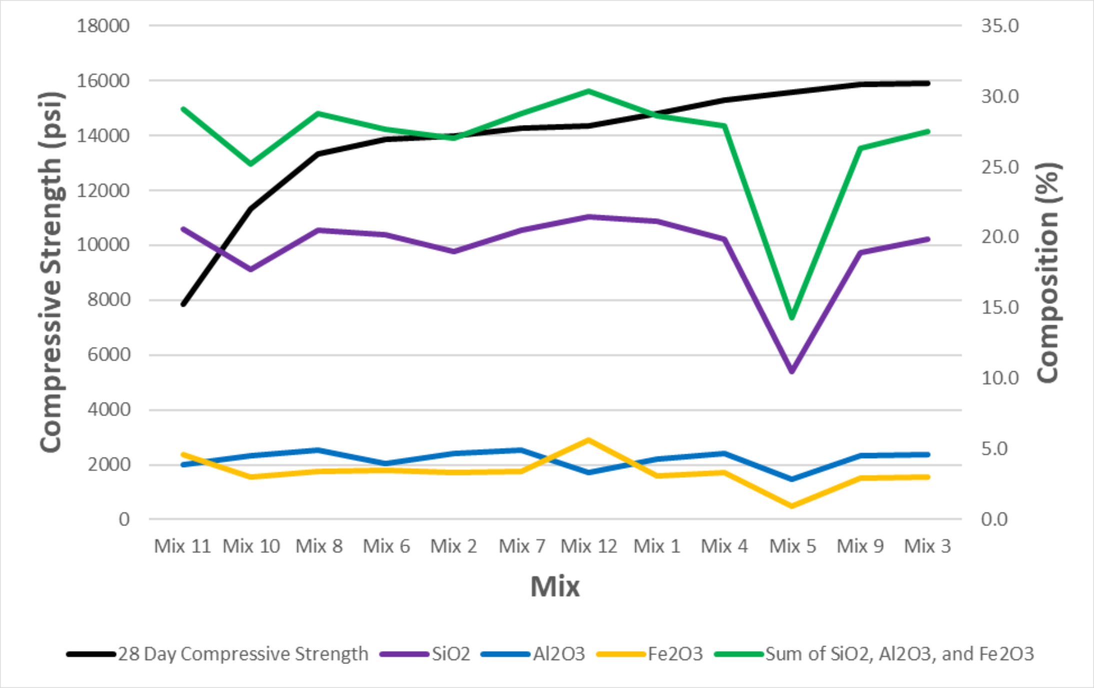

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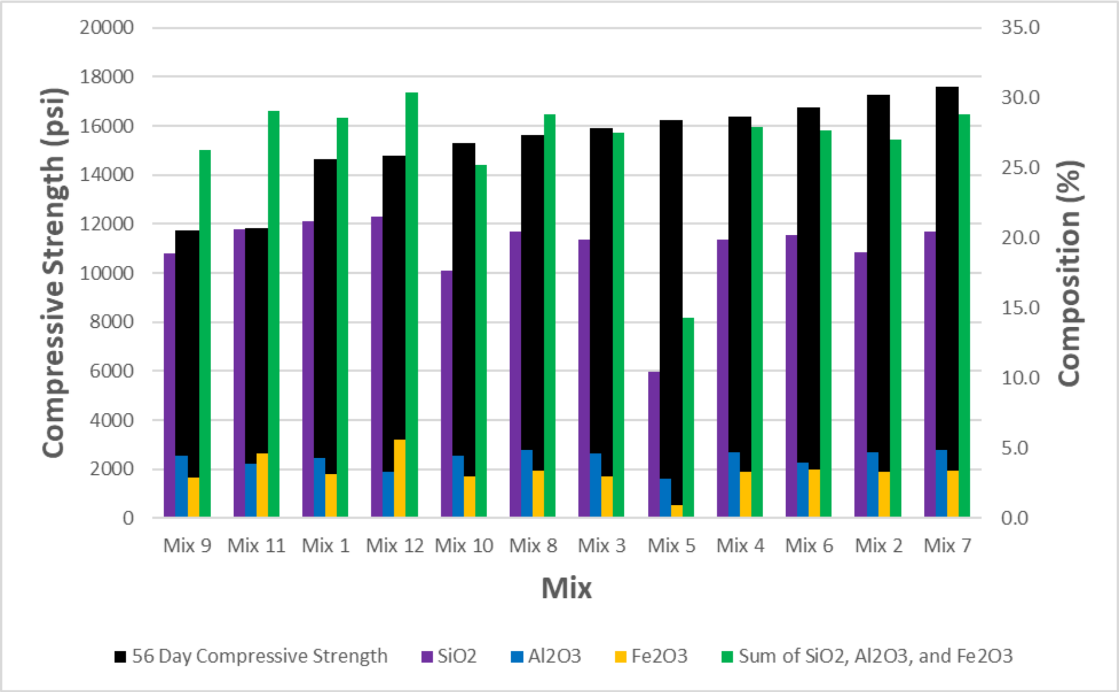
Figure 6.7 Oxide Composition Specification Comparison, 28 Day Compressive Strength

Table 6.11 Oxide Composition Specification Comparison, 56 Day Compressive Strength

	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Sum of SiO_2, Al_2O_3, and Fe_2O_3 (%)	56 Day Compressive Strength (psi)
Mix 9	18.9	4.5	2.9	26.3	11,740
Mix 11	20.6	3.9	4.6	29.1	11,810
Mix 1	21.2	4.3	3.1	28.6	14,630
Mix 12	21.5	3.3	5.6	30.4	14,790
Mix 10	17.7	4.5	3.0	25.2	15,310
Mix 8	20.5	4.9	3.4	28.8	15,640
Mix 3	19.9	4.6	3.0	27.5	15,890
Mix 5	10.5	2.9	1.0	14.3	16,260
Mix 4	19.9	4.7	3.3	27.9	16,400
Mix 6	20.2	4.0	3.5	27.7	16,740
Mix 2	19.0	4.7	3.3	27.0	17,280
Mix 7	20.5	4.9	3.4	28.8	17,580



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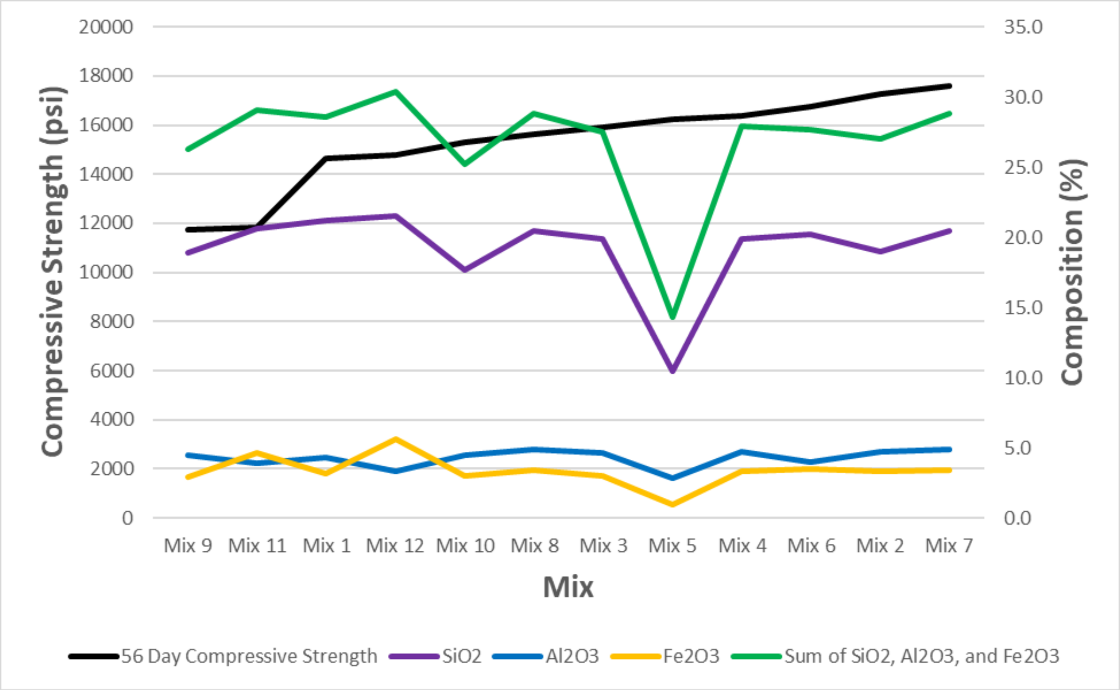

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Figure 6.8 Oxide Composition Specification Comparison, 56 Day Compressive Strength

As with the uncategorized specifications in Section 6.3.1, there appears to be no trend between the individual oxide compositions or their sum. As with the specifications in Section 6.3.1 again, the oxide compositions of all compared mixes were fairly consistent, with one exception in Mix 5. This is likely due to the specified limits set by ASTM C150 for each component being similar enough for all types and classes of cement that the significant differences necessary to establish trends are unlikely to be seen in commercially available cements.

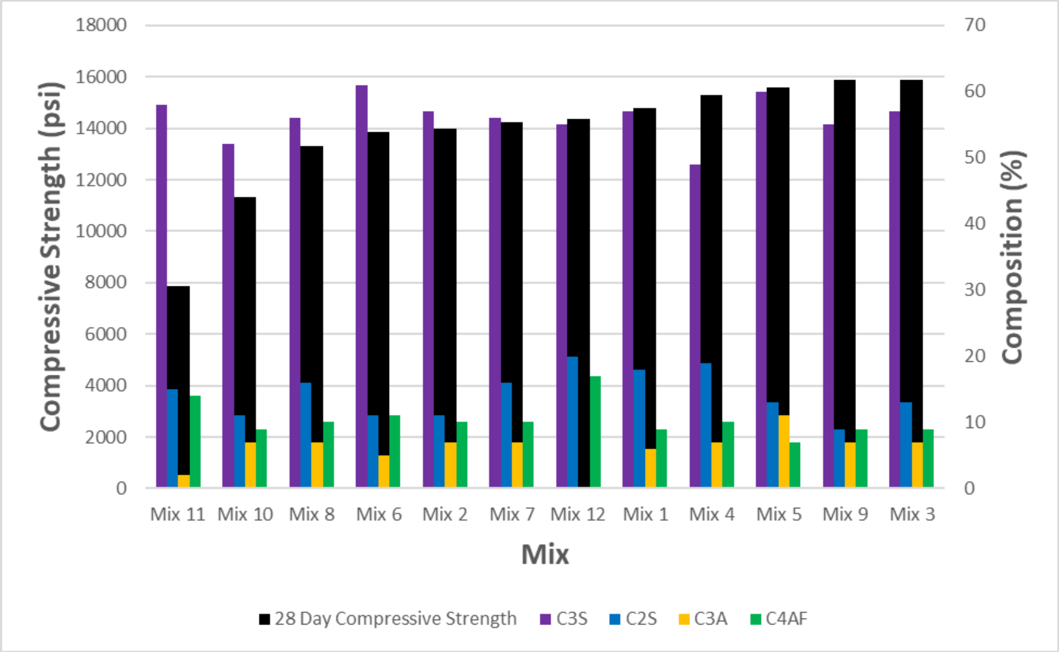
6.3.3 Calcium Compound Composition Mill Cert Specifications

The third group of specifications combined for analysis was the calcium compound group. This group contains C_3S, C_2S, C_3A, C_4AF, and $C_3S+4.75*C_3A$. As was the case in Section 6.3.1, some mixes' mill certs were missing values necessary for comparison, specifically the C_2S and C_4AF values for Mixes 11 and 12. Fortunately, the values missing from the mill certs could be calculated using guidance from ASTM C150. These calculated values provide a better replacement value than a calculated average value. Tables 6.13 and 6.14 show the comparisons of these values for 28 days, accompanied by Figures 6.9 and 6.10, respectively. The comparisons for 56 day strength are shown in Tables 6.15 and 6.16, accompanied by Figures 6.11 and 6.12, respectively.

Table 6.12 Calcium Compound Composition Specification Comparison, 28 Day Compressive Strength

	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	28 Day Compressive Strength (psi)
Mix 11	58	15**	2	14**	7,860
Mix 10	52	11	7	9	11,320
Mix 8	56	16	7	10	13,320
Mix 6	61	11	5	11	13,860
Mix 2	57	11	7	10	13,970
Mix 7	56	16	7	10	14,250
Mix 12	55	20**	0	17**	14,340
Mix 1	57	18	6	9	14,790
Mix 4	49	19	7	10	15,280
Mix 5	60	13	11	7	15,570
Mix 9	55	9	7	9	15,880
Mix 3	57	13	7	9	15,890

**Indicates a value calculated using ASTM C150, value not included in mill cert



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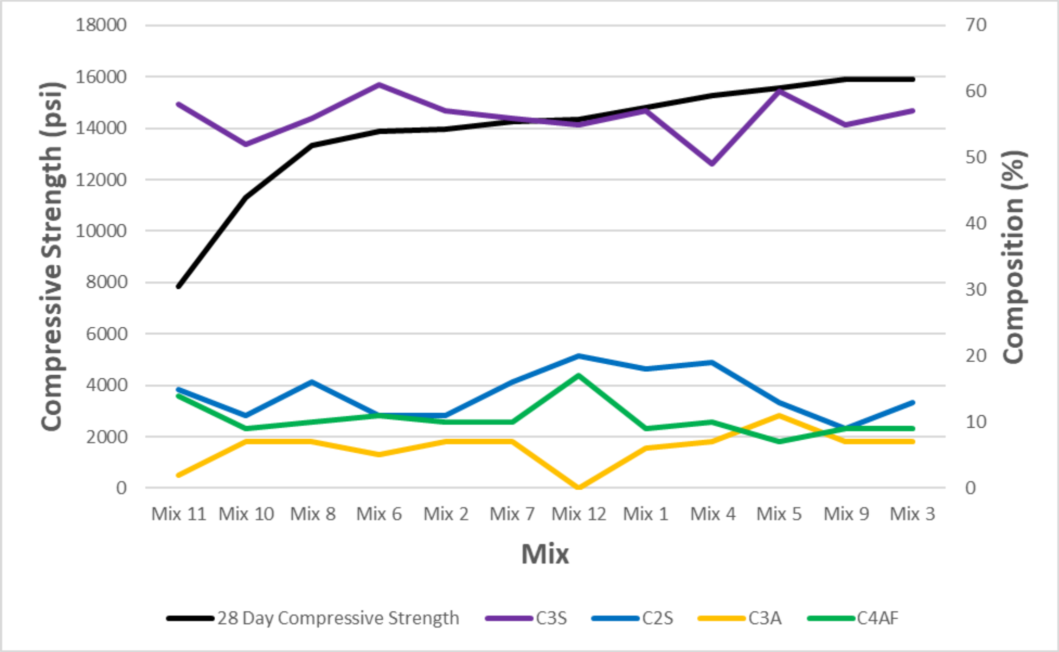

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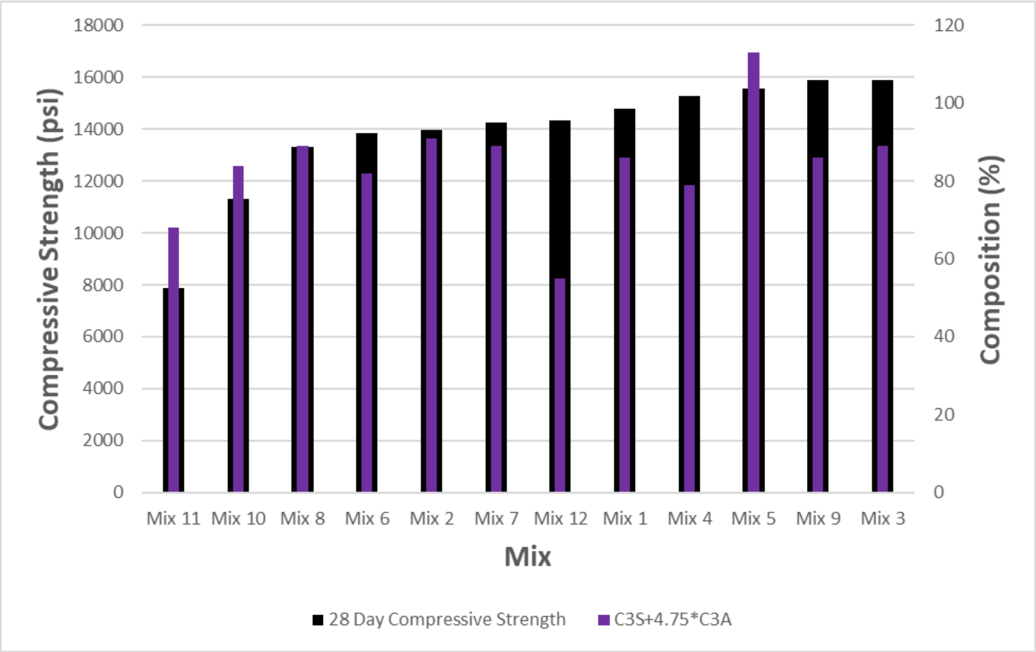
Figure 6.9 Calcium Compound Composition Specification Comparison, 28 Day Compressive Strength

Table 6.13 $C_3S+4.75*C_3A$ Composition Specification Comparison, 28 Day Compressive Strength

	$C_3S+4.75*C_3A$ (%)	**28 Day Compressive Strength (psi)**
Mix 11	68	7,860
Mix 10	84	11,320
Mix 8	89	13,320
Mix 6	82	13,860
Mix 2	91	13,970
Mix 7	89	14,250
Mix 12	55	14,340
Mix 1	86	14,790
Mix 4	79	15,280
Mix 5	113	15,570
Mix 9	86	15,880
Mix 3	89	15,890



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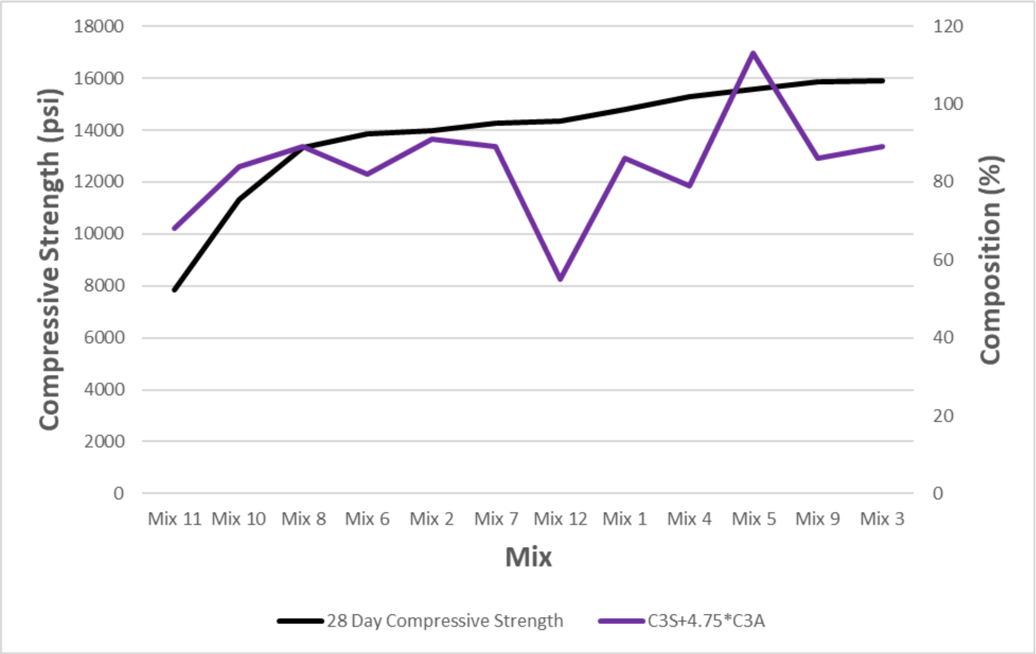

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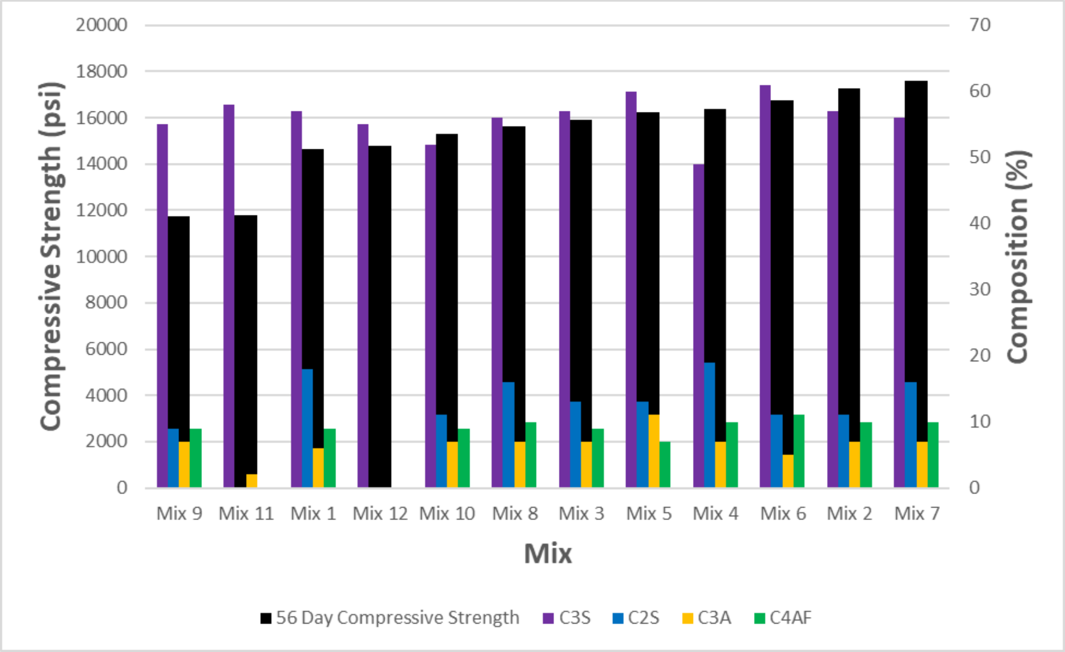
Figure 6.10 $C_3S+4.75*C_3A$ *Composition Specification Comparison, 28 Day Compressive Strength*

Table 6.14 Calcium Compound Composition Specification Comparison, 56 Day Compressive Strength

	C_3S (%)	**C_2S (%)**	**C_3A (%)**	**C_4AF (%)**	**56 Day Compressive Strength (psi)**
Mix 9	55	9	7	9	11,740
Mix 11	58	15**	2	14**	11,810
Mix 1	57	18	6	9	14,630
Mix 12	55	20**	0	17**	14,790
Mix 10	52	11	7	9	15,310
Mix 8	56	16	7	10	15,640
Mix 3	57	13	7	9	15,890
Mix 5	60	13	11	7	16,260
Mix 4	49	19	7	10	16,400
Mix 6	61	11	5	11	16,740
Mix 2	57	11	7	10	17,280
Mix 7	56	16	7	10	17,580
**Indicates a value calculated using ASTM C150, value not included in mill cert					



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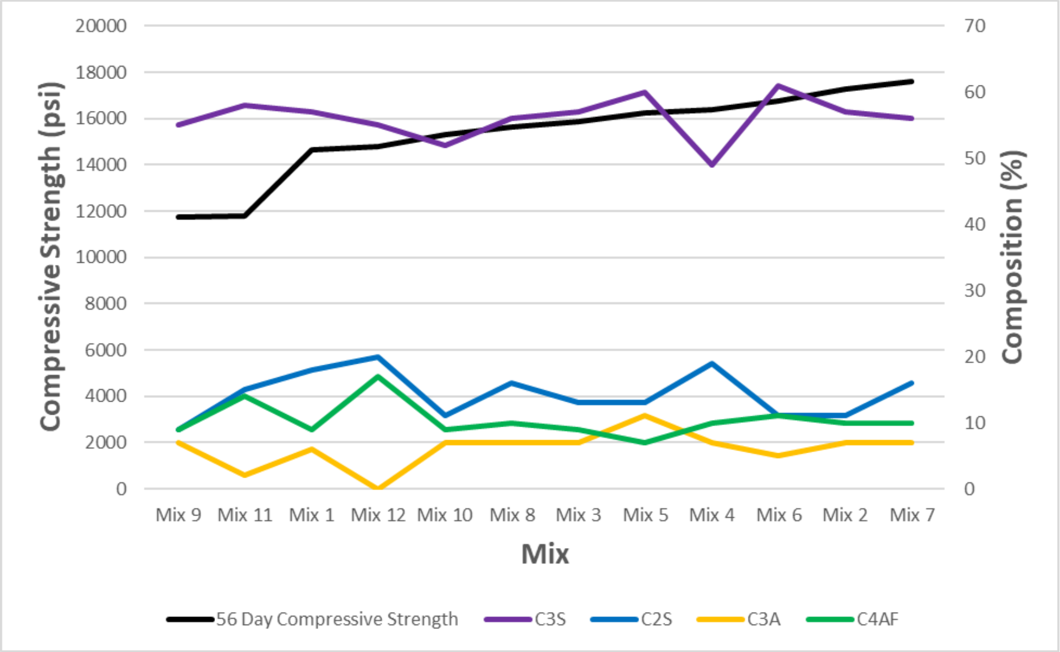

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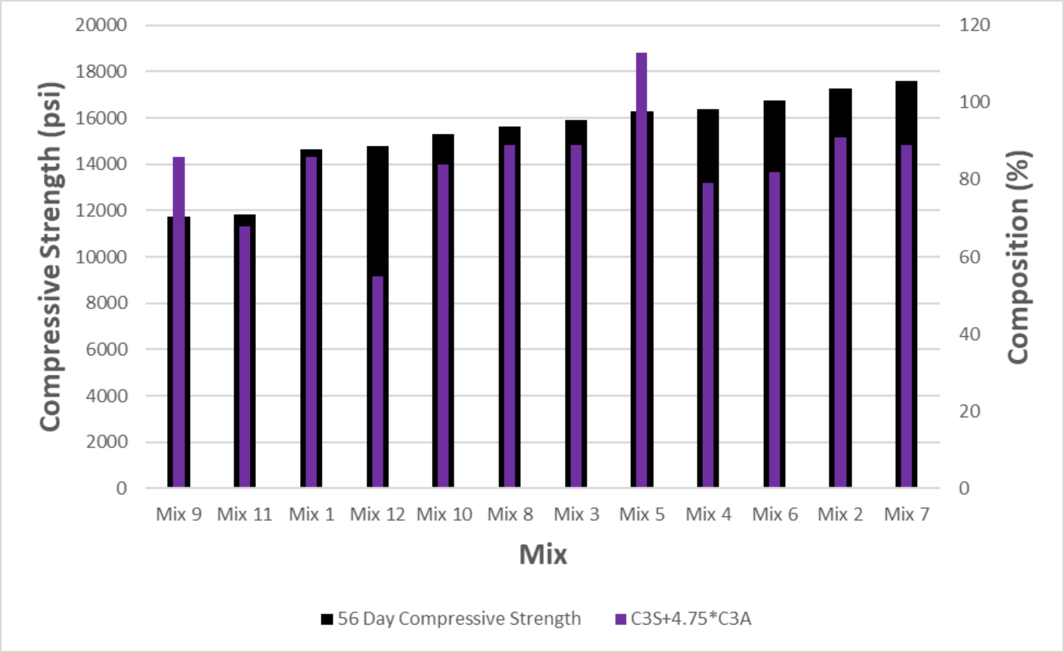
Figure 6.11 Calcium Compound Composition Specification Comparison, 56 Day Compressive Strength

Table 6.15 $C_3S+4.75*C_3A$ Composition Specification Comparison, 56 Day Compressive Strength

	C_3S+4.75*C3A (%)	**56 Day Compressive Strength (psi)**
Mix 9	86	11,740
Mix 11	68	11,810
Mix 1	86	14,630
Mix 12	55	14,790
Mix 10	84	15,310
Mix 8	89	15,640
Mix 3	89	15,890
Mix 5	113	16,260
Mix 4	79	16,400
Mix 6	82	16,740
Mix 2	91	17,280
Mix 7	89	17,580



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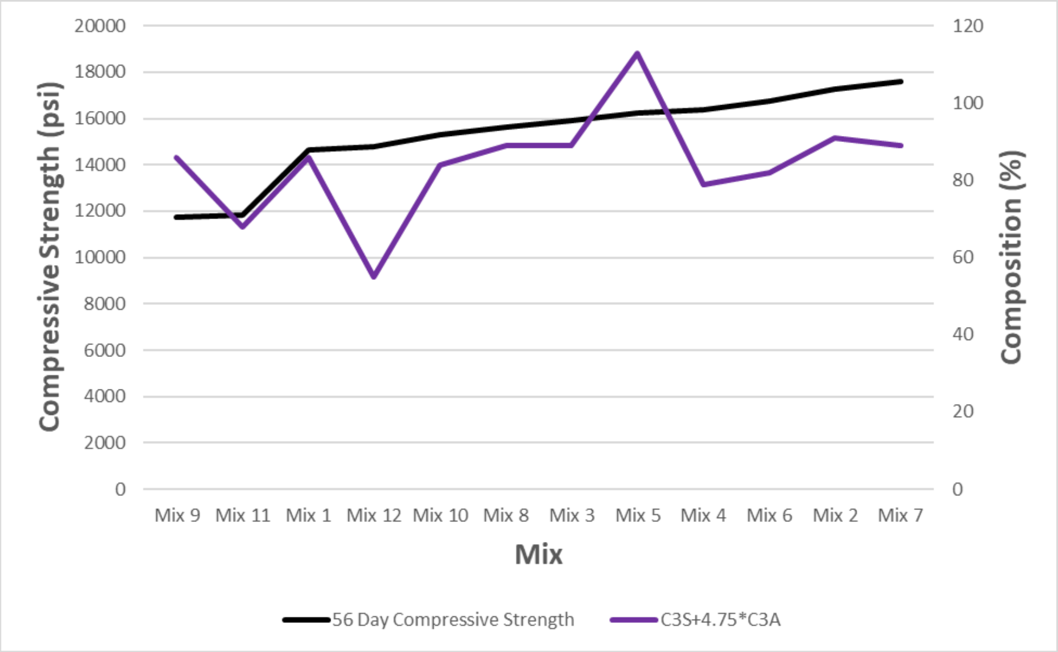

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Figure 6.12 $C_3S+4.75*C_3A$ Composition Specification Comparison, 56 Day Compressive Strength

There appears to be a slight trend between higher C_3S and $C_3S+4.75*C_3A$ compositions and higher compressive strength at both 28 days and 56 days. The other calcium compounds do not appear to follow a trend.

6.3.4 Blaine Fineness Mill Cert Specifications

The final specification from the cement mill certs that was used for analysis was the Blaine fineness of each cement. Table 6.17 and Figure 6.13 show the data for 28 days, while Table 6.18 and Figure 6.14 show the data for 56 days.

Table 6.16 Blaine Fineness Specification Comparison, 28 Day Compressive Strength

	Blaine Fineness (m^2/kg)	**28 Day Compressive Strength (psi)**
Mix 11	444	7,860
Mix 10	418	11,320
Mix 8	526	13,320
Mix 6	410	13,860
Mix 2	400	13,970
Mix 7	526	14,250
Mix 12	274	14,340
Mix 1	404	14,790
Mix 4	411	15,280
Mix 5	381	15,570
Mix 9	386	15,880
Mix 3	364	15,890

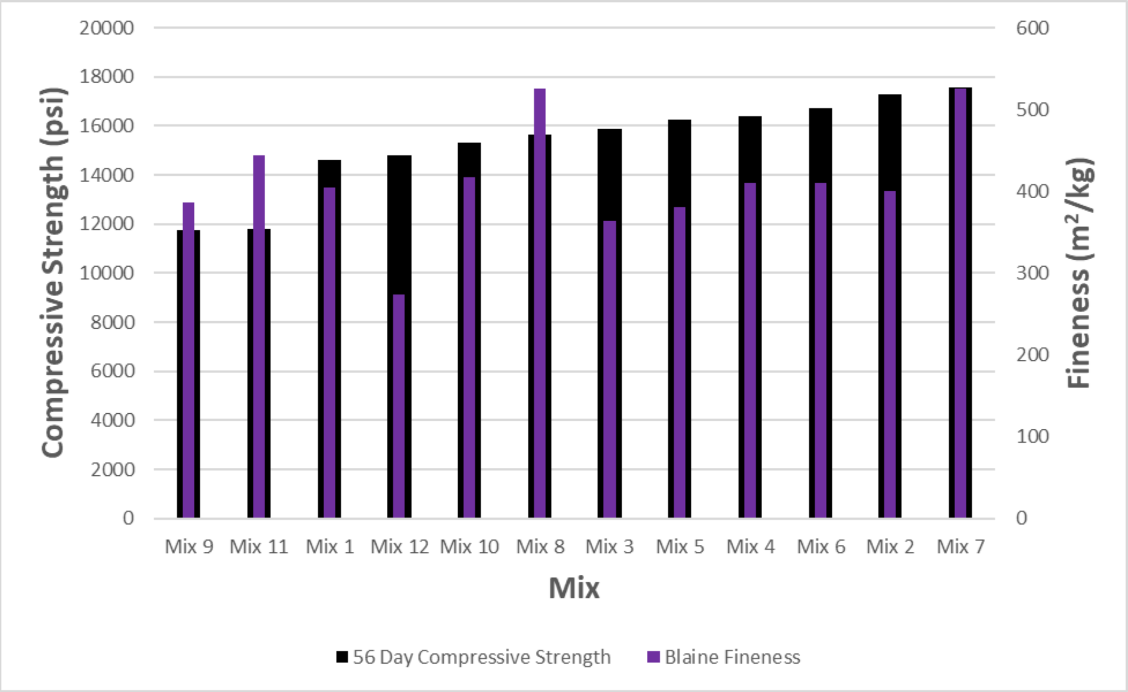
(a)

(b)

Figure 6.13 Blaine Fineness Specification Comparison, 28 Day Compressive Strength

Table 6.17 Blaine Fineness Specification Comparison, 56 Day Compressive Strength

	Blaine Fineness (m^2/kg)	**56 Day Compressive Strength (psi)**
Mix 9	386	11,740
Mix 11	444	11,810
Mix 1	404	14,630
Mix 12	274	14,790
Mix 10	418	15,310
Mix 8	526	15,640
Mix 3	364	15,890
Mix 5	381	16,260
Mix 4	411	16,400
Mix 6	410	16,740
Mix 2	400	17,280
Mix 7	526	17,580



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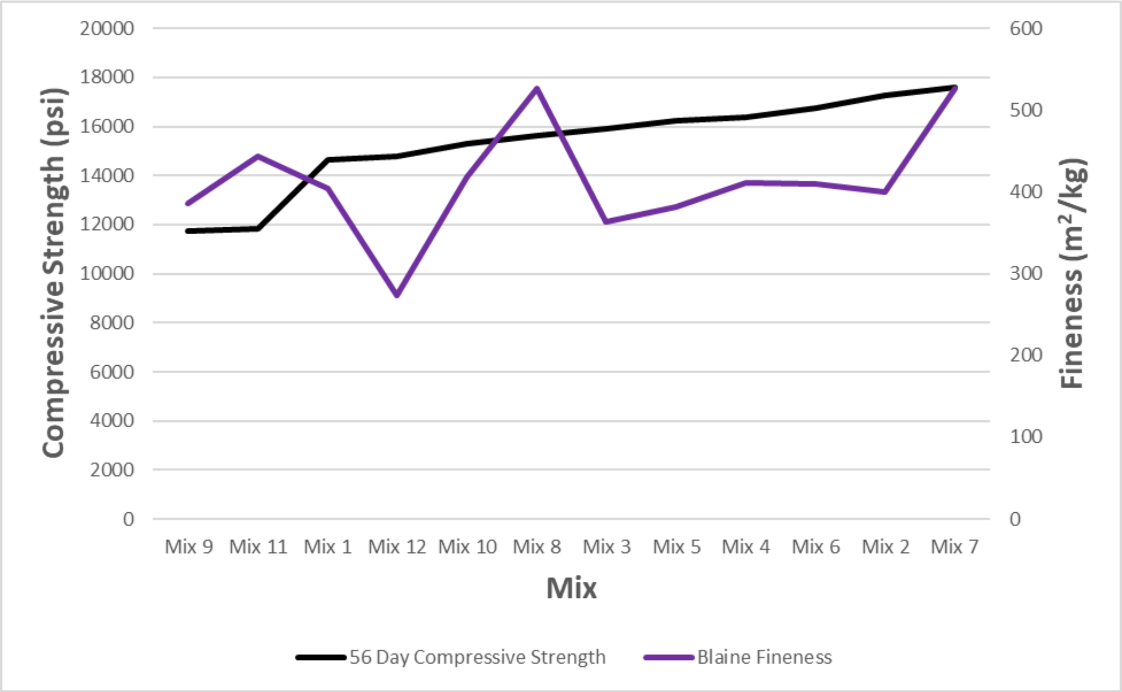

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Figure 6.14 Blaine Fineness Specification Comparison, 56 Day Compressive Strength

Both testing ages appear to show a trend between Blaine fineness and compressive strength. Interestingly, the trends appear to be opposite to each other. At 28 days, there appears to be a slight trend between lower fineness values and higher compressive strengths, while at 56 days there appears to be a slight trend between higher fineness values and higher compressive strengths. This could be due to the method of curing used in the project. All specimens were continually wet-cured in a lime-water bath, which provided the specimens constant access to water for further hydration. The larger cement particle surface areas of the finer cements could be the cause of additional strength gain over the longer period of curing.

6.4 Analysis Based on Calorimetry Data

6.4.1 Thermal Profile Analysis

Another phase of analysis performed on the test mixes was based on the collected calorimetry data. The trimmed and adjusted calorimetry data was analyzed further with regards to the peak ΔTemp, lengths of time to reach the peak ΔTemp, and the lowest point of the dormancy period. Additionally, the length of time between the lowest point of the dormancy period and the peak ΔTemp was identified to provide more information about the speed of hydration for each mix. Finally, to learn more about the time length of hydration, points were identified before and after the peak ΔTemp that equaled 50% of the magnitude of the peak ΔTemp. The time between these points was also used for comparison. As with the earlier analysis of the mill cert specifications, both 28 day and 56 day compressive strengths were considered. Table 6.18 shows the data, referred to as the thermal profile, of all thirteen mixes independent of compressive strength.

Table 6.18 Thermal Profiles of all Mixes

			Time From:			
Mix	**Cement Type/Class**	**Peak ΔTemp, ˚F**	**Test Start to Peak ΔTemp, min**	**Test Start to Lowest Point of Dormancy, min**	**Lowest Point of Dormancy to Peak ΔTemp, min**	**50% of Peak ΔTemp (Before Peak) to 50% of Peak ΔTemp (After Peak), min**
Mix 1	I/II	56.46	764	299	465	749
Mix 2	I/II	57.86	720	312	408	731
Mix 3	I/II	64.41	689	268	421	695
Mix 4	I/II	50.99	680	245	435	810
Mix 5	I	68.54	664	323	341	625
Mix 6	II/V	48.86	964	351	613	937
Mix 7	III	73.90	649	198	451	684
Mix 8	III	70.20	650	202	448	681
Mix 9	1L	54.87	678	246	432	758
Mix 10	1L	57.17	754	260	494	776
Mix 11	C	51.54	767	295	472	769
Mix 12	H	27.32	1,712	787	925	1,329
Mix 13	I/II and H	39.11	1,094	421	673	977

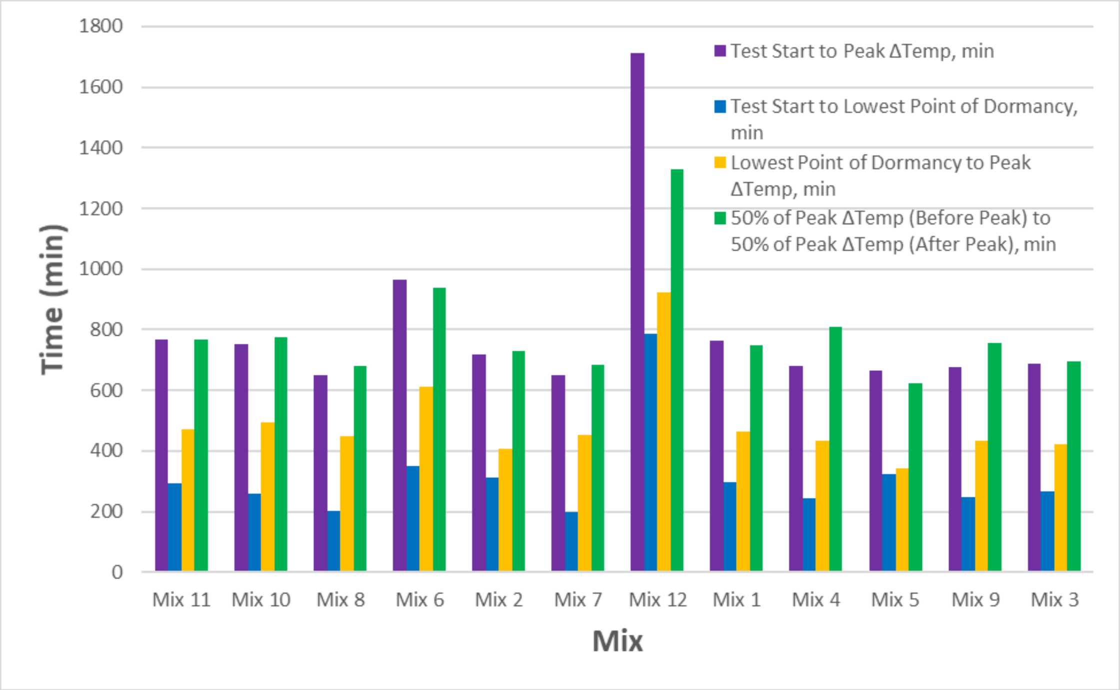
Unsurprisingly, mixes of the same cement type had similar peak ΔTemp values. Most portland cement mixes fit within the range of 54-74˚F for peak ΔTemp, with the exceptions of Mix 4 (Type I/II) and Mix 6 (Type II/V). Though Class C oil well cements are compared to Type III portland cements, Mix 11 (Class C) had a significantly lower peak ΔTemp than mixes 7 and 8 (Type IIIs). Mixes 12 (Class H) and 13 (blended Type I/II and Class H) had the lowest peak ΔTemp values of all thirteen mixes, along with the longest times in all categories. These slower, more drawn out thermal profiles are paralleled by the slower compressive strength gains of these mixes.

To understand the thermal profiles in the context of compressive strength, Table 6.19 shows the thermal profiles of Mixes 1-12 in ascending order of 28 day compressive strength, and Figure

6.15 shows the same data. Table 6.20 singles out the peak ΔTemp values, again reordered by 28 day compressive strength, with Figure 6.16 accompanying it. Table 6.21, Table 6.22, Figure 6.17, and Figure 6.18 show the corresponding data for 56 day compressive strength.

Table 6.19 Thermal Profiles Reordered by 28 Day Compressive Strength

			Time from:			
Mix	**Cement Type/Class**	**Compressive Strength (psi)**	**Test Start to Peak ΔTemp, min**	**Test Start to Lowest Point of Dormancy, min**	**Lowest Point of Dormancy to Peak ΔTemp, min**	**50% of Peak ΔTemp (Before Peak) to 50% of Peak ΔTemp (After Peak), min**
Mix 11	C	7,860	767	295	472	769
Mix 10	1L	11,320	754	260	494	776
Mix 8	III	13,320	650	202	448	681
Mix 6	II/V	13,860	964	351	613	937
Mix 2	I/II	13,970	720	312	408	731
Mix 7	III	14,250	649	198	451	684
Mix 12	H	14,340	1,712	787	925	1,329
Mix 1	I/II	14,790	764	299	465	749
Mix 4	I/II	15,280	680	245	435	810
Mix 5	I	15,570	664	323	341	625
Mix 9	1L	15,880	678	246	432	758
Mix 3	I/II	15,890	689	268	421	695



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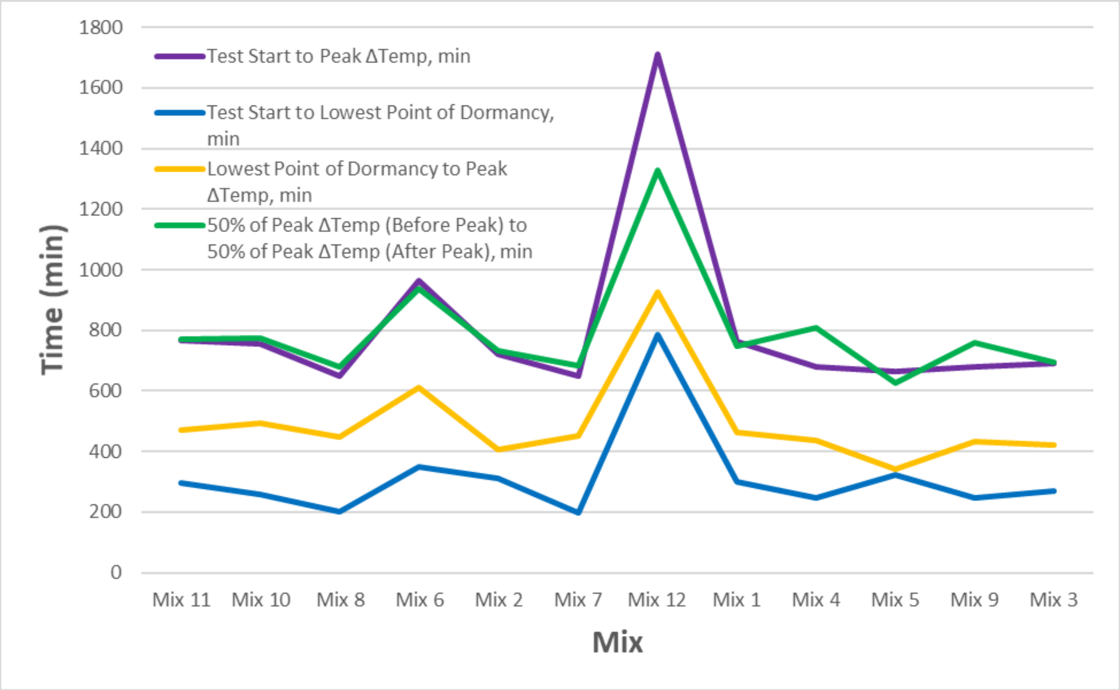

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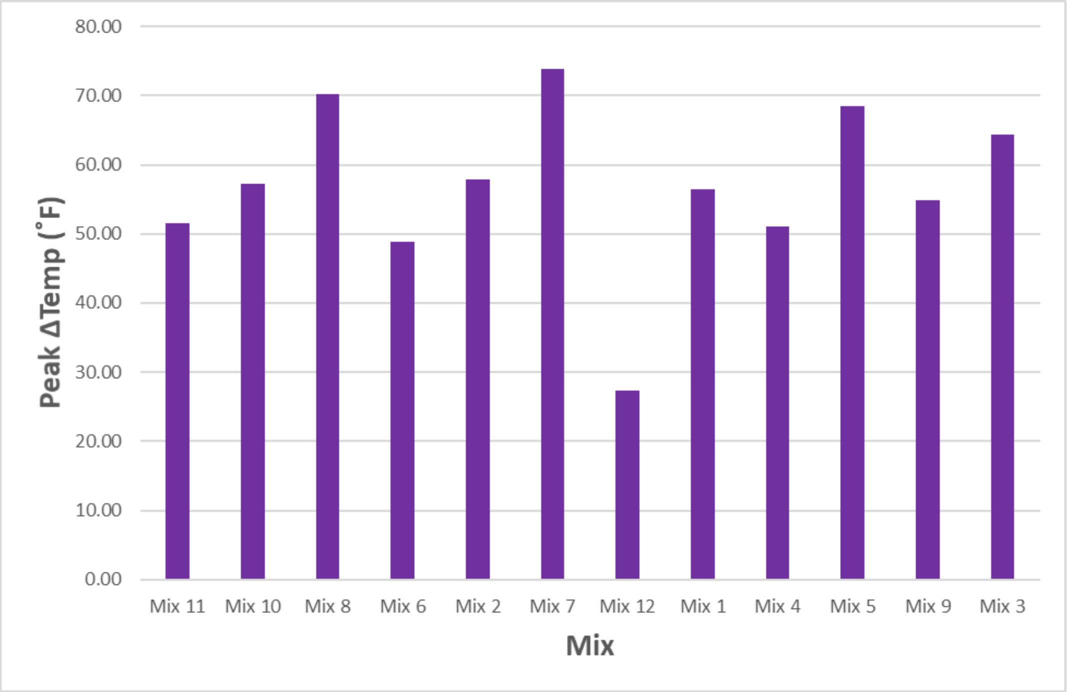
Figure 6.15 Thermal Profiles Reordered by 28 Day Compressive Strength

Table 6.20 Peak ΔTemp of Mixes Reordered by 28 Day Compressive Strength

Mix	Peak ΔTemp, ˚F
Mix 11	51.54
Mix 10	57.17
Mix 8	70.20
Mix 6	48.86
Mix 2	57.86
Mix 7	73.90
Mix 12	27.32
Mix 1	56.46
Mix 4	50.99
Mix 5	68.54
Mix 9	54.87
Mix 3	64.41



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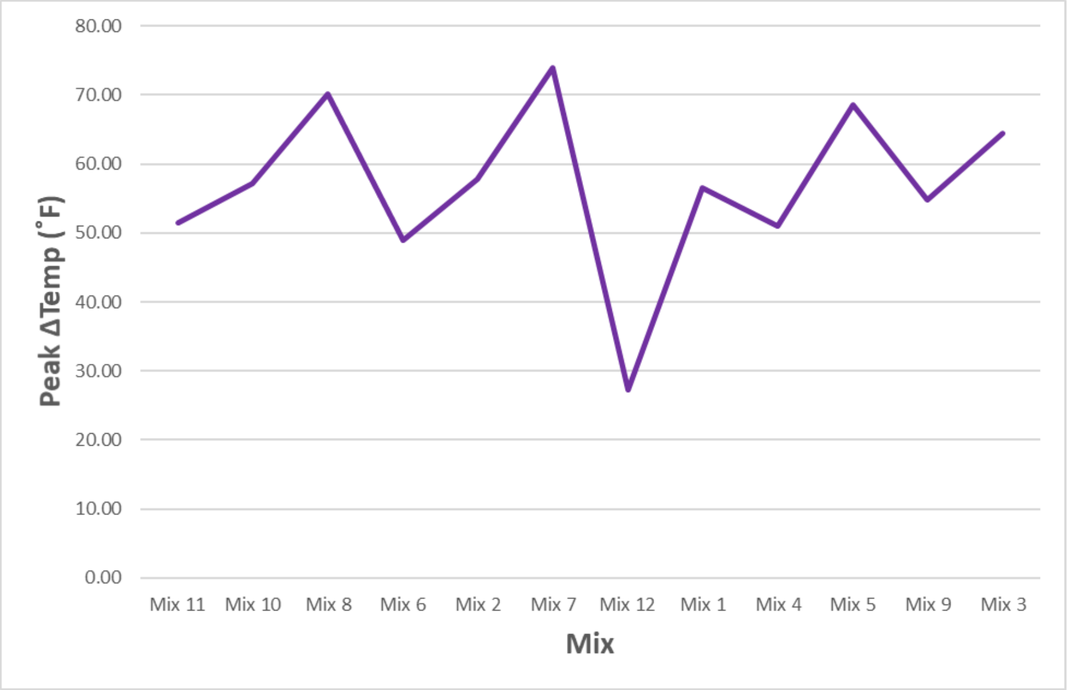

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Figure 6.16 Peak ΔTemp of Mixes Reordered by 28 Day Compressive Strength

Table 6.21 Thermal Profiles Reordered by 56 Day Compressive Strength

			Time From:			
Mix	**Cement Type/Class**	**Compressive Strength (psi)**	**Test Start to Peak ΔTemp, min**	**Test Start to Lowest Point of Dormancy, min**	**Lowest Point of Dormancy to Peak ΔTemp, min**	**50% of Peak ΔTemp (Before Peak) to 50% of Peak ΔTemp (After Peak), min**
Mix 9	1L	11,740	678	246	432	758
Mix 11	C	11,810	767	295	472	769
Mix 1	I/II	14,630	764	299	465	749
Mix 12	H	14,790	1,712	787	925	1,329
Mix 10	1L	15,310	754	260	494	776
Mix 8	III	15,640	650	202	448	681
Mix 3	I/II	15,890	689	268	421	695
Mix 5	I	16,260	664	323	341	625
Mix 4	I/II	16,400	680	245	435	810
Mix 6	II/V	16,740	964	351	613	937
Mix 2	I/II	17,280	720	312	408	731
Mix 7	III	17,580	649	198	451	684

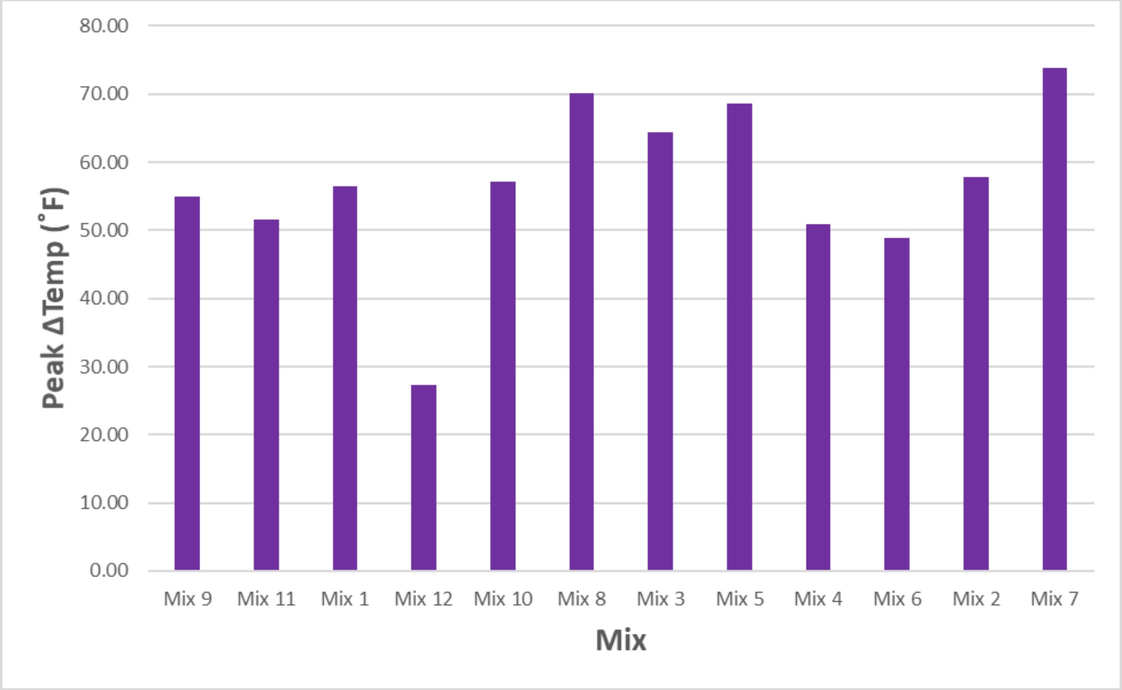
(a)

(b)

Figure 6.17 Thermal Profiles Reordered by 56 Day Compressive Strength

Table 6.22 Peak ΔTemp of Mixes Reordered by 56 Day Compressive Strength

Mix	**Peak ΔTemp, ˚F**
Mix 9	54.87
Mix 11	51.54
Mix 1	56.46
Mix 12	27.32
Mix 10	57.17
Mix 8	70.20
Mix 3	64.41
Mix 5	68.54
Mix 4	50.99
Mix 6	48.86
Mix 2	57.86
Mix 7	73.90



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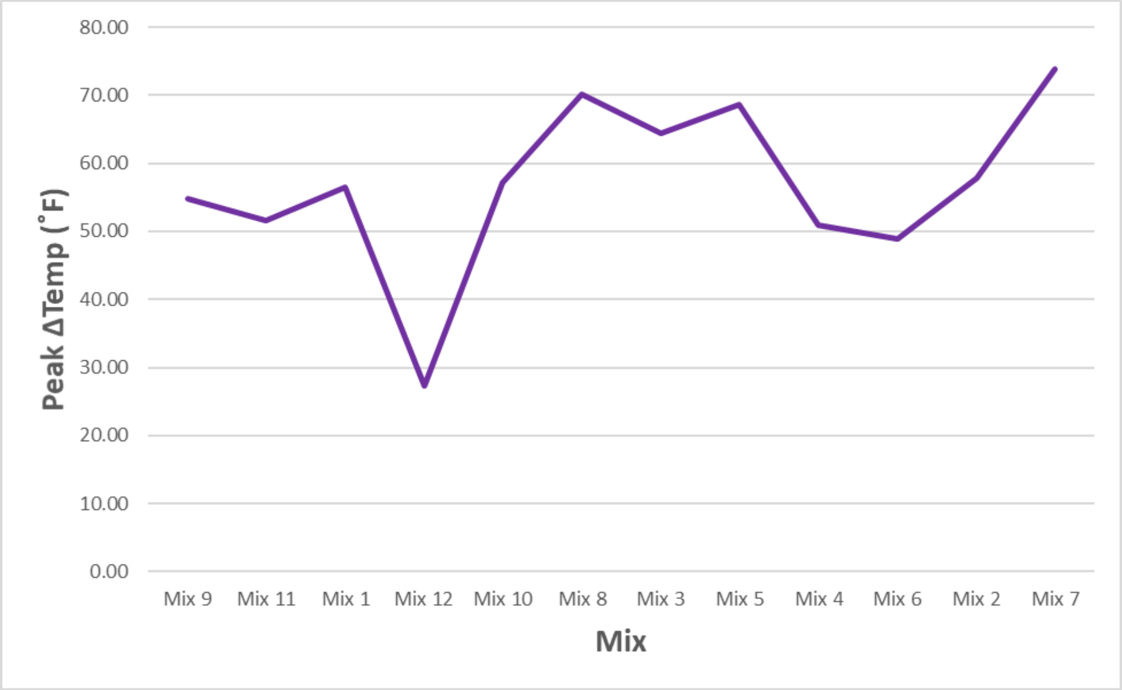

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Figure 6.18 Peak ΔTemp of Mixes Reordered by 56 Day Compressive Strength

There appears to be a very slight trend between higher peak ΔTemp values and higher compressive strength, particularly at 28 days. Otherwise, the thermal profiles of these twelve mixes do not show noticeable trends.

6.4.1.1 Blended Cement Thermal Profile Analysis

A separate analysis of the blended cement mix, Mix 13, was conducted. The mixes used for comparison, Mix 1 and Mix 12, contained the cements used in the blend in Mix 13. The thermal profiles of Mix 1, Mix 12, and Mix 13 are shown in Table 6.23.

Table 6.23 Blended Cement Thermal Profile Comparison

Time From:	**Mix 1**	**Mix 12**	**Mix 13**	
Cement Type/Class	I/II	H	I/II and H	**Average of Mix 1 and Mix 12**
Peak ΔTemp, ˚F	56.46	27.32	39.11	**41.89**
Test Start to Peak ΔTemp, min	764	1,712	1,094	**1,238**
Test Start to Lowest Point of Dormancy, min	299	787	421	**543**
Lowest Point of Dormancy to Peak ΔTemp, min	465	925	673	**695**
50% of Peak ΔTemp (Before Peak) to 50% of Peak ΔTemp (After Peak), min	749	1,329	977	**1,039**

Interestingly, Mix 13, as a 50/50 blend of Mix 1 and Mix 12, performed roughly like an average of Mix 1 and Mix 12 with regards to its thermal profile. This makes sense, as the hydration of the cement is the driving force behind the heat generation measured by calorimetry. It follows that the thermal profile of the blended cement would behave proportionally to its constituents. Future testing could be performed to verify if this behavior holds for other blended cements.

6.4.2 Area Under Calorimetry Curve Analysis

The thermal profile analysis of the thirteen test mixes did not present much in the way of trend behaviors, but it was not the only analysis performed using the calorimetry data. It was believed that there was possibly a connection between the areas under the various calorimetry curves and the compressive strengths of the corresponding specimens. This area was believed to be analogous to the total amount of hydration that occurred within the specimens, thus a larger area would correspond to higher compressive strength. To perform this analysis, the area under the calorimetry curves was calculated for the time spans of 24 hours, 48 hours, and the full 72 hours. The testing ages of 1 day, 3 days, 7 days, 28 days, and 56 days were all considered in this analysis. Tables 6.24 through 6.27 and Figures 6.19 through 6.23 show this data.

Table 6.24 Area Under Calorimetry Curves, 1 Day Compressive Strength

	Area Under 24 Hour Curve (˚F-min)	**1 Day Compressive Strength (psi)**
Mix 12	9,514	1,080
Mix 13	29,288	3,110
Mix 7	53,850	4,640
Mix 6	39,091	4,800
Mix 10	44,162	5,400
Mix 11	40,108	5,880
Mix 1	44,126	6,350
Mix 3	48,258	6,360
Mix 4	40,841	6,790
Mix 2	44,855	7,180
Mix 5	47,394	7,190
Mix 9	43,309	7,830
Mix 8	51,063	8,640

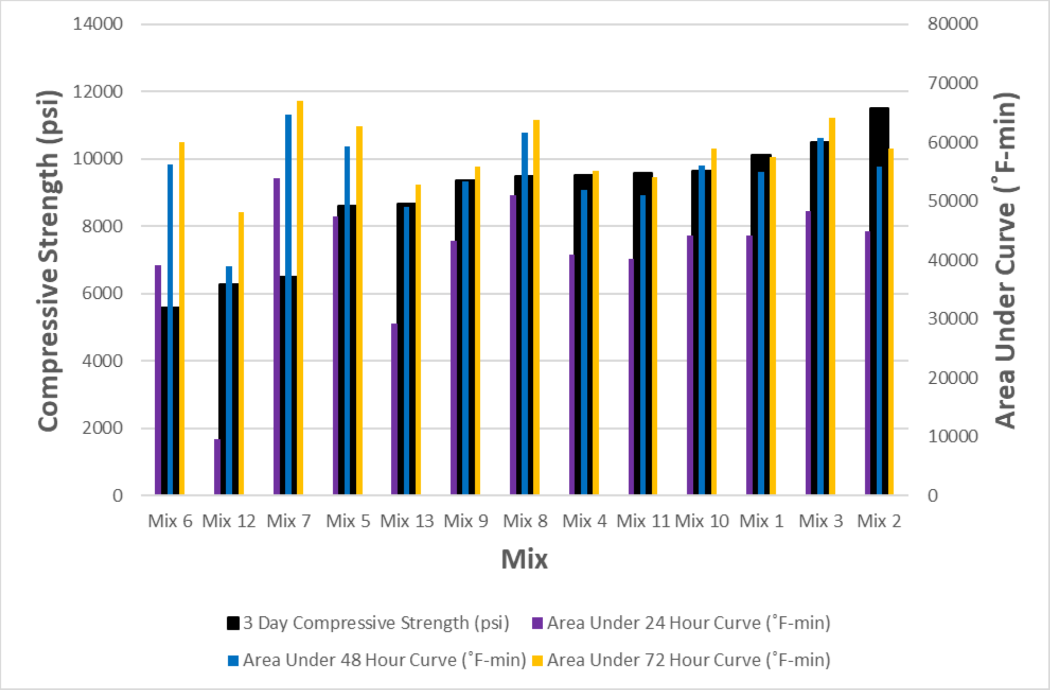
(a)

(b)

Figure 6.19 Area Under Calorimetry Curves, 1 Day Compressive Strength

Table 6.25 Area Under Calorimetry Curves, 3 Day Compressive Strength

	Area Under 24 Hour Curve (˚F-min)	**Area Under 48 Hour Curve (˚F-min)**	**Area Under 72 Hour Curve (˚F-min)**	**3 Day Compressive Strength (psi)**
Mix 6	39,091	56,282	60,032	5,570
Mix 12	9,514	38,964	48,136	6,280
Mix 7	53,850	64,672	67,014	6,490
Mix 5	47,394	59,351	62,736	8,610
Mix 13	29,288	49,014	52,823	8,670
Mix 9	43,309	53,370	55,766	9,360
Mix 8	51,063	61,698	63,837	9,500
Mix 4	40,841	51,971	55,172	9,530
Mix 11	40,108	50,962	54,075	9,590
Mix 10	44,162	55,956	58,960	9,660
Mix 1	44,126	54,943	57,497	10,110
Mix 3	48,258	60,790	64,163	10,490
Mix 2	44,855	55,811	58,931	11,510



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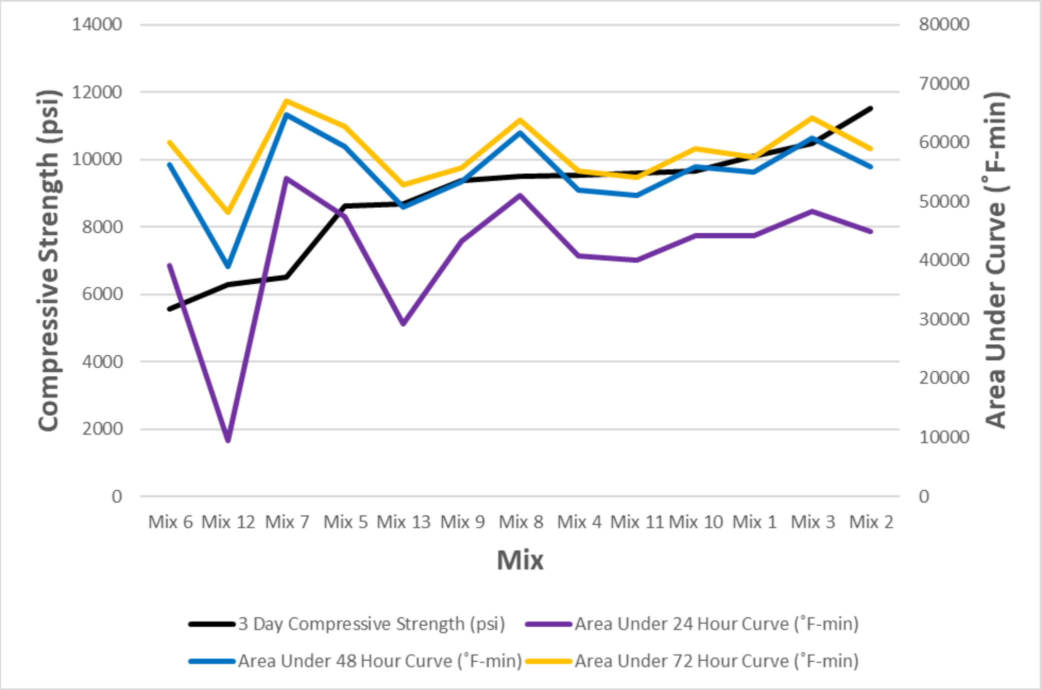

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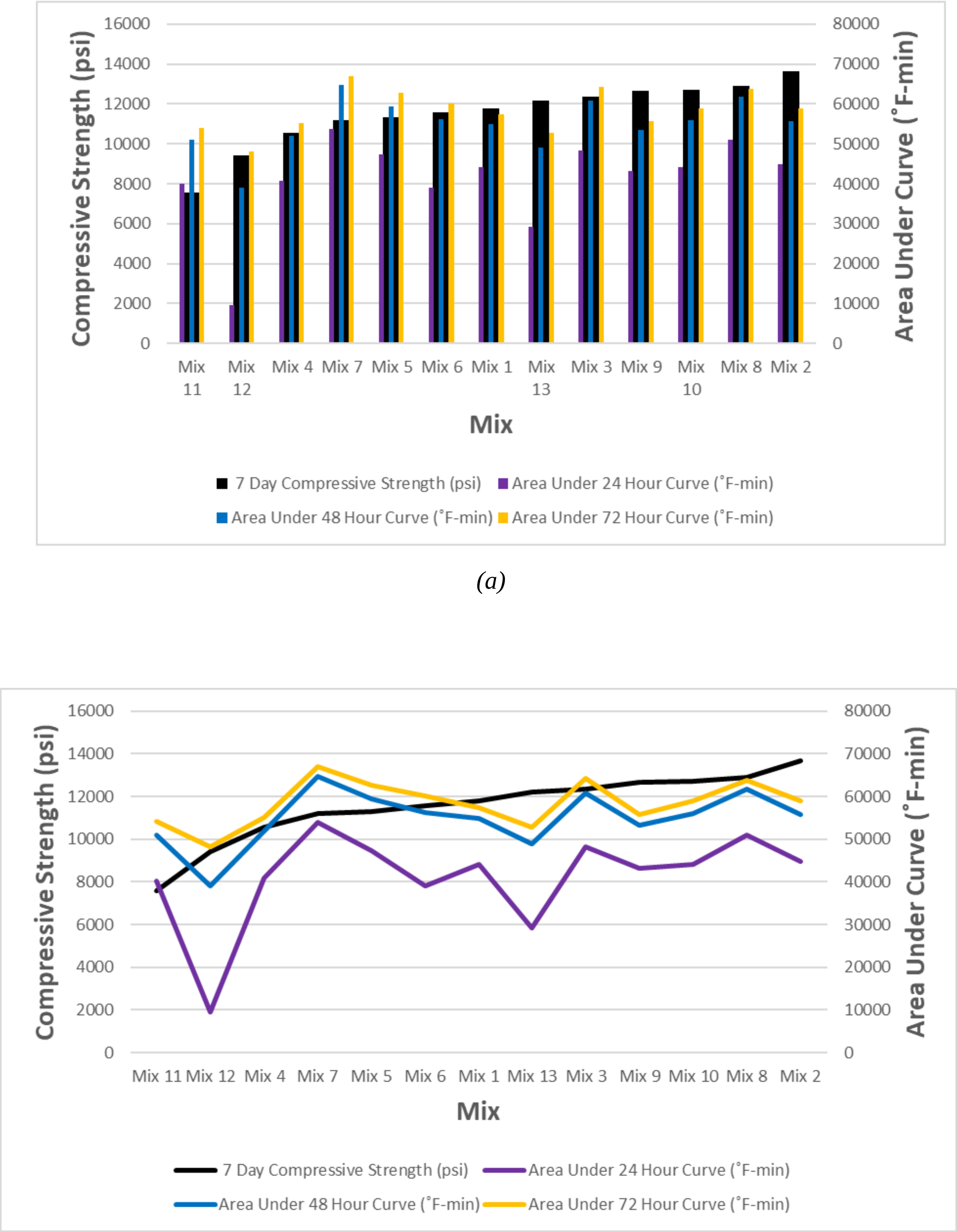
Figure 6.20 Area Under Calorimetry Curves, 3 Day Compressive Strength

Table 6.26 Area Under Calorimetry Curves, 7 Day Compressive Strength

	Area Under 24 Hour Curve (˚F-min)	**Area Under 48 Hour Curve (˚F-min)**	**Area Under 72 Hour Curve (˚F-min)**	**7 Day Compressive Strength (psi)**
Mix 11	40,108	50,962	54,075	7,570
Mix 12	9,514	38,964	48,136	9,430
Mix 4	40,841	51,971	55,172	10,560
Mix 7	53,850	64,672	67,014	11,190
Mix 5	47,394	59,351	62,736	11,310
Mix 6	39,091	56,282	60,032	11,580
Mix 1	44,126	54,943	57,497	11,780
Mix 13	29,288	49,014	52,823	12,190
Mix 3	48,258	60,790	64,163	12,360
Mix 9	43,309	53,370	55,766	12,670
Mix 10	44,162	55,956	58,960	12,720
Mix 8	51,063	61,698	63,837	12,880
Mix 2	44,855	55,811	58,931	13,660



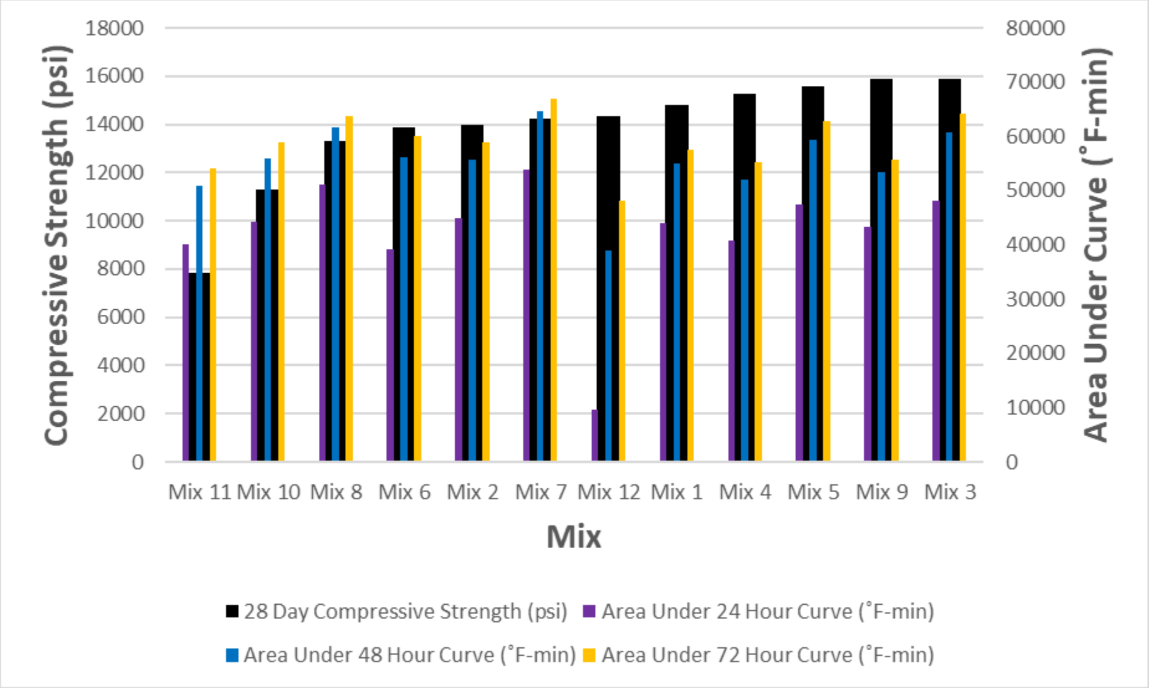
(a)

(b)

Figure 6.21 Area Under Calorimetry Curves, 7 Day Compressive Strength

Table 6.27 Area Under Calorimetry Curves, 28 Day Compressive Strength

	Area Under 24 Hour Curve (˚F-min)	**Area Under 48 Hour Curve (˚F-min)**	**Area Under 72 Hour Curve (˚F-min)**	**28 Day Compressive Strength (psi)**
Mix 11	40,108	50,962	54,075	7,860
Mix 10	44,162	55,956	58,960	11,320
Mix 8	51,063	61,698	63,837	13,320
Mix 6	39,091	56,282	60,032	13,860
Mix 2	44,855	55,811	58,931	13,970
Mix 7	53,850	64,672	67,014	14,250
Mix 12	9,514	38,964	48,136	14,340
Mix 1	44,126	54,943	57,497	14,790
Mix 4	40,841	51,971	55,172	15,280
Mix 5	47,394	59,351	62,736	15,570
Mix 9	43,309	53,370	55,766	15,880
Mix 3	48,258	60,790	64,163	15,890



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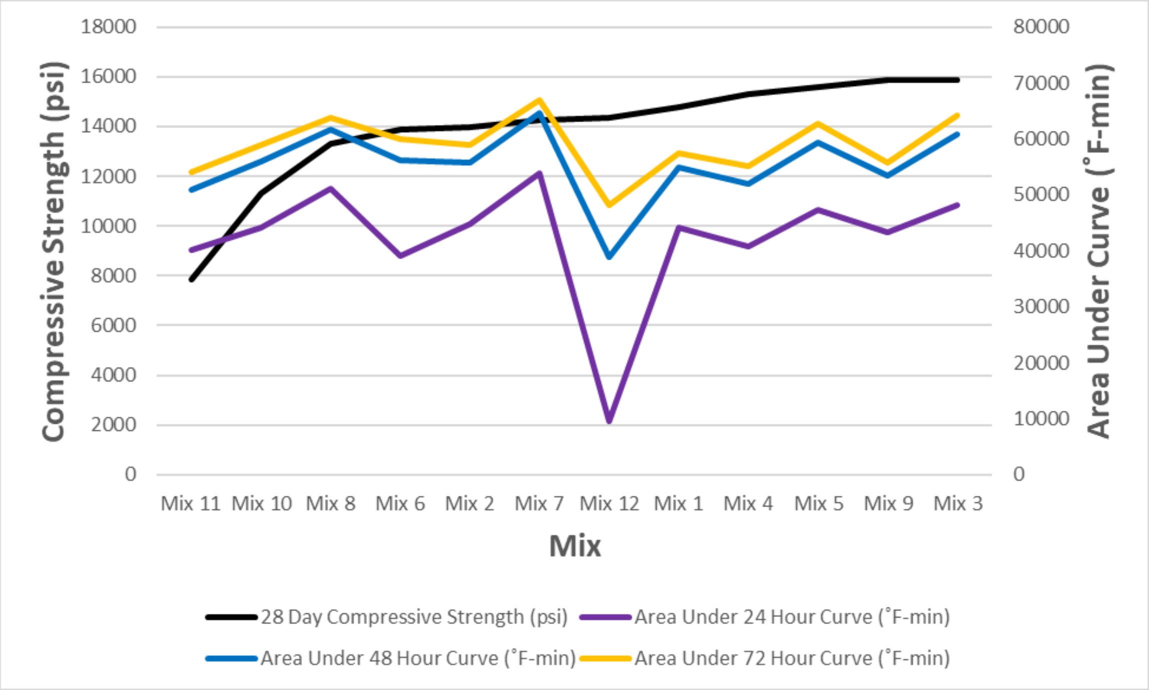
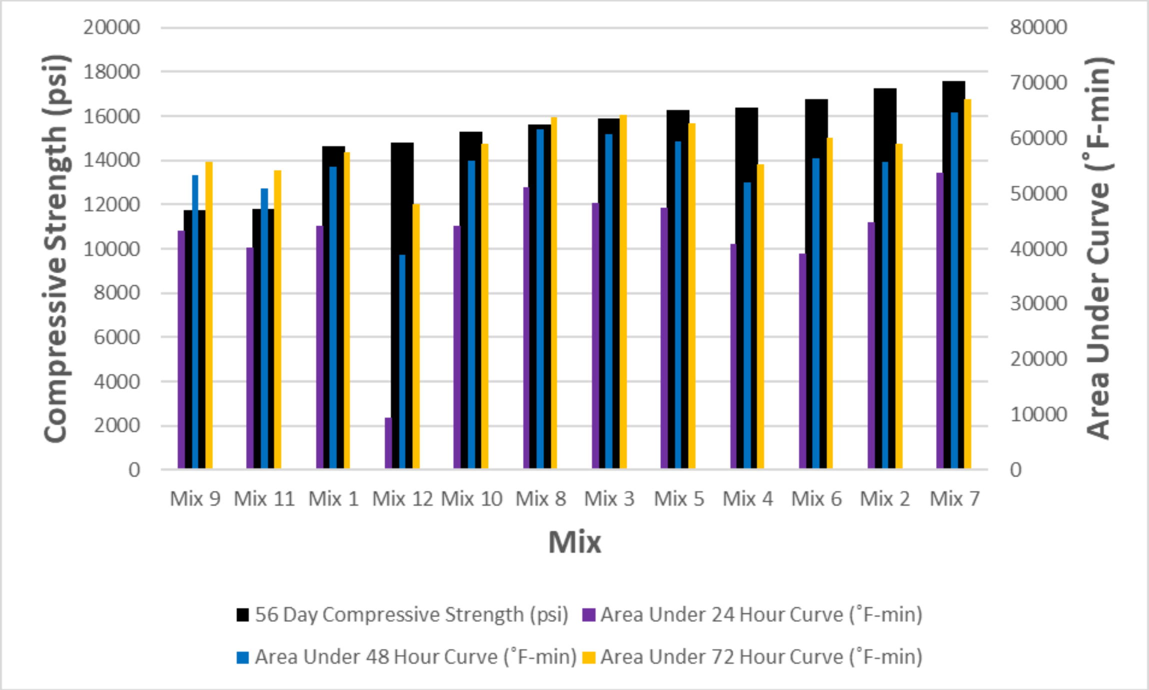


(b)

Figure 6.22 Area Under Calorimetry Curves, 28 Day Compressive Strength

Table 6.28 Area Under Calorimetry Curves, 56 Day Compressive Strength

	Area Under 24 Hour Curve (˚F-min)	Area Under 48 Hour Curve (˚F-min)	Area Under 72 Hour Curve (˚F-min)	56 Day Compressive Strength (psi)
Mix 9	43,309	53,370	55,766	11,740
Mix 11	40,108	50,962	54,075	11,810
Mix 1	44,126	54,943	57,497	14,630
Mix 12	9,514	38,964	48,136	14,790
Mix 10	44,162	55,956	58,960	15,310
Mix 8	51,063	61,698	63,837	15,640
Mix 3	48,258	60,790	64,163	15,890
Mix 5	47,394	59,351	62,736	16,260
Mix 4	40,841	51,971	55,172	16,400
Mix 6	39,091	56,282	60,032	16,740
Mix 2	44,855	55,811	58,931	17,280
Mix 7	53,850	64,672	67,014	17,580



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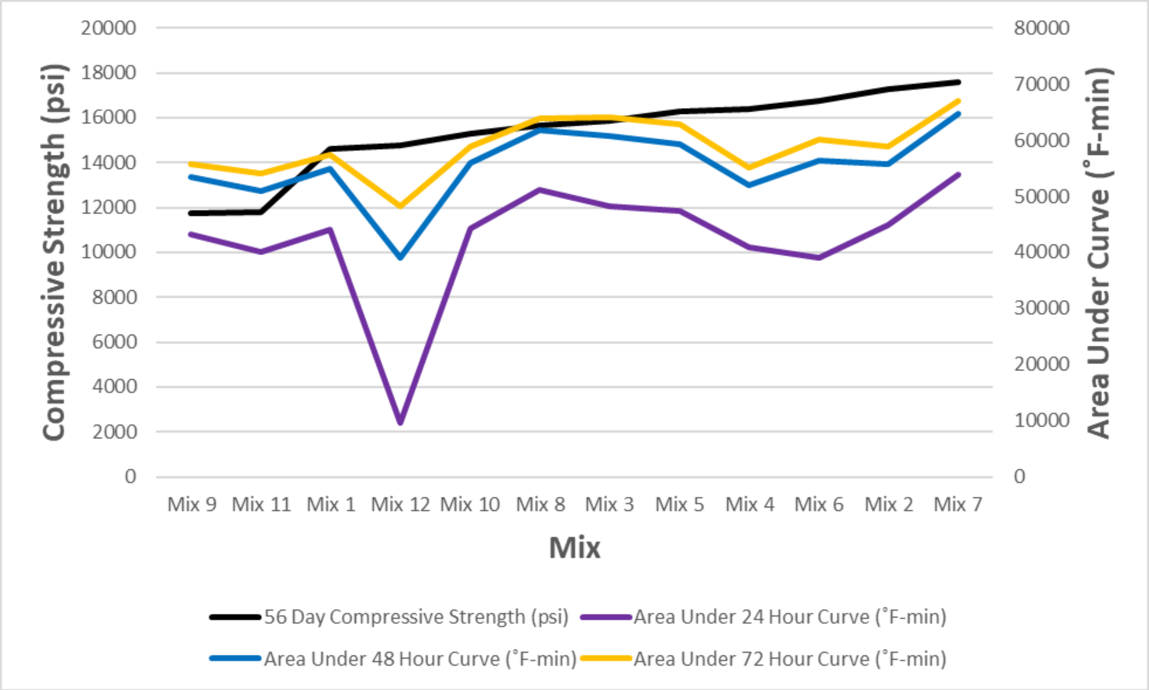

(b)

Figure 6.23 Area Under Calorimetry Curves, 56 Day Compressive Strength

At all testing ages, there appears to be a positive trend between the area under the calorimetry curves and the compressive strength. This trend appears the strongest at the earliest testing ages of 1 day and 3 days. This trend is potentially useful in future research and applications, as calorimetry data can be collected early in the testing process. Though calorimetry testing in this project was performed for 72 hours, the data indicates that the area under the 48 hour curve could provide a useful indication of relative compressive strength.

7 Findings, Conclusions, and Recommendations

The following chapter summarizes the findings, conclusions, and recommendations of this research project.

7.1 Findings

The following findings were observed over the course of this project:

- Variations in ambient temperature and humidity had significant impact on flow of the fresh concretes.
- Consistency in the mixing process was difficult to maintain, each cement required different amounts of mixing and HRWR to achieve acceptable flow.
- Using linear interpolation to estimate required HRWR dosage for a mix to fall within the acceptable range was an effective method for estimation.
- The high silica fume content meant that some test mixes required significant dosages of HRWR to meet the acceptable flow parameters.
- Using a preload of 50% of the expected ultimate load had the chance of premature failure during compressive testing, necessitating a capped preload of 18,000 lb (4,500 psi) at all ages.
- In terms of compressive strength, the Type I/II cements performed consistently and above average, while the Type I and Type 1L cements performed moderately well but closer to or below average.
- The two mixes that used the same Type III cement performed average or above average overall, but each had results at three compressive strength testing ages that ranked in the lowest three positions.

- The Class H oil well cement had very slow strength gain at early ages, but later age strength gain was more comparable to mixes that used other cement types.
- In terms of compressive strength, the oil well cements performed the worst overall by a significant margin.
- At both 28 days and 56 days, two non-blended mixes significantly underperformed compared to the other ten non-blended mixes. Using the average of just the higher ten mixes showed that the remaining group all performed fairly close to the new average compressive strength.
- The blended cement mix, Mix 13, performed similarly to the average of its unblended counterparts, both in terms of compressive strength and thermal profile.
- At 28 and 56 days, there appeared to be very few trends between any of the chemical compositions and higher compressive strength. There appeared to be a slight trend between higher C_3S and $C_3S+4.75*C_3A$ compositions and higher compressive strengths.
- There appeared to be trends between Blaine fineness and compressive strength at both 28 days and 56 days, but these trends seemed to be opposite of each other. At 28 days, there was a slight trend between lower fineness values and higher compressive strengths, while at 56 days the higher fineness values corresponded to higher compressive strengths.
- There was a very slight trend between higher peak ΔTemp values and higher compressive strength at 28 days, but otherwise no other trends were noticeable in the thermal profiles.
- There was a positive trend between larger areas under the calorimetry curve and compressive strength, especially for 1 and 3 day strengths.
- Calorimetry data beyond 48 hours offered very little additional information that was not already shown at 48 hours.

7.2 Conclusions

Based on the outlined findings, the following conclusions were made:

- Of the tested cements, the Type I/II cements performed as the best overall group. As Type I/II cements are quite common in most areas, using locally available Type I/II cement will likely result in a UHPC that is comparably strong to a mix with a more specialized cement while offering greater cost efficiency.
- There appeared to be few individual cement properties that correlated to higher compressive strength on their own. Cements with higher C_3S content, $C_3S+4.75*C_3A$ content, and Blaine fineness tended to have higher strength after 56 days.
- The specified limits on cement properties for each type/class likely limit the different compositions enough that the significant differences necessary to see strong trends are simply not going to be present without deviating from the standard types/classes.
- Measuring calorimetry for 48 hours and using the area under the calorimetry curve to predict the relative strengths of different mixes in a study appears to be a viable approach.
- A blended cement mix may be a viable approach for tailoring a UHPC mix with specific desired properties. The constituent cements appear to proportionally affect the compressive strength and thermal profile.

7.3 Recommendations

The goal of this research project was to determine the cement properties best suited for use in optimizing UHPC formulations. The findings and conclusions drawn from this research have led to the following recommendations for future study:

- Investigate UHPC mixes with cements that have larger variations in chemical compositions.
- Investigate the correlation between the area under the calorimetry curve and early age compressive strengths.
- Investigate the proportionality of blended cement constituents and their effects on compressive strength.

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Appendix A: Compressive Strength Raw Testing Data

Table A.1 Test Mix Casting Data

Mix #	Mix Label	Casting Date	Mortar Flow (in)	Ambient Temperature at Time of Mixing (˚F)	Relative Humidity (%)	Initial HRWR Dosage (oz/cwt)	Total HRWR Dosage (oz/cwt)
Mix 1	AG3	9/7/2021	10.00	73.2	46	31.2	31.2
Mix 2	CC12D-2	9/13/2021	9.69	73.0	49	30.0	30.0
Mix 3	CC12H-2	9/15/2021	9.53	72.0	52	28.0	28.0
Mix 4	ARG12C-1	9/23/2021	8.88	71.8	47	28.0	28.0
Mix 5	TL1B-1	9/27/2021	9.28	72.5	52	28.0	36.0
Mix 6	LFH25DS-1	9/29/2021	9.91	72.5	52	28.0	32.0
Mix 7	ARG3H-2	10/1/2021	9.97	72.5	52	25.0	25.0
Mix 8	ARG3-REP	10/5/2021	9.31	71.8	48	24.0	24.0
Mix 9	CC1LD-1	10/13/2021	9.22	73.2	53	28.0	30.0
Mix 10	CC1LH-1	10/15/2021	8.00	73.0	53	28.0	28.0
Mix 11	CPCT-1	10/19/2021	8.47	73.4	61	24.0	26.0
Mix 12	CPHT-RE2	11/2/2021	4.91	71.8	57	33.0	33.0
Mix 13	BLND-2	12/6/2021	8.97	-	-	33.0	33.0

Table A.2 Mix 1 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1*	2.000	2.000	4.000	26,313	6,578.3
	Cube 2	2.000	2.000	4.000	24,526	6,131.5
	Cube 3	2.000	2.000	4.000	23,042	5,760.5
	All Specimens	**Standard Deviation (psi)**	334.3	**Adjusted for Variance**	**Standard Deviation (psi)**	185.5
		COV	5.4%		**COV**	3.1%
		Average (psi)	6,156.8		**Average (psi)**	5,946.0
3 Day	Cube 1*	2.002	1.998	4.000	25,064	6,266.0
	Cube 2	2.005	1.984	3.977	41,053	10,323.7
	Cube 3	1.998	1.959	3.914	38,711	9,890.2
	All Specimens	**Standard Deviation (psi)**	1,819.3	**Adjusted for Variance**	**Standard Deviation (psi)**	216.7
		COV	20.6%		**COV**	2.1%
		Average (psi)	8,826.6		**Average (psi)**	10,106.9
7 Day	Cube 1*	1.997	1.956	3.907	42,746	**10,941.44**
	Cube 2	1.997	1.974	3.943	45,057	11,427.9
	Cube 3	1.997	2.007	4.008	48,582	12,121.3
	All Specimens	**Standard Deviation (psi)**	484.2	**Adjusted for Variance**	**Standard Deviation (psi)**	346.7
		COV	4.2%		**COV**	2.9%
		Average (psi)	11,496.9		**Average (psi)**	11774.6
*Denotes specimen removed for variance						

Table A.3 Mix 1 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1*	2.003	1.979	3.963	47,337	11,943.9
	Cube 2	2.007	1.963	3.940	52,272	13,265.7
	Cube 3	2.004	2.030	4.067	56,295	13,842.7
	All Specimens	**Standard Deviation (psi)**	794.8	**Adjusted for Variance**	**Standard Deviation (psi)**	288.5
		COV	6.1%		**COV**	2.1%
		Average (psi)	13,017.4		**Average (psi)**	13,554.2
28 Day	Cube 1*	2.005	1.953	3.914	60,086	15,349.8
	Cube 2	2.005	1.965	3.941	56,043	14,220.0
	Cube 3	2.000	1.980	3.959	53,924	13,619.4
	All Specimens	**Standard Deviation (psi)**	717.4	**Adjusted for Variance**	**Standard Deviation (psi)**	300.3
		COV	5.0%		**COV**	2.2%
		Average (psi)	14,396.4		**Average (psi)**	13,919.7
56 Day	Cube 1	1.996	1.976	3.945	58,070	14,718.3
	Cube 2	1.997	1.970	3.934	57,217	14,543.9
	Cube 3	1.993	1.970	3.926	57,398	14,619.2
	All Specimens	**Standard Deviation (psi)**	71.4	**Adjusted for Variance**	**Standard Deviation (psi)**	71.4
		COV	0.5%		**COV**	0.5%
		Average (psi)	14,627.2		**Average (psi)**	14,627.1
*Denotes specimen removed for variance						

Table A.4 Mix 2 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1	2.004	1.983	3.973	28,770	7,240.9
	Cube 2	2.008	1.946	3.908	28,950	7,408.7
	Cube 3	1.941	2.006	3.895	26,797	6,879.9
	All Specimens	**Standard Deviation (psi)**	220.6	**Adjusted for Variance**	**Standard Deviation (psi)**	220.6
		COV	3.1%		**COV**	3.1%
		Average (psi)	7,176.5		**Average (psi)**	7,176.5
3 Day	Cube 1*	2.011	2.013	4.048	39,692	9,805.0
	Cube 2	2.004	1.952	3.911	45,150	11,543.9
	Cube 3	2.000	1.948	3.896	44,710	11,475.9
	All Specimens	**Standard Deviation (psi)**	804.2	**Adjusted for Variance**	**Standard Deviation (psi)**	34.0
		COV	7.3%		**COV**	0.3%
		Average (psi)	10,941.6		**Average (psi)**	11,509.9
7 Day	Cube 1	2.001	1.991	3.985	54,807	13,754.5
	Cube 2	2.003	2.003	4.013	53,393	13,306.1
	Cube 3	1.999	1.993	3.985	55,460	13,918.3
	All Specimens	**Standard Deviation (psi)**	258.8	**Adjusted for Variance**	**Standard Deviation (psi)**	258.8
		COV	1.9%		**COV**	1.9%
		Average (psi)	13,659.6		**Average (psi)**	13,659.6
*Denotes specimen removed for variance						

Table A.5 Mix 2 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	1.996	1.962	3.917	49,500	12,635.7
	Cube 2	2.002	1.953	3.911	49,740	12,719.4
	Cube 3	2.004	1.950	3.907	53,384	13,663.2
	All Specimens	**Standard Deviation (psi)**	465.9	**Adjusted for Variance**	**Standard Deviation (psi)**	465.9
		COV	3.6%		**COV**	3.6%
		Average (psi)	13,006.1		**Average (psi)**	13,006.1
28 Day	Cube 1	1.997	1.936	3.866	53,998	13,966.7
	Cube 2	2.005	1.968	3.946	48,508	12,291.4
	Cube 3	2.005	1.960	3.930	54,882	13,963.3
	All Specimens	**Standard Deviation (psi)**	788.9	**Adjusted for Variance**	**Standard Deviation (psi)**	1.7
		COV	5.9%		**COV**	0.0%
		Average (psi)	13,407.1		**Average (psi)**	13,965.0
56 Day	Cube 1	2.000	2.000	3.999	70,643	17,663.7
	Cube 2	2.000	1.954	3.907	67,070	17,165.1
	Cube 3	2.002	1.935	3.873	65,920	17,019.5
	All Specimens	**Standard Deviation (psi)**	275.8	**Adjusted for Variance**	**Standard Deviation (psi)**	275.8
		COV	1.6%		**COV**	1.6%
		Average (psi)	17,282.8		**Average (psi)**	17,282.8
*Denotes specimen removed for variance						

Table A.6 Mix 3 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	2.001	1.973	3.949	25,192	6,379.9
	Cube 2	1.998	1.978	3.953	25,033	6,332.1
	All Specimens	**Standard Deviation (psi)**	23.9	**Adjusted for Variance**	**Standard Deviation (psi)**	23.9
		COV	0.4%		**COV**	0.4%
		Average (psi)	6,356.0		**Average (psi)**	6,356.0
3 Day	Cube 1	1.999	1.962	3.922	41,829	10,665.2
	Cube 2	2.002	1.955	3.914	40,809	10,426.6
	Cube 3	2.011	1.959	3.940	40,859	10,371.4
	All Specimens	**Standard Deviation (psi)**	127.5	**Adjusted for Variance**	**Standard Deviation (psi)**	127.5
		COV	1.2%		**COV**	1.2%
		Average (psi)	10,487.7		**Average (psi)**	10,487.7
7 Day	Cube 1	1.999	1.952	3.901	48,396	12,404.8
	Cube 2	2.002	1.967	3.938	47,731	12,120.8
	Cube 3	2.001	1.944	3.890	48,846	12,556.9
	All Specimens	**Standard Deviation (psi)**	180.7	**Adjusted for Variance**	**Standard Deviation (psi)**	180.7
		COV	1.5%		**COV**	1.5%
		Average (psi)	12,360.9		**Average (psi)**	12,360.9
*Denotes specimen removed for variance						

Table A.7 Mix 3 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	2.006	1.947	3.907	50,917	13,032.3
	Cube 2	2.003	1.953	3.911	49,872	12,753.2
	Cube 3*	2.006	1.953	3.918	43,153	11,013.0
	All Specimens	**Standard Deviation (psi)**	893.4	**Adjusted for Variance**	**Standard Deviation (psi)**	139.5
		COV	7.3%		**COV**	1.1%
		Average (psi)	12,266.1		**Average (psi)**	12,892.7
28 Day	Cube 1	1.998	1.960	3.915	62,655	16,002.1
	Cube 2	2.007	1.953	3.918	61,913	15,800.8
	Cube 3	2.000	1.953	3.906	61,948	15,859.8
	All Specimens	**Standard Deviation (psi)**	84.5	**Adjusted for Variance**	**Standard Deviation (psi)**	84.5
		COV	0.5%		**COV**	0.5%
		Average (psi)	15,887.6		**Average (psi)**	15,887.6
56 Day	Cube 1	2.003	1.957	3.921	60,834	15,516.8
	Cube 2	2.000	2.024	4.048	65,823	16,260.6
	Cube 3*	2.006	1.958	3.928	23,838	6,068.1
	All Specimens	**Standard Deviation (psi)**	4,639.4	**Adjusted for Variance**	**Standard Deviation (psi)**	371.9
		COV	36.8%		**COV**	2.3%
		Average (psi)	12,615.2		**Average (psi)**	15,888.7
*Denotes specimen removed for variance						

Table A.8 Mix 4 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1	2.003	1.963	3.931	26,764	6,808.8
	Cube 2	2.006	1.969	3.951	27,008	6,835.5
	Cube 3	2.006	1.970	3.952	26,559	6,719.6
	All Specimens	**Standard Deviation (psi)**	49.6	**Adjusted for Variance**	**Standard Deviation (psi)**	49.6
		COV	0.7%		**COV**	0.7%
		Average (psi)	6,787.9		**Average (psi)**	6,787.9
3 Day	Cube 1*	2.003	1.980	3.967	32,973	8,312.7
	Cube 2	2.001	1.968	3.937	36,424	9,252.5
	Cube 3	2.007	1.956	3.924	38,476	9,804.4
	All Specimens	**Standard Deviation (psi)**	615.8	**Adjusted for Variance**	**Standard Deviation (psi)**	275.9
		COV	6.8%		**COV**	2.9%
		Average (psi)	9,123.2		**Average (psi)**	9,528.5
7 Day	Cube 1*	2.000	1.957	3.913	36,299	9,275.7
	Cube 2	2.015	1.949	3.928	40,199	10,234.3
	Cube 3	2.006	1.947	3.905	42,492	10,881.3
	All Specimens	**Standard Deviation (psi)**	659.6	**Adjusted for Variance**	**Standard Deviation (psi)**	323.5
		COV	6.5%		**COV**	3.1%
		Average (psi)	10,130.4		**Average (psi)**	10,557.8
*Denotes specimen removed for variance						

Table A.9 Mix 4 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	2.010	1.953	3.926	49,680	12,653.5
	Cube 2	1.997	1.977	3.949	52,454	13,283.7
	Cube 3	2.003	1.958	3.921	51,176	13,051.1
	All Specimens	**Standard Deviation (psi)**	260.2	**Adjusted for Variance**	**Standard Deviation (psi)**	260.2
		COV	2.0%		**COV**	2.0%
		Average (psi)	12,996.1		**Average (psi)**	12,996.1
28 Day	Cube 1	2.002	1.960	3.923	60,308	15,374.5
	Cube 2	2.005	1.955	3.920	59,546	15,191.2
	Cube 3	2.004	1.964	3.935	55,232	14,035.4
	All Specimens	**Standard Deviation (psi)**	592.8	**Adjusted for Variance**	**Standard Deviation (psi)**	91.6
		COV	4.0%		**COV**	0.6%
		Average (psi)	14,867.1		**Average (psi)**	15,282.9
56 Day	Cube 1	2.003	1.975	3.956	62,951	15,913.1
	Cube 2	1.998	1.982	3.959	60,470	15,272.6
	Cube 3	2.004	1.948	3.904	65,941	16,891.5
	All Specimens	**Standard Deviation (psi)**	665.7	**Adjusted for Variance**	**Standard Deviation (psi)**	489.2
		COV	4.2%		**COV**	3.0%
		Average (psi)	16,025.8		**Average (psi)**	16,402.3
*Denotes specimen removed for variance						

Table A.10 Mix 5 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	1.997	1.944	3.882	27,984	7,208.4
	Cube 2	1.997	1.953	3.899	28,119	7,210.9
	Cube 3	2.005	1.975	3.960	28,271	7,139.3
	All Specimens	**Standard Deviation (psi)**	33.2	**Adjusted for Variance**	**Standard Deviation (psi)**	33.2
		COV	0.5%		**COV**	0.5%
		Average (psi)	7,186.2		**Average (psi)**	7,186.2
3 Day	Cube 1	2.000	1.966	3.932	34,415	8,752.5
	Cube 2	2.000	1.980	3.961	33,536	8,467.3
	Cube 3*	2.004	2.010	4.028	28,095	6,974.9
	All Specimens	**Standard Deviation (psi)**	779.5	**Adjusted for Variance**	**Standard Deviation (psi)**	142.6
		COV	9.7%		**COV**	1.7%
		Average (psi)	8,064.9		**Average (psi)**	8,609.9
7 Day	Cube 1*	2.000	1.975	3.949	18,176	4,602.3
	Cube 2	1.998	1.961	3.918	42,953	10,962.7
	Cube 3	2.013	1.970	3.965	46,251	11,665.0
	All Specimens	**Standard Deviation (psi)**	3,176.8	**Adjusted for Variance**	**Standard Deviation (psi)**	351.1
		COV	35.0%		**COV**	3.1%
		Average (psi)	9,076.7		**Average (psi)**	11,313.9
*Denotes specimen removed for variance						

Table A.11 Mix 5 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	1.999	1.972	3.943	40,899	10,371.6
	Cube 2	2.002	1.977	3.957	42,684	10,786.2
	Cube 3	1.998	1.977	3.949	39,171	9,918.3
	All Specimens	**Standard Deviation (psi)**	354.4	**Adjusted for Variance**	**Standard Deviation (psi)**	354.4
		COV	3.4%		**COV**	3.4%
		Average (psi)	10,358.7		**Average (psi)**	10,358.7
28 Day	Cube 1	2.004	2.032	4.071	57,837	14,205.5
	Cube 2	1.997	1.977	3.949	60,520	15,323.9
	Cube 3	1.997	1.962	3.918	61,958	15,813.2
	All Specimens	**Standard Deviation (psi)**	672.9	**Adjusted for Variance**	**Standard Deviation (psi)**	244.7
		COV	4.5%		**COV**	1.6%
		Average (psi)	15,114.2		**Average (psi)**	15,568.5
56 Day	Cube 1	2.005	1.971	3.953	64,725	16,372.9
	Cube 2	2.006	1.952	3.916	62,026	15,840.3
	Cube 3	2.011	1.974	3.968	65,738	16,565.4
	All Specimens	**Standard Deviation (psi)**	306.7	**Adjusted for Variance**	**Standard Deviation (psi)**	306.7
		COV	1.9%		**COV**	1.9%
		Average (psi)	16,259.5		**Average (psi)**	16,259.5
*Denotes specimen removed for variance						

Table A.12 Mix 6 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	2.016	1.958	3.948	19,204	4,864.2
	Cube 2	2.009	1.963	3.942	19,485	4,942.5
	Cube 3	2.005	2.000	4.009	18,335	4,573.8
	All Specimens	**Standard Deviation (psi)**	158.6	**Adjusted for Variance**	**Standard Deviation (psi)**	39.1
		COV	3.3%		**COV**	0.8%
		Average (psi)	4,793.5		**Average (psi)**	4,903.4
3 Day	Cube 1	2.004	1.959	3.926	22,191	5,651.6
	Cube 2	2.001	1.978	3.959	21,619	5,461.2
	Cube 3	2.012	1.973	3.971	22,255	5,604.4
	All Specimens	**Standard Deviation (psi)**	81.0	**Adjusted for Variance**	**Standard Deviation (psi)**	81.0
		COV	1.5%		**COV**	1.5%
		Average (psi)	5,572.4		**Average (psi)**	5,572.4
7 Day	Cube 1	1.995	1.956	3.902	45,056	11,546.2
	Cube 2	2.010	1.974	3.968	46,045	11,604.8
	Cube 3*	2.000	1.963	3.927	41,193	10,490.6
	All Specimens	**Standard Deviation (psi)**	512.0	**Adjusted for Variance**	**Standard Deviation (psi)**	29.3
		COV	4.6%		**COV**	0.3%
		Average (psi)	11,213.9		**Average (psi)**	11,575.5
*Denotes specimen removed for variance						

Table A.13 Mix 6 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1	2.007	1.973	3.960	51,948	13,118.8
	Cube 2	2.007	1.967	3.948	57,051	14,449.0
	Cube 3	2.005	1.974	3.959	58,299	14,727.4
	All Specimens	**Standard Deviation (psi)**	701.9	**Adjusted for Variance**	**Standard Deviation (psi)**	139.2
		COV	5.0%		**COV**	1.0%
		Average (psi)	14,098.4		**Average (psi)**	14,588.2
28 Day	Cube 1	1.998	1.983	3.961	54,903	13,861.9
	Cube 2	2.003	1.961	3.929	52,788	13,434.8
	Cube 3	2.001	1.990	3.981	56,904	14,295.1
	All Specimens	**Standard Deviation (psi)**	351.2	**Adjusted for Variance**	**Standard Deviation (psi)**	351.2
		COV	2.5%		**COV**	2.5%
		Average (psi)	13,863.9		**Average (psi)**	13,863.9
56 Day	Cube 1	2.000	1.977	3.954	66,997	16,944.1
	Cube 2	2.002	1.969	3.941	66,436	16,856.4
	Cube 3	1.996	1.999	3.990	65,546	16,427.5
	All Specimens	**Standard Deviation (psi)**	225.7	**Adjusted for Variance**	**Standard Deviation (psi)**	225.7
		COV	1.3%		**COV**	1.3%
		Average (psi)	16,742.7		**Average (psi)**	16,742.7
*Denotes specimen removed for variance						

Table A.14 Mix 7 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1*	1.997	1.998	3.991	8,413	2,108.2
	Cube 2*	2.002	1.997	3.999	2750, 17904	687.7, 4477.5
	Cube 3	2.000	2.009	4.019	19,322	4,808.1
	All Specimens	**Standard Deviation (psi)**	1,202.4	**Adjusted for Variance**	**Standard Deviation (psi)**	165.3
	(Cube 1, Cube 2 Load 2, Cube 3)	**COV**	31.7%	(Cube 2 Load 2, Cube 3)	**COV**	3.6%
		Average (psi)	3,797.9		**Average (psi)**	4,642.8
3 Day	Cube 1	2.004	1.992	3.991	28,901	7,241.0
	Cube 2	2.003	2.004	4.015	23,003	5,729.7
	Cube 3	2.002	2.020	4.043	17,859	4,417.6
	All Specimens	**Standard Deviation (psi)**	1,153.6	**Adjusted for Variance**	**Standard Deviation (psi)**	755.6
		COV	19.9%		**COV**	11.7%
		Average (psi)	5,796.1		**Average (psi)**	6,485.4
7 Day	Cube 1	2.002	2.023	4.050	44,195	10,912.2
	Cube 2	1.997	2.016	4.027	47,368	11,761.8
	Cube 3	1.998	2.012	4.021	43,811	10,896.5
	All Specimens	**Standard Deviation (psi)**	404.2	**Adjusted for Variance**	**Standard Deviation (psi)**	404.2
		COV	3.6%		**COV**	3.6%
		Average (psi)	11,190.2		**Average (psi)**	11,190.2
*Denotes specimen removed for variance						

Table A.15 Mix 7 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1	2.000	2.010	4.019	58,601	14,579.8
	Cube 2	1.996	2.004	3.999	48,676	12,171.1
	Cube 3	1.994	1.988	3.964	62,016	15,644.5
	All Specimens	**Standard Deviation (psi)**	1,453.0	**Adjusted for Variance**	**Standard Deviation (psi)**	532.4
		COV	10.3%		**COV**	3.5%
		Average (psi)	14,131.8		**Average (psi)**	15,112.2
28 Day	Cube 1	2.000	1.999	3.999	58,071	14,522.6
	Cube 2	2.002	2.000	4.005	53,159	13,274.3
	Cube 3	1.994	2.001	3.990	55,774	13,978.5
	All Specimens	**Standard Deviation (psi)**	511.0	**Adjusted for Variance**	**Standard Deviation (psi)**	511.0
		COV	3.7%		**COV**	3.7%
		Average (psi)	13,925.1		**Average (psi)**	13,925.1
56 Day	Cube 1	2.008	2.012	4.039	69,378	17,175.2
	Cube 2	1.999	2.050	4.098	70,035	17,090.3
	Cube 3	1.997	2.016	4.026	74,313	18,458.5
	All Specimens	**Standard Deviation (psi)**	625.9	**Adjusted for Variance**	**Standard Deviation (psi)**	42.5
		COV	3.6%		**COV**	0.2%
		Average (psi)	17,574.7		**Average (psi)**	17,132.7
*Denotes specimen removed for variance						

Table A.16 Mix 8 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1	2.002	1.935	3.874	34,029	8,784.3
	Cube 2	2.008	1.961	3.937	32,851	8,344.1
	Cube 3	2.001	1.983	3.967	34,917	8,801.2
	All Specimens	**Standard Deviation (psi)**	211.6	**Adjusted for Variance**	**Standard Deviation (psi)**	211.6
		COV	2.4%		**COV**	2.4%
		Average (psi)	8,643.2		**Average (psi)**	8,643.2
3 Day	Cube 1	2.001	1.960	3.921	40,887	10,426.9
	Cube 2	2.001	1.970	3.943	37,697	9,561.4
	Cube 3	2.003	1.957	3.921	36,976	9,429.8
	All Specimens	**Standard Deviation (psi)**	442.3	**Adjusted for Variance**	**Standard Deviation (psi)**	65.8
		COV	4.5%		**COV**	0.7%
		Average (psi)	9,806.0		**Average (psi)**	9,495.6
7 Day	Cube 1	1.998	1.959	3.915	49,918	12,751.3
	Cube 2	2.000	1.950	3.901	50,731	13,005.7
	Cube 3*	2.009	1.969	3.956	43,428	10,978.5
	All Specimens	**Standard Deviation (psi)**	901.7	**Adjusted for Variance**	**Standard Deviation (psi)**	127.2
		COV	7.4%		**COV**	1.0%
		Average (psi)	12,245.2		**Average (psi)**	12,878.5
*Denotes specimen removed for variance						

Table A.17 Mix 8 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	1.993	1.961	3.908	52,838	13,521.8
	Cube 2	1.994	1.970	3.930	56,960	14,495.5
	Cube 3	1.993	1.959	3.905	56,112	14,369.4
	All Specimens	**Standard Deviation (psi)**	432.4	**Adjusted for Variance**	**Standard Deviation (psi)**	432.4
		COV	3.1%		**COV**	3.1%
		Average (psi)	14,128.9		**Average (psi)**	14,128.9
28 Day	Cube 1	1.999	1.946	3.891	51,248	13,171.9
	Cube 2	2.000	1.973	3.947	53,119	13,459.2
	Cube 3	2.002	1.943	3.889	43,520	11,189.9
	All Specimens	**Standard Deviation (psi)**	1,008.9	**Adjusted for Variance**	**Standard Deviation (psi)**	143.7
		COV	8.0%		**COV**	1.1%
		Average (psi)	12,607.0		**Average (psi)**	13,315.5
56 Day	Cube 1	2.002	1.978	3.960	69,149	17,462.1
	Cube 2	2.004	1.967	3.942	60,251	15,284.8
	Cube 3	2.001	1.965	3.933	62,918	15,999.0
	All Specimens	**Standard Deviation (psi)**	906.2	**Adjusted for Variance**	**Standard Deviation (psi)**	357.1
		COV	5.6%		**COV**	2.3%
		Average (psi)	16,248.6		**Average (psi)**	15,641.9
*Denotes specimen removed for variance						

Table A.18 Mix 9 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1	1.996	1.974	3.941	31,794	8,068.0
	Cube 2	1.997	2.037	4.067	30,881	7,592.7
	Cube 3*	1.995	2.004	3.998	26,002	6,503.8
	All Specimens	**Standard Deviation (psi)**	654.8	**Adjusted for Variance**	**Standard Deviation (psi)**	237.6
		COV	8.9%		**COV**	3.0%
		Average (psi)	7,388.1		**Average (psi)**	7,830.3
3 Day	Cube 1	2.004	1.956	3.920	36,080	9,202.9
	Cube 2	2.007	1.942	3.898	36,423	9,344.9
	Cube 3	2.006	1.944	3.899	37,214	9,544.5
	All Specimens	**Standard Deviation (psi)**	140.1	**Adjusted for Variance**	**Standard Deviation (psi)**	140.1
		COV	1.5%		**COV**	1.5%
		Average (psi)	9,364.1		**Average (psi)**	9,364.1
7 Day	Cube 1	2.000	1.960	3.921	50,216	12,805.9
	Cube 2	1.996	1.962	3.917	48,230	12,313.6
	Cube 3	1.995	1.981	3.951	50,886	12,877.9
	All Specimens	**Standard Deviation (psi)**	250.8	**Adjusted for Variance**	**Standard Deviation (psi)**	250.8
		COV	2.0%		**COV**	2.0%
		Average (psi)	12,665.8		**Average (psi)**	12,665.8
*Denotes specimen removed for variance						

Table A.19 Mix 9 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1	2.001	1.952	3.907	53,245	13,627.2
	Cube 2	2.000	1.953	3.907	52,867	13,530.3
	Cube 3	2.001	1.955	3.911	49,351	12,619.7
	All Specimens	**Standard Deviation (psi)**	453.8	**Adjusted for Variance**	**Standard Deviation (psi)**	453.8
		COV	3.4%		**COV**	3.4%
		Average (psi)	13,259.0		**Average (psi)**	13,259.0
28 Day	Cube 1*	1.999	1.962	3.922	21,319	5,435.7
	Cube 2	2.005	1.976	3.961	64,680	16,328.3
	Cube 3	2.002	1.950	3.903	60,232	15,431.2
	All Specimens	**Standard Deviation (psi)**	4,937.0	**Adjusted for Variance**	**Standard Deviation (psi)**	448.5
		COV	39.8%		**COV**	2.8%
		Average (psi)	12,398.4		**Average (psi)**	15,879.8
56 Day	Cube 1	2.009	2.018	4.056	46,167	11,383.8
	Cube 2	1.997	2.017	4.027	48,750	12,107.0
	Cube 3*	2.002	1.951	3.907	35,988	9,212.2
	All Specimens	**Standard Deviation (psi)**	1,230.1	**Adjusted for Variance**	**Standard Deviation (psi)**	361.6
		COV	11.3%		**COV**	3.1%
		Average (psi)	10,901.0		**Average (psi)**	11,745.4
*Denotes specimen removed for variance						

Table A.20 Mix 10 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	2.010	1.962	3.943	21,019	5,330.8
	Cube 2	2.013	1.975	3.976	21,822	5,488.9
	Cube 3	2.001	1.980	3.962	21,339	5,385.9
	All Specimens	**Standard Deviation (psi)**	65.5	**Adjusted for Variance**	**Standard Deviation (psi)**	65.5
		COV	1.2%		**COV**	1.2%
		Average (psi)	5,401.9		**Average (psi)**	5,401.9
3 Day	Cube 1*	2.009	1.993	4.004	33,280	8,311.8
	Cube 2	2.003	2.035	4.075	38,982	9,566.7
	Cube 3	2.003	2.003	4.013	39,162	9,759.6
	All Specimens	**Standard Deviation (psi)**	641.9	**Adjusted for Variance**	**Standard Deviation (psi)**	96.4
		COV	7.0%		**COV**	1.0%
		Average (psi)	9,212.7		**Average (psi)**	9,663.1
7 Day	Cube 1	1.997	1.978	3.951	50,671	12,825.7
	Cube 2	1.997	1.990	3.975	49,943	12,563.1
	Cube 3	2.000	1.993	3.987	50,897	12,766.8
	All Specimens	**Standard Deviation (psi)**	112.5	**Adjusted for Variance**	**Standard Deviation (psi)**	112.5
		COV	0.9%		**COV**	0.9%
		Average (psi)	12,718.6		**Average (psi)**	12,718.6
*Denotes specimen removed for variance						

Table A.21 Mix 10 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1*	1.999	2.023	4.043	54,630	13,511.2
	Cube 2	1.997	1.990	3.974	47,834	12,036.6
	Cube 3	1.999	1.969	3.936	46,237	11,747.1
	All Specimens	**Standard Deviation (psi)**	772.5	**Adjusted for Variance**	**Standard Deviation (psi)**	144.8
		COV	6.2%		**COV**	1.2%
		Average (psi)	12,431.7		**Average (psi)**	11,891.9
28 Day	Cube 1*	1.997	2.007	4.009	52,129	13,004.1
	Cube 2	1.996	1.979	3.950	43,950	11,126.3
	Cube 3	2.005	2.018	4.045	46,533	11,502.6
	All Specimens	**Standard Deviation (psi)**	811.2	**Adjusted for Variance**	**Standard Deviation (psi)**	188.2
		COV	6.8%		**COV**	1.7%
		Average (psi)	11,877.7		**Average (psi)**	11,314.5
56 Day	Cube 1	1.994	1.951	3.891	57,401	14,752.5
	Cube 2	2.003	1.990	3.986	61,855	15,518.2
	Cube 3	2.000	2.016	4.033	63,138	15,656.6
	All Specimens	**Standard Deviation (psi)**	397.6	**Adjusted for Variance**	**Standard Deviation (psi)**	397.6
		COV	2.6%		**COV**	2.6%
		Average (psi)	15,309.1		**Average (psi)**	15,309.1
*Denotes specimen removed for variance						

Table A.22 Mix 11 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
1 Day	Cube 1	2.005	1.962	3.932	22,864	5,814.1
	Cube 2	2.005	1.972	3.955	23,562	5,957.2
	Cube 3	2.001	1.985	3.973	23,229	5,846.3
	All Specimens	**Standard Deviation (psi)**	61.3	**Adjusted for Variance**	**Standard Deviation (psi)**	61.3
		COV	1.0%		**COV**	1.0%
		Average (psi)	5,872.5		**Average (psi)**	5,872.5
3 Day	Cube 1	2.000	2.000	4.000	38,676	9,669.0
	Cube 2	2.000	2.000	4.000	37,500	9,375.0
	Cube 3	2.000	2.000	4.000	38,874	9,718.5
	All Specimens	**Standard Deviation (psi)**	151.6	**Adjusted for Variance**	**Standard Deviation (psi)**	151.6
		COV	1.6%		**COV**	1.6%
		Average (psi)	9,587.5		**Average (psi)**	9,587.5
7 Day	Cube 1*	1.999	1.963	3.925	26,625	6,784.0
	Cube 2	1.997	1.980	3.954	29,864	7,552.8
	Cube 3	1.999	1.952	3.901	29,604	7,588.1
	All Specimens	**Standard Deviation (psi)**	371.0	**Adjusted for Variance**	**Standard Deviation (psi)**	17.7
		COV	5.1%		**COV**	0.2%
		Average (psi)	7,308.3		**Average (psi)**	7,570.4
*Denotes specimen removed for variance						

Table A.23 Mix 11 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	Specimen	Dimensions (in)		Bearing Surface Area (in^2)	Load (lb)	Stress (psi)
14 Day	Cube 1	2.009	1.955	3.928	50,301	12,807.1
	Cube 2	2.008	1.968	3.951	52,242	13,222.2
	Cube 3	2.006	1.960	3.932	48,139	12,243.6
	All Specimens	**Standard Deviation (psi)**	401.0	**Adjusted for Variance**	**Standard Deviation (psi)**	401.0
		COV	3.1%		**COV**	3.1%
		Average (psi)	12,757.6		**Average (psi)**	12,757.6
28 Day	Cube 1	1.998	2.009	4.014	40,255	10,028.7
	Cube 2	2.003	1.982	3.971	29,854	7,518.8
	Cube 3	2.003	1.980	3.965	32,516	8,200.2
	All Specimens	**Standard Deviation (psi)**	1,059.7	**Adjusted for Variance**	**Standard Deviation (psi)**	340.7
		COV	12.3%		**COV**	4.3%
		Average (psi)	8,582.5		**Average (psi)**	7,859.5
56 Day	Cube 1	2.002	1.969	3.942	43,181	10,954.3
	Cube 2	1.997	1.975	3.945	45,914	11,637.4
	Cube 3	1.999	1.979	3.955	47,373	11,978.9
	All Specimens	**Standard Deviation (psi)**	426.0	**Adjusted for Variance**	**Standard Deviation (psi)**	426.0
		COV	3.7%		**COV**	3.7%
		Average (psi)	11,523.5		**Average (psi)**	11,523.5
*Denotes specimen removed for variance						

Table A.24 Mix 12 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	2.009	2.001	4.019	4,423	1,100.6
	Cube 2	2.010	1.989	3.999	4,389	1,097.5
	Cube 3	2.013	1.999	4.023	4,194	1,042.6
	All Specimens	**Standard Deviation (psi)**	26.6	**Adjusted for Variance**	**Standard Deviation (psi)**	26.6
		COV	2.5%		**COV**	2.5%
		Average (psi)	1,080.2		**Average (psi)**	1,080.2
3 Day	Cube 1	1.997	1.964	3.921	24,059	6,135.2
	Cube 2	1.997	1.937	3.868	23,708	6,128.9
	Cube 3	1.997	1.946	3.886	25,503	6,563.6
	All Specimens	**Standard Deviation (psi)**	203.4	**Adjusted for Variance**	**Standard Deviation (psi)**	203.4
		COV	3.2%		**COV**	3.2%
		Average (psi)	6,275.9		**Average (psi)**	6,275.9
7 Day	Cube 1	2.004	1.974	3.955	39,030	9,869.6
	Cube 2	1.995	1.916	3.822	35,287	9,231.6
	Cube 3	2.005	1.929	3.867	35,557	9,195.0
	All Specimens	**Standard Deviation (psi)**	309.7	**Adjusted for Variance**	**Standard Deviation (psi)**	309.7
		COV	3.3%		**COV**	3.3%
		Average (psi)	9,432.1		**Average (psi)**	9,432.1
*Denotes specimen removed for variance						

Table A.25 Mix 12 14 Day, 28 Day, and 56 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
14 Day	Cube 1*	2.005	2.002	4.015	22,629	5,635.6
	Cube 2	2.003	1.940	3.885	47,140	12,133.3
	Cube 3	2.003	1.943	3.892	46,430	11,930.2
	All Specimens	**Standard Deviation (psi)**	3,016.3	**Adjusted for Variance**	**Standard Deviation (psi)**	101.6
		COV	30.5%		**COV**	0.8%
		Average (psi)	9,899.7		**Average (psi)**	12,031.7
28 Day	Cube 1	2.003	1.937	3.880	57,565	14,834.6
	Cube 2	2.002	1.968	3.940	57,081	14,487.8
	Cube 3*	2.006	1.964	3.940	53,923	13,684.5
	All Specimens	**Standard Deviation (psi)**	481.7	**Adjusted for Variance**	**Standard Deviation (psi)**	173.4
		COV	3.4%		**COV**	1.2%
		Average (psi)	14,335.6		**Average (psi)**	14,661.2
56 Day	Cube 1	2.006	1.951	3.914	58,127	14,852.1
	Cube 2*	2.003	1.991	3.987	54,298	13,617.7
	Cube 3	1.999	1.913	3.823	56,329	14,732.6
	All Specimens	**Standard Deviation (psi)**	555.9	**Adjusted for Variance**	**Standard Deviation (psi)**	59.7
		COV	3.9%		**COV**	0.4%
		Average (psi)	14,400.8		**Average (psi)**	14,792.4
*Denotes specimen removed for variance						

Table A.26 Mix 13 1 Day, 3 Day, and 7 Day Raw Compressive Strength Data

Testing Age	**Specimen**	**Dimensions (in)**		**Bearing Surface Area (in^2)**	**Load (lb)**	**Stress (psi)**
1 Day	Cube 1	2.002	1.922	3.848	11,938	3,102.5
	Cube 2	1.995	1.942	3.875	12,240	3,158.8
	Cube 3	1.996	1.939	3.870	11,866	3,066.5
	All Specimens	**Standard Deviation (psi)**	38.0	**Adjusted for Variance**	**Standard Deviation (psi)**	38.0
		COV	1.2%		**COV**	1.2%
		Average (psi)	3,109.2		**Average (psi)**	3,109.2
3 Day	Cube 1	1.994	1.951	3.892	33,683	8,655.3
	Cube 2	2.000	1.927	3.853	33,605	8,721.0
	Cube 3	2.000	1.932	3.865	33,370	8,633.2
	All Specimens	**Standard Deviation (psi)**	37.3	**Adjusted for Variance**	**Standard Deviation (psi)**	37.3
		COV	0.4%		**COV**	0.4%
		Average (psi)	8,669.8		**Average (psi)**	8,669.8
7 Day	Cube 1	2.000	1.941	3.881	47,617	12,268.2
	Cube 2	2.001	1.932	3.865	47,884	12,388.3
	Cube 3	1.999	1.933	3.863	45,982	11,901.9
	All Specimens	**Standard Deviation (psi)**	206.9	**Adjusted for Variance**	**Standard Deviation (psi)**	206.9
		COV	1.7%		**COV**	1.7%
		Average (psi)	12,186.1		**Average (psi)**	12,186.1
*Denotes specimen removed for variance						

Appendix B: Raw Calorimetry Data

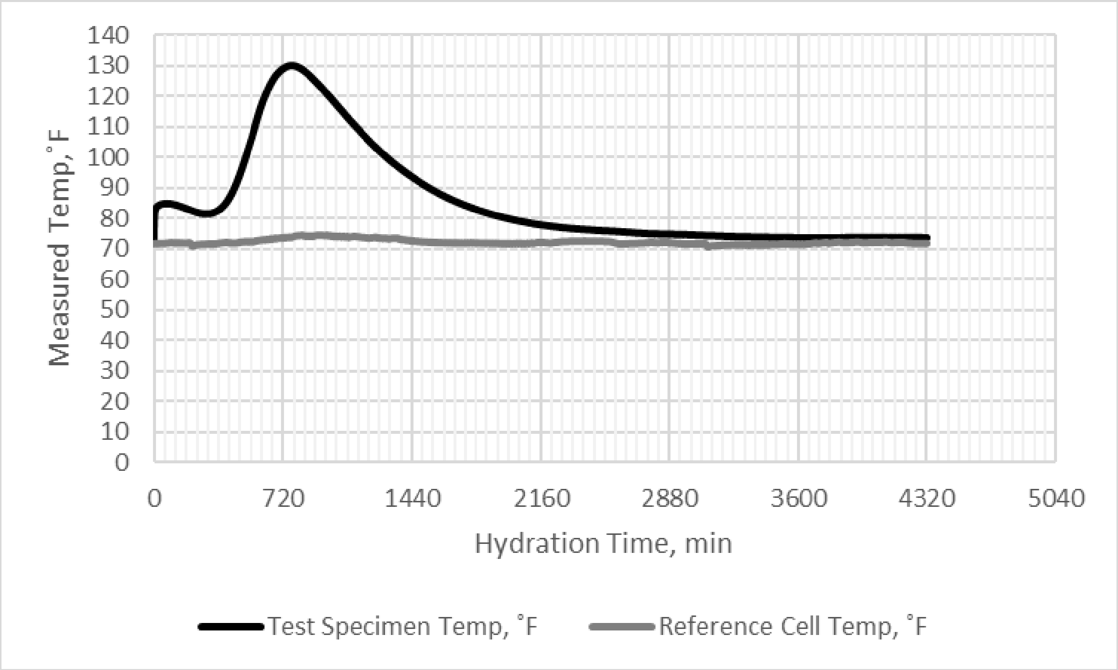


Figure B.1 Mix 1 Measured Calorimetry Data

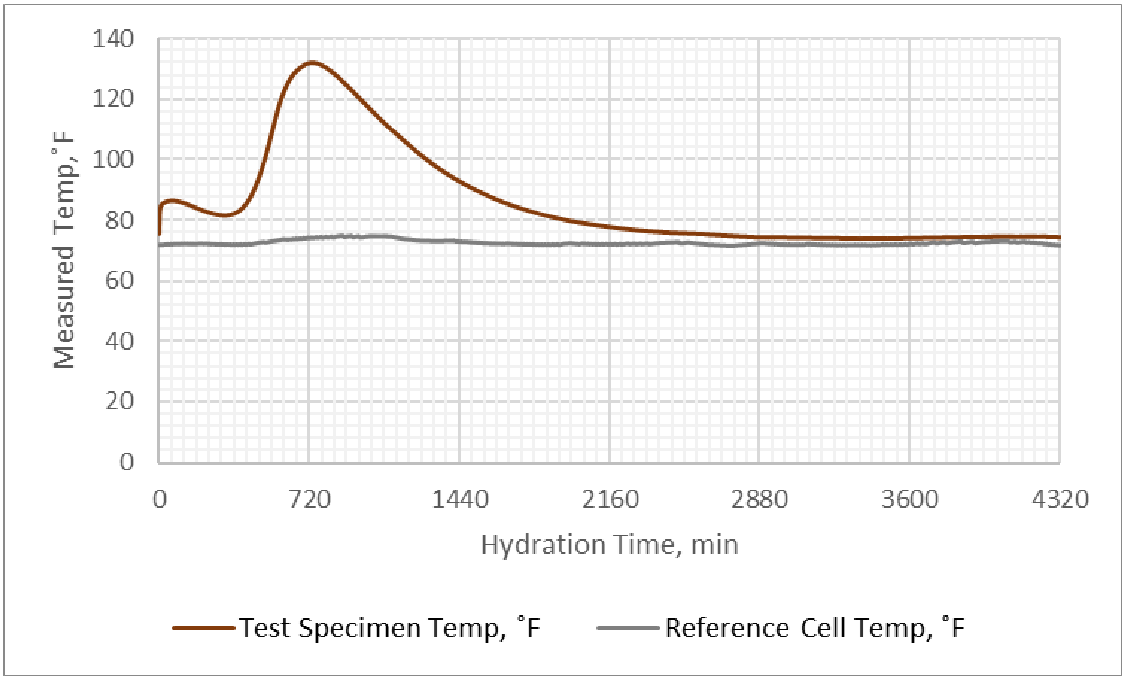


Figure B.2 Mix 2 Measured Calorimetry Data

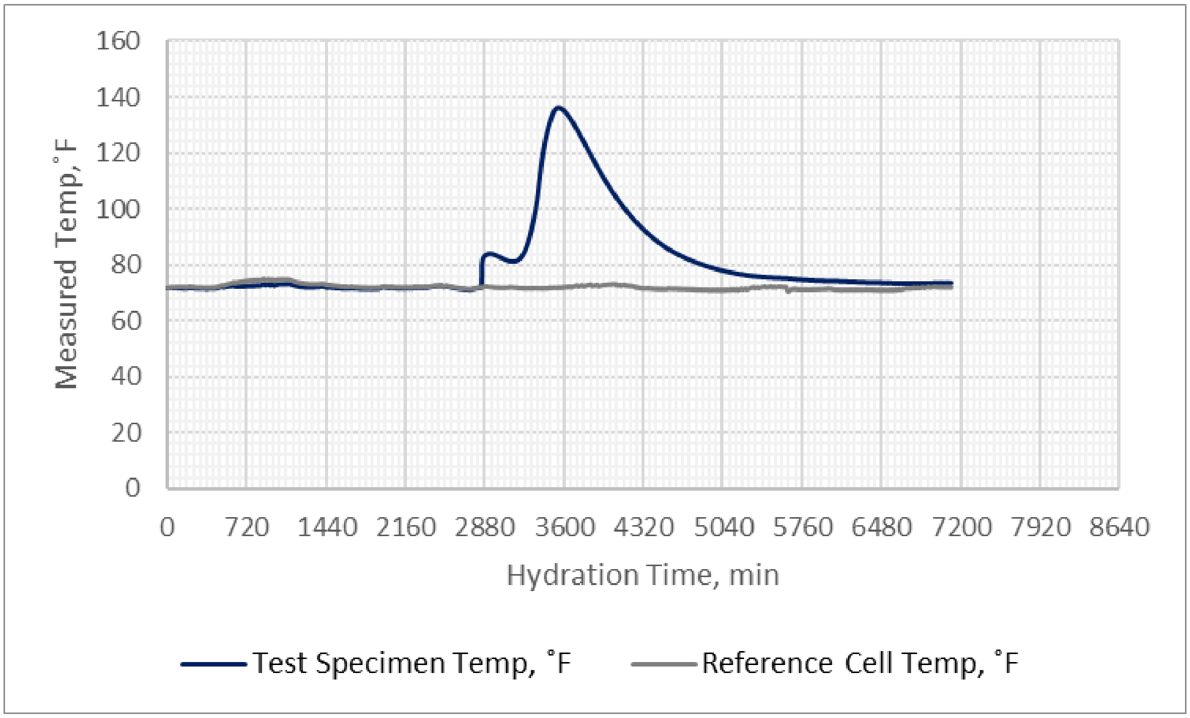


Figure B.3 Mix 3 Measured Calorimetry Data

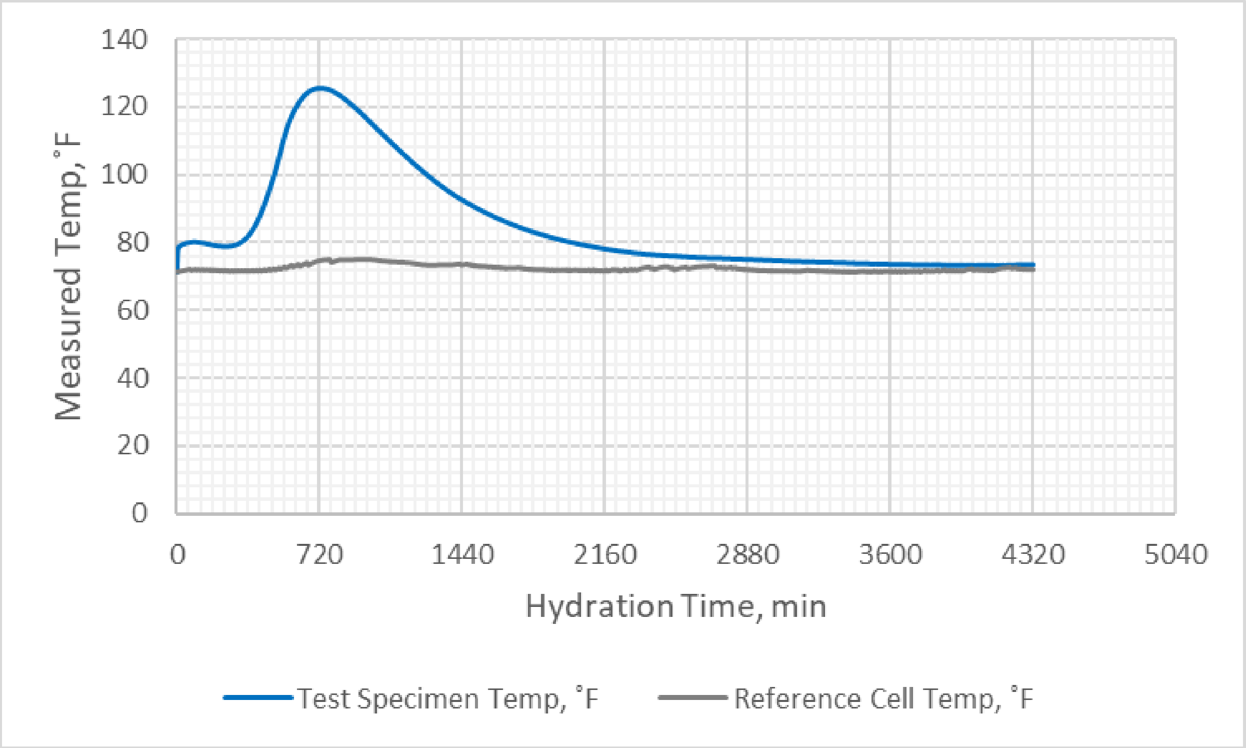


Figure B.4 Mix 4 Measured Calorimetry Data

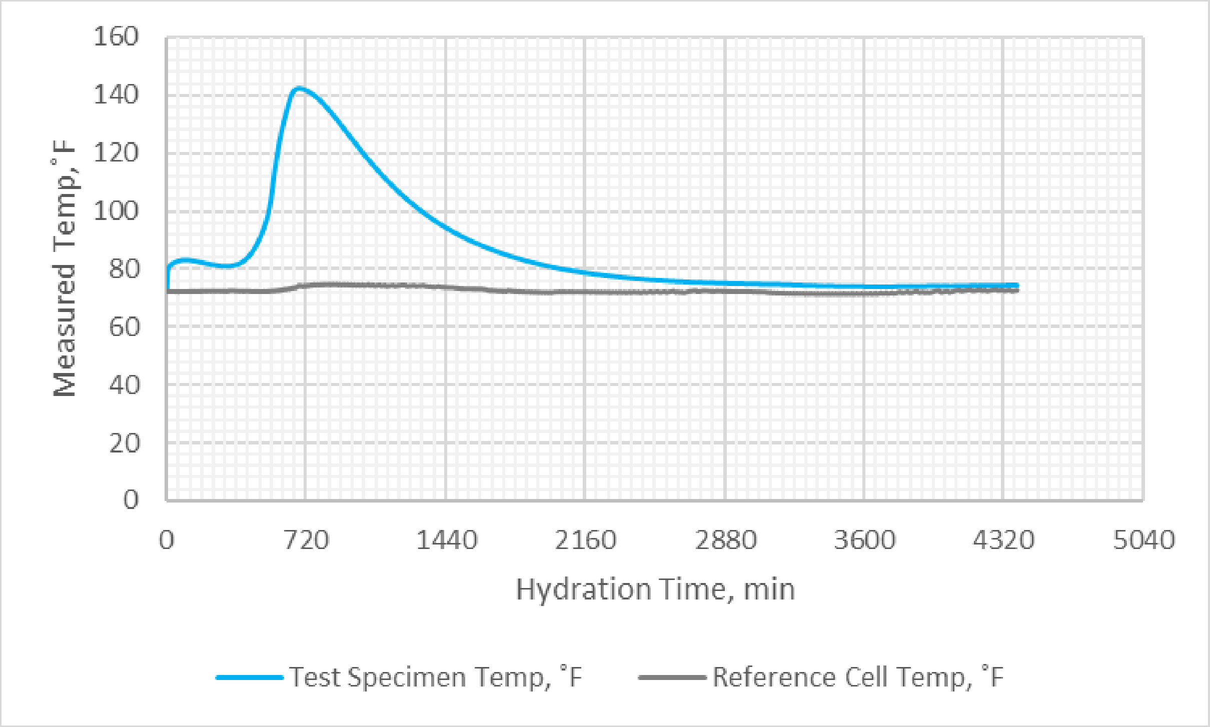


Figure B.5 Mix 5 Measured Calorimetry Data

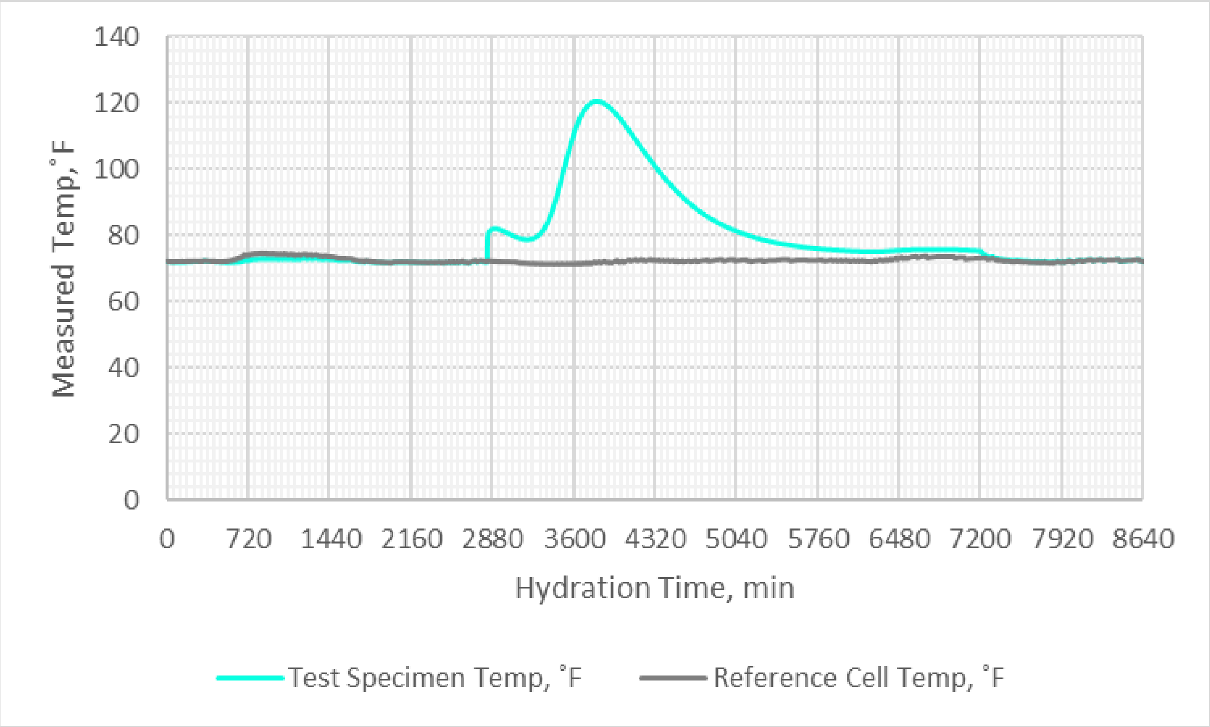


Figure B.6 Mix 6 Measured Calorimetry Data

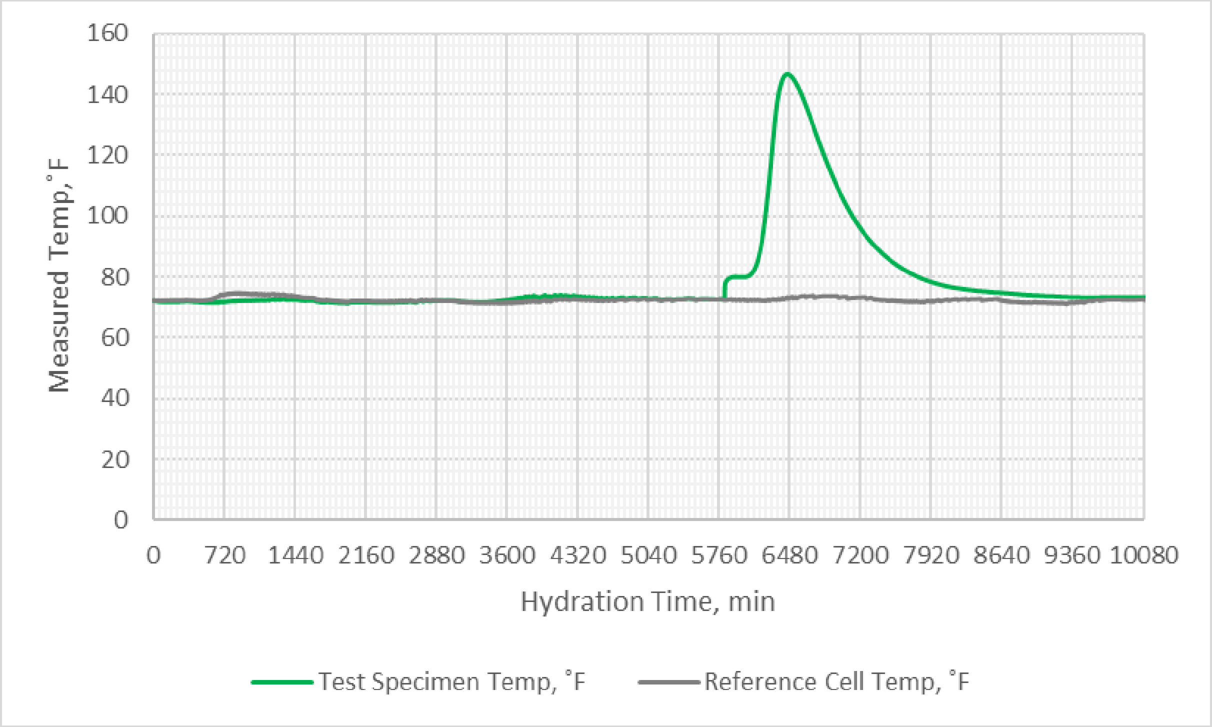


Figure B.7 Mix 7 Measured Calorimetry Data

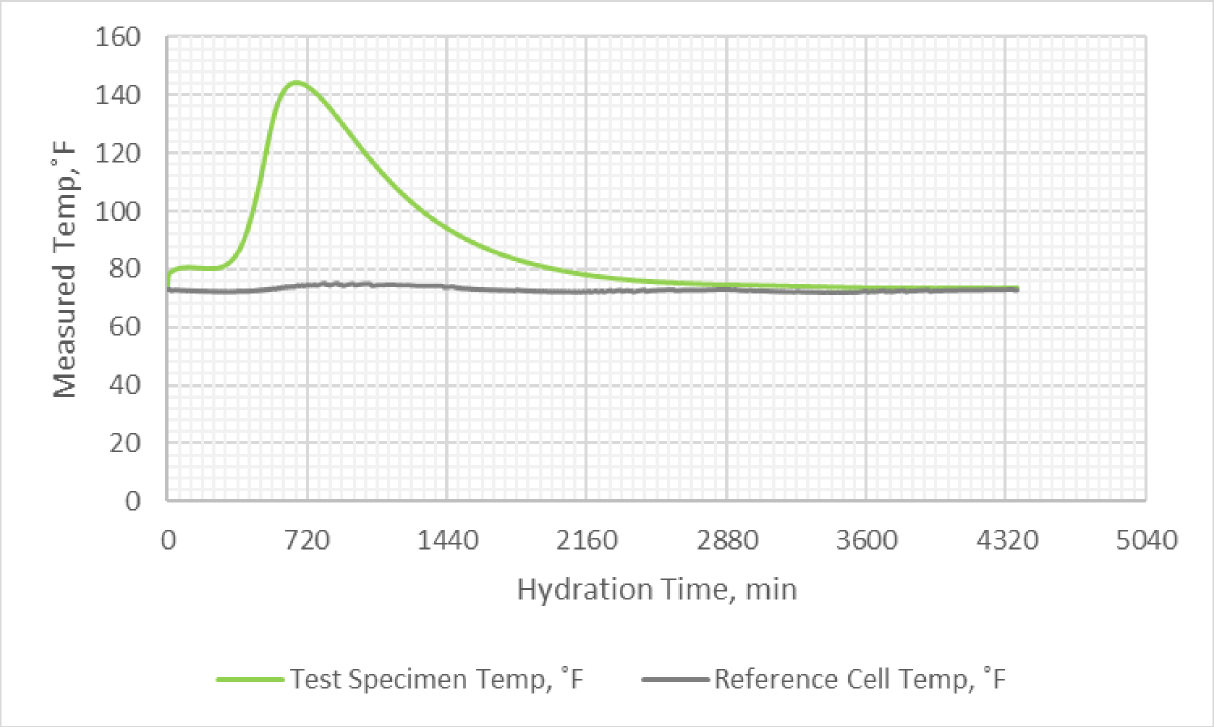


Figure B.8 Mix 8 Measured Calorimetry Data

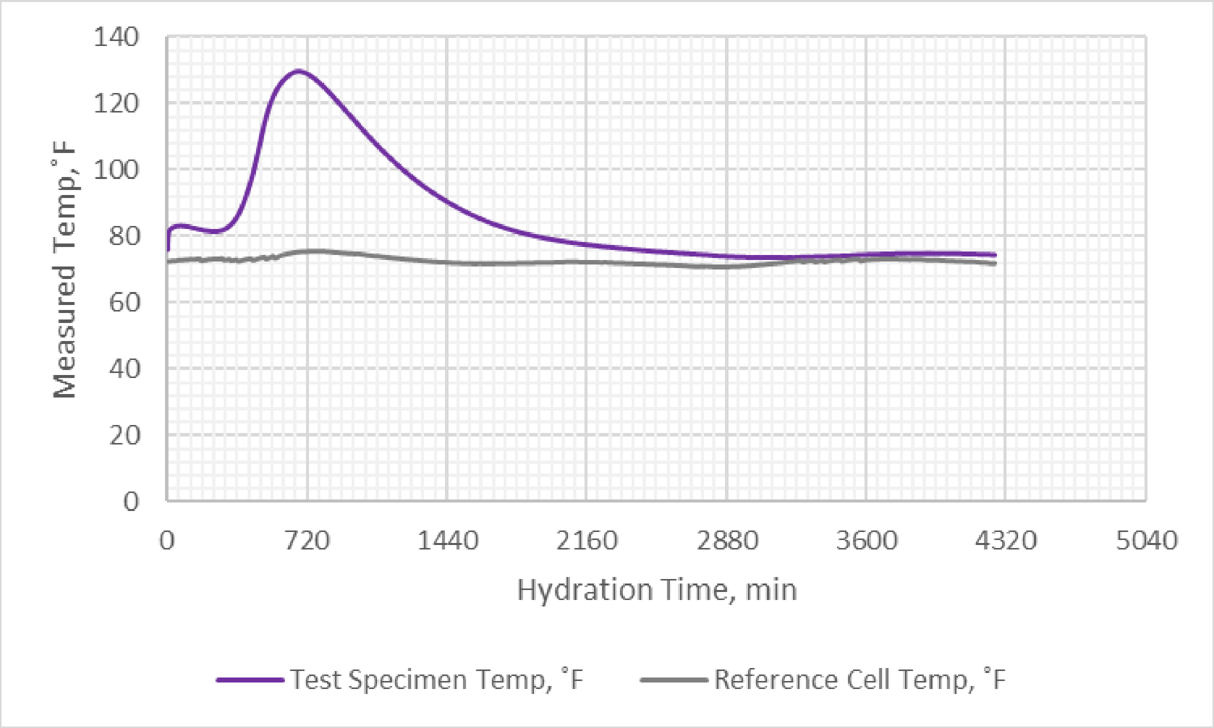


Figure B.9 Mix 9 Measured Calorimetry Data

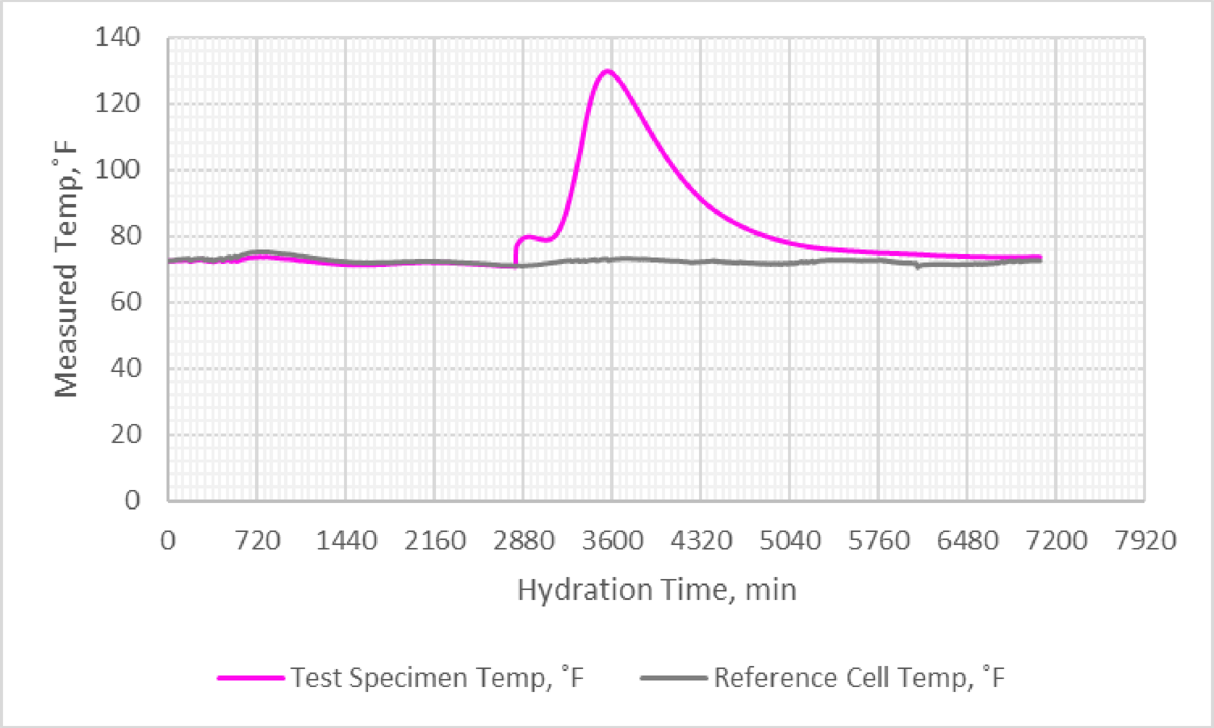


Figure B.10 Mix 10 Measured Calorimetry Data

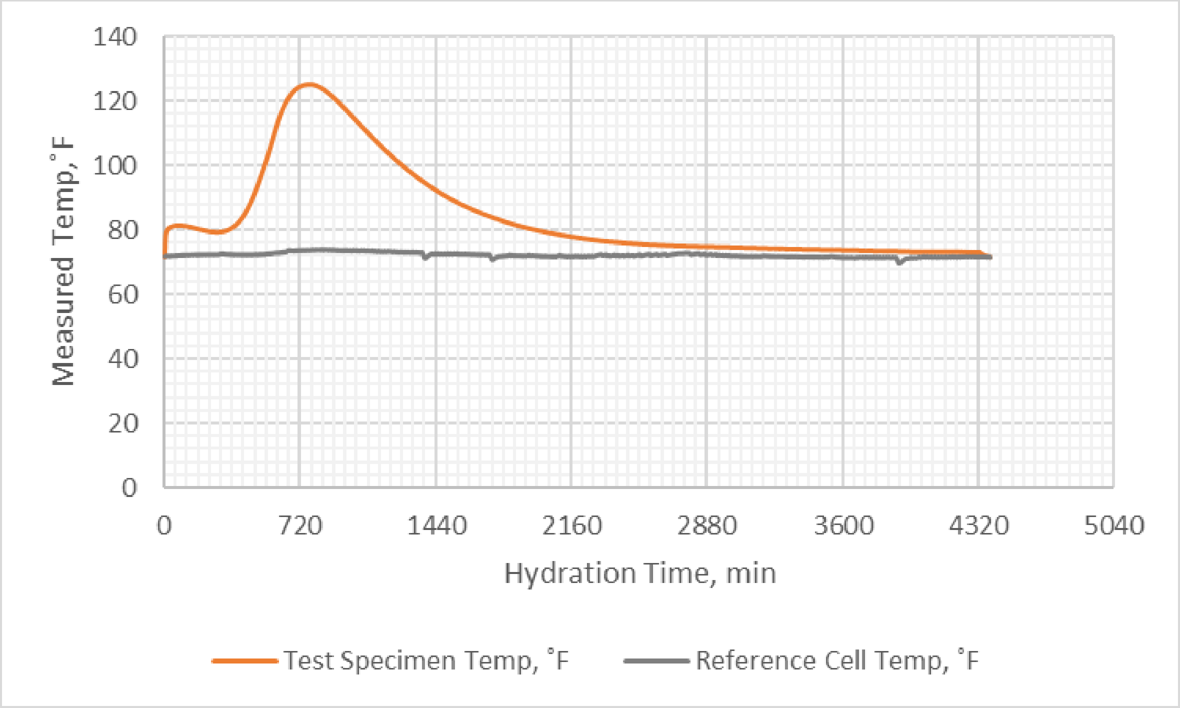


Figure B.11 Mix 11 Measured Calorimetry Data

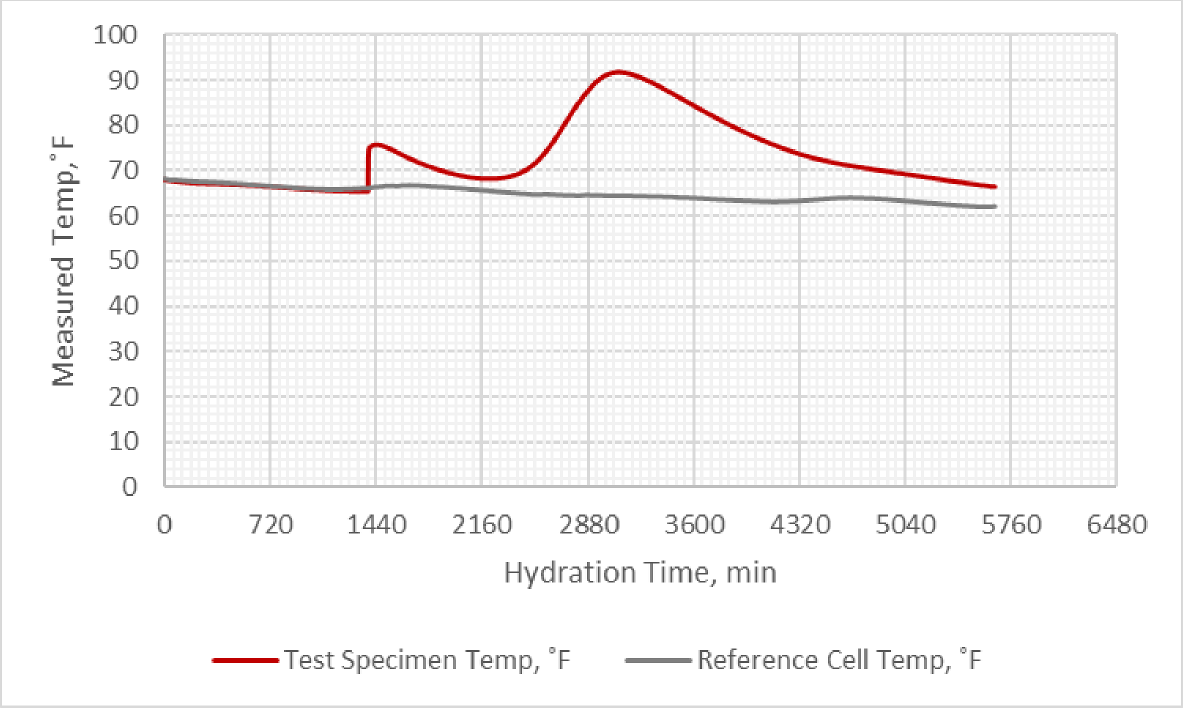


Figure B.12 Mix 12 Measured Calorimetry Data

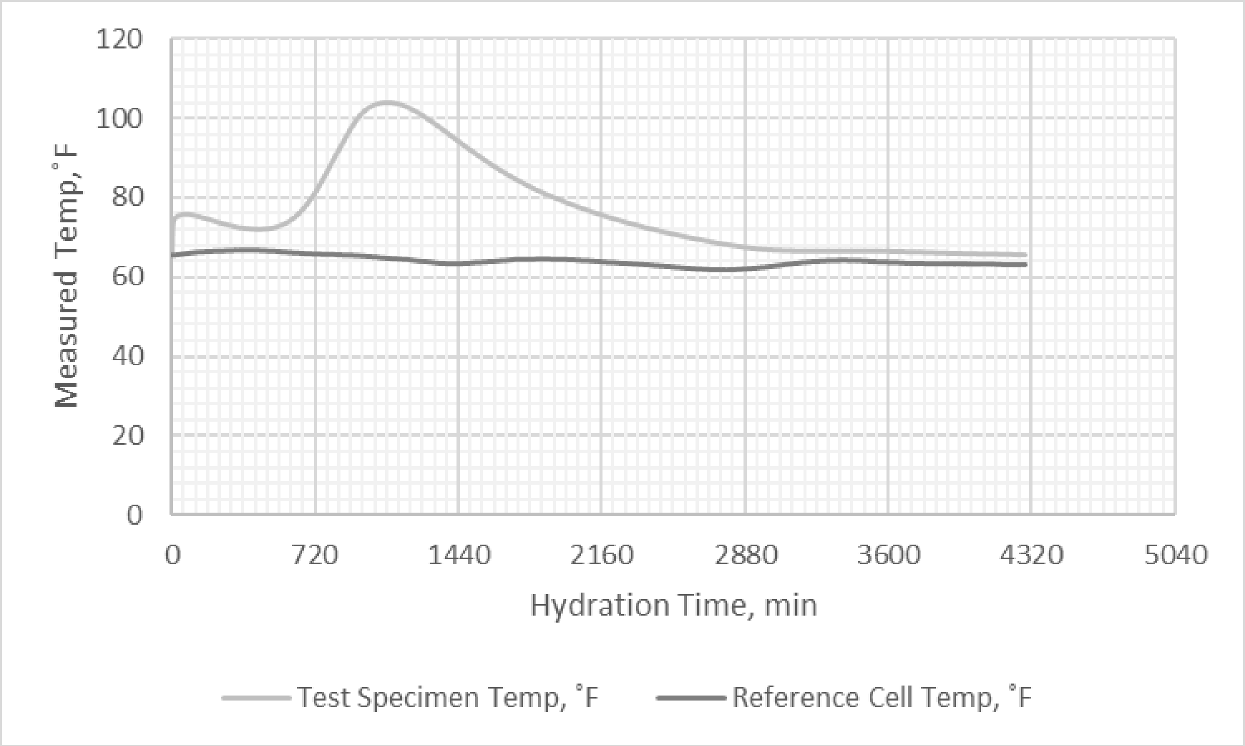
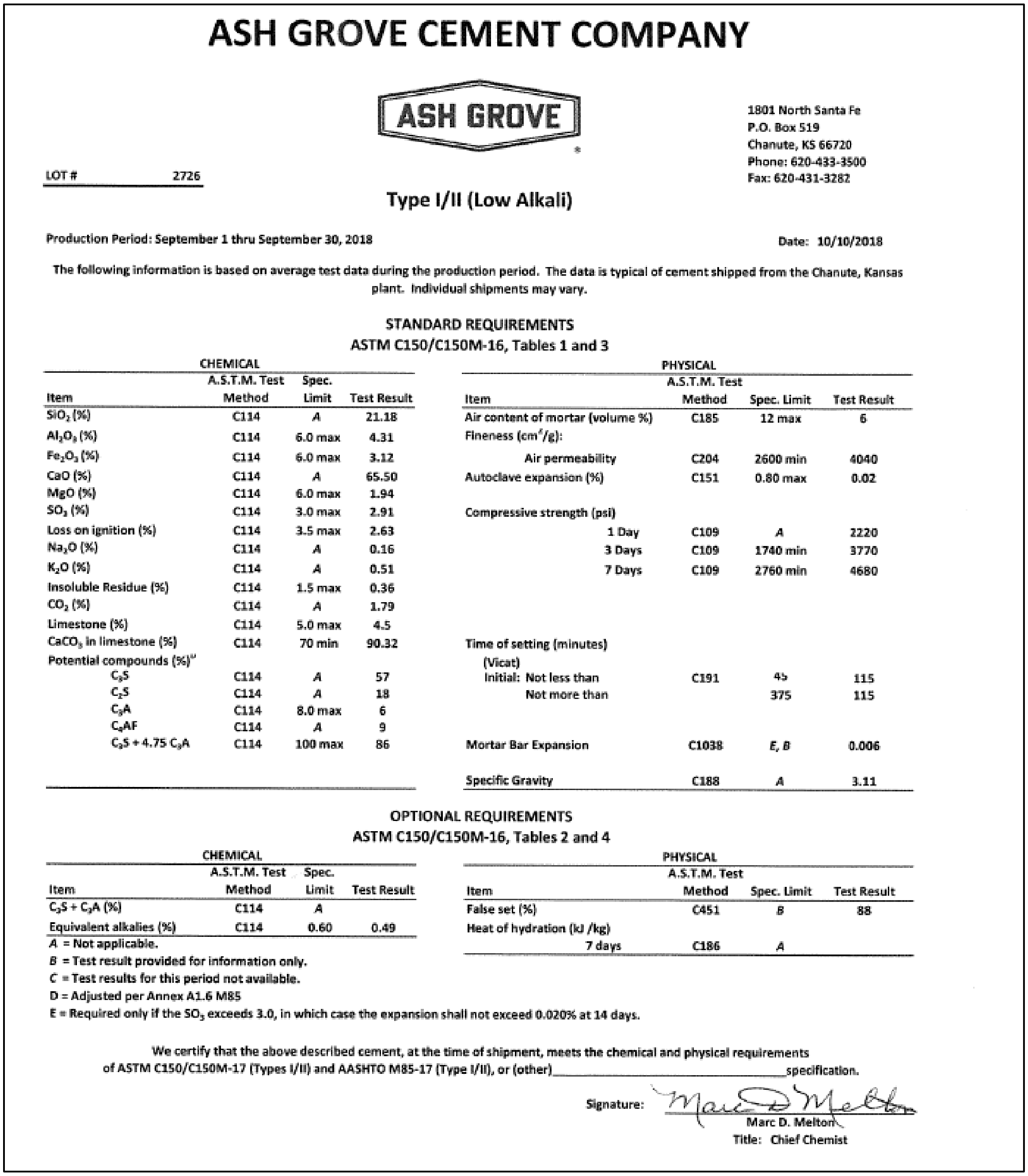


Figure B.13 Mix 13 Measured Calorimetry Data

Appendix C: Cement Mill Certificates



ASH GROVE CEMENT COMPANY

ASH GROVE

1801 North Santa Fe
P.O. Box 519
Chanute, KS 66720
Phone: 620-433-3500
Fax: 620-431-3282

LOT # 2726

Type I/II (Low Alkali)

Production Period: September 1 thru September 30, 2018

Date: 10/10/2018

The following information is based on average test data during the production period. The data is typical of cement shipped from the Chanute, Kansas plant. Individual shipments may vary.

STANDARD REQUIREMENTS
ASTM C150/C150M-16, Tables 1 and 3

CHEMICAL

Item	A.S.T.M. Test Method	Spec. Limit	Test Result
SiO_2 (%)	C114	*A*	21.18
Al_2O_3 (%)	C114	6.0 max	4.31
Fe_2O_3 (%)	C114	6.0 max	3.12
CaO (%)	C114	*A*	65.50
MgO (%)	C114	6.0 max	1.94
SO_3 (%)	C114	3.0 max	2.91
Loss on ignition (%)	C114	3.5 max	2.63
Na_2O (%)	C114	*A*	0.16
K_2O (%)	C114	*A*	0.51
Insoluble Residue (%)	C114	1.5 max	0.36
CO_2 (%)	C114	*A*	1.79
Limestone (%)	C114	5.0 max	4.5
$CaCO_3$ in limestone (%)	C114	70 min	90.32
Potential compounds (%)^D			
C_3S	C114	*A*	57
C_2S	C114	*A*	18
C_3A	C114	8.0 max	6
C_4AF	C114	*A*	9
$C_3S + 4.75\ C_3A$	C114	100 max	86

PHYSICAL

Item	A.S.T.M. Test Method	Spec. Limit	Test Result
Air content of mortar (volume %)	C185	12 max	6
Fineness (cm^2/g):			
Air permeability	C204	2600 min	4040
Autoclave expansion (%)	C151	0.80 max	0.02
Compressive strength (psi)			
1 Day	C109	*A*	2220
3 Days	C109	1740 min	3770
7 Days	C109	2760 min	4680
Time of setting (minutes) (Vicat)			
Initial: Not less than	C191	45	115
Not more than		375	115
Mortar Bar Expansion	C1038	*E, B*	0.006
Specific Gravity	C188	*A*	3.11

OPTIONAL REQUIREMENTS
ASTM C150/C150M-16, Tables 2 and 4

CHEMICAL

Item	A.S.T.M. Test Method	Spec. Limit	Test Result
$C_3S + C_3A$ (%)	C114	*A*	
Equivalent alkalies (%)	C114	0.60	0.49

PHYSICAL

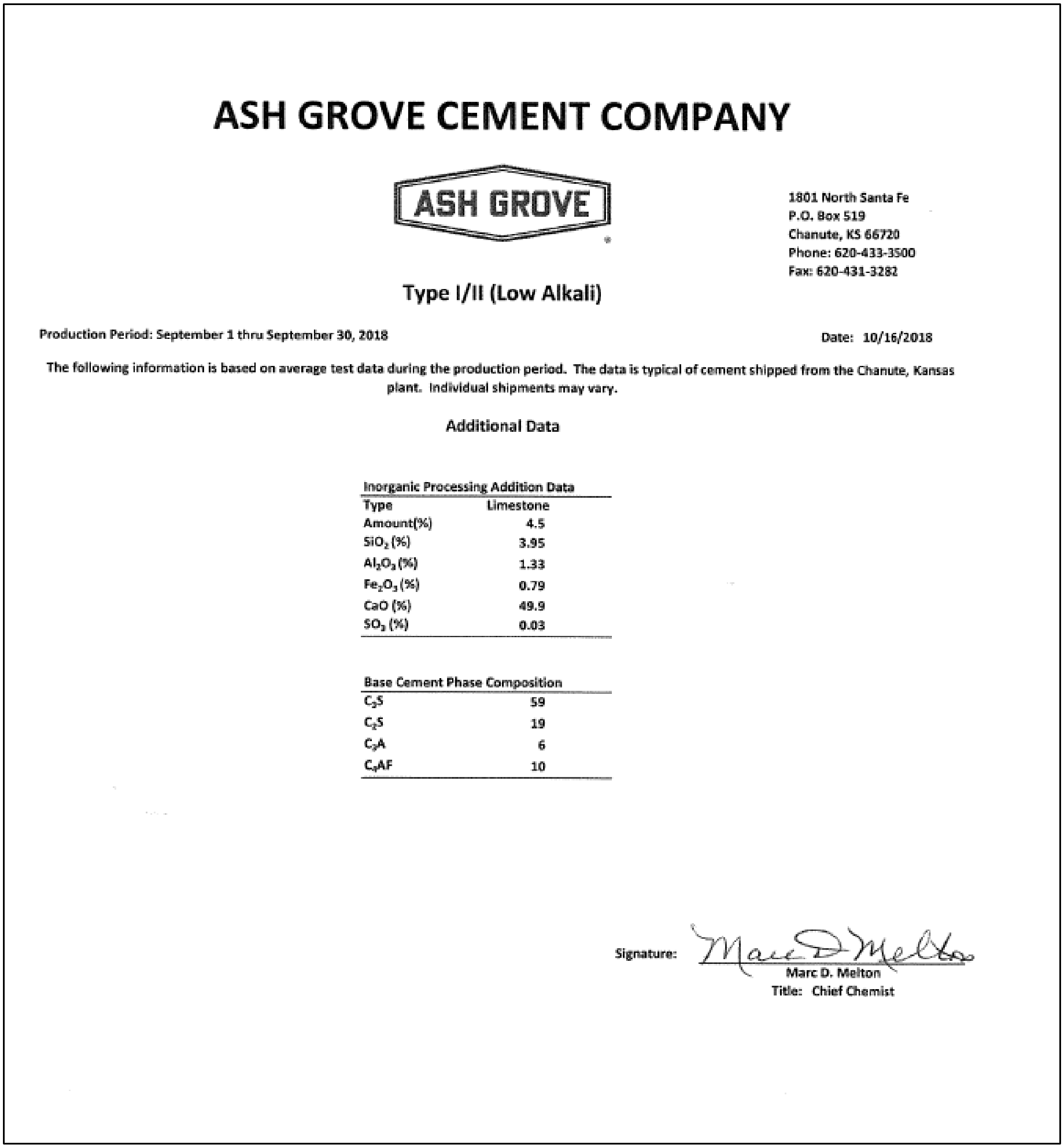
Item	A.S.T.M. Test Method	Spec. Limit	Test Result
False set (%)	C451	*B*	88
Heat of hydration (kJ /kg)			
7 days	C186	*A*	

A = Not applicable.
B = Test result provided for information only.
C = Test results for this period not available.
D = Adjusted per Annex A1.6 M85
E = Required only if the SO_3 exceeds 3.0, in which case the expansion shall not exceed 0.020% at 14 days.

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of ASTM C150/C150M-17 (Types I/II) and AASHTO M85-17 (Type I/II), or (other)____________________ specification.

Signature: Marc D Melton
Marc D. Melton
Title: Chief Chemist

(a)



ASH GROVE CEMENT COMPANY

ASH GROVE

1801 North Santa Fe
P.O. Box 519
Chanute, KS 66720
Phone: 620-433-3500
Fax: 620-431-3282

Type I/II (Low Alkali)

Production Period: September 1 thru September 30, 2018 **Date: 10/16/2018**

The following information is based on average test data during the production period. The data is typical of cement shipped from the Chanute, Kansas plant. Individual shipments may vary.

Additional Data

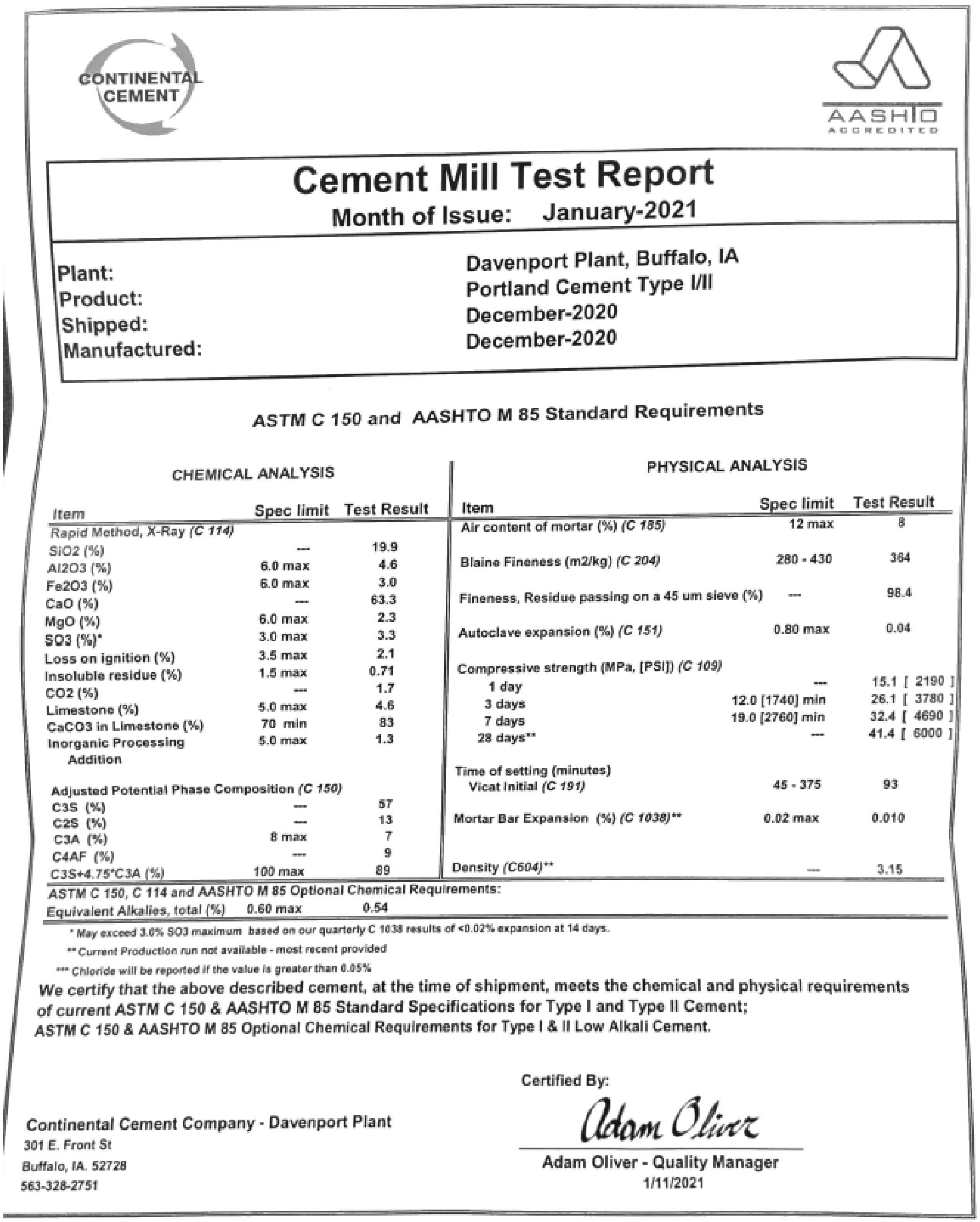
Inorganic Processing Addition Data	
Type	Limestone
Amount(%)	4.5
SiO_2 (%)	3.95
Al_2O_3 (%)	1.33
Fe_2O_3 (%)	0.79
CaO (%)	49.9
SO_3 (%)	0.03

Base Cement Phase Composition	
C_3S	59
C_2S	19
C_3A	6
C_4AF	10

Signature: Marc D. Melton
Marc D. Melton
Title: Chief Chemist

(b)

Figure C.1 Mix 1 Mill Cert



CONTINENTAL CEMENT

AASHTO ACCREDITED

Cement Mill Test Report

Month of Issue: January-2021

Plant:	**Davenport Plant, Buffalo, IA**
Product:	**Portland Cement Type I/II**
Shipped:	**December-2020**
Manufactured:	**December-2020**

ASTM C 150 and AASHTO M 85 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray (C 114)		
SiO_2 (%)	---	19.9
Al_2O_3 (%)	6.0 max	4.6
Fe_2O_3 (%)	6.0 max	3.0
CaO (%)	---	63.3
MgO (%)	6.0 max	2.3
SO_3 (%)*	3.0 max	3.3
Loss on ignition (%)	3.5 max	2.1
Insoluble residue (%)	1.5 max	0.71
CO_2 (%)	---	1.7
Limestone (%)	5.0 max	4.6
$CaCO_3$ in Limestone (%)	70 min	83
Inorganic Processing Addition	5.0 max	1.3
Adjusted Potential Phase Composition *(C 150)*		
C_3S (%)	---	57
C_2S (%)	---	13
C_3A (%)	8 max	7
C_4AF (%)	---	9
$C_3S+4.75{*}C_3A$ (%)	100 max	89
ASTM C 150, C 114 and AASHTO M 85 Optional Chemical Requirements:		
Equivalent Alkalies, total (%)	0.60 max	0.54

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%) *(C 185)*	12 max	8
Blaine Fineness (m2/kg) *(C 204)*	280 - 430	364
Fineness, Residue passing on a 45 um sieve (%)	---	98.4
Autoclave expansion (%) *(C 151)*	0.80 max	0.04
Compressive strength (MPa, [PSI]) *(C 109)*		
1 day	---	15.1 [2190]
3 days	12.0 [1740] min	26.1 [3780]
7 days	19.0 [2760] min	32.4 [4690]
28 days**	---	41.4 [6000]
Time of setting (minutes)		
Vicat Initial *(C 191)*	45 - 375	93
Mortar Bar Expansion (%) *(C 1038)***	0.02 max	0.010
Density *(C604)***	---	3.15

* *May exceed 3.0% SO3 maximum based on our quarterly C 1038 results of <0.02% expansion at 14 days.*

** *Current Production run not available - most recent provided*

*** *Chloride will be reported if the value is greater than 0.05%*

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 150 & AASHTO M 85 Standard Specifications for Type I and Type II Cement;
ASTM C 150 & AASHTO M 85 Optional Chemical Requirements for Type I & II Low Alkali Cement.

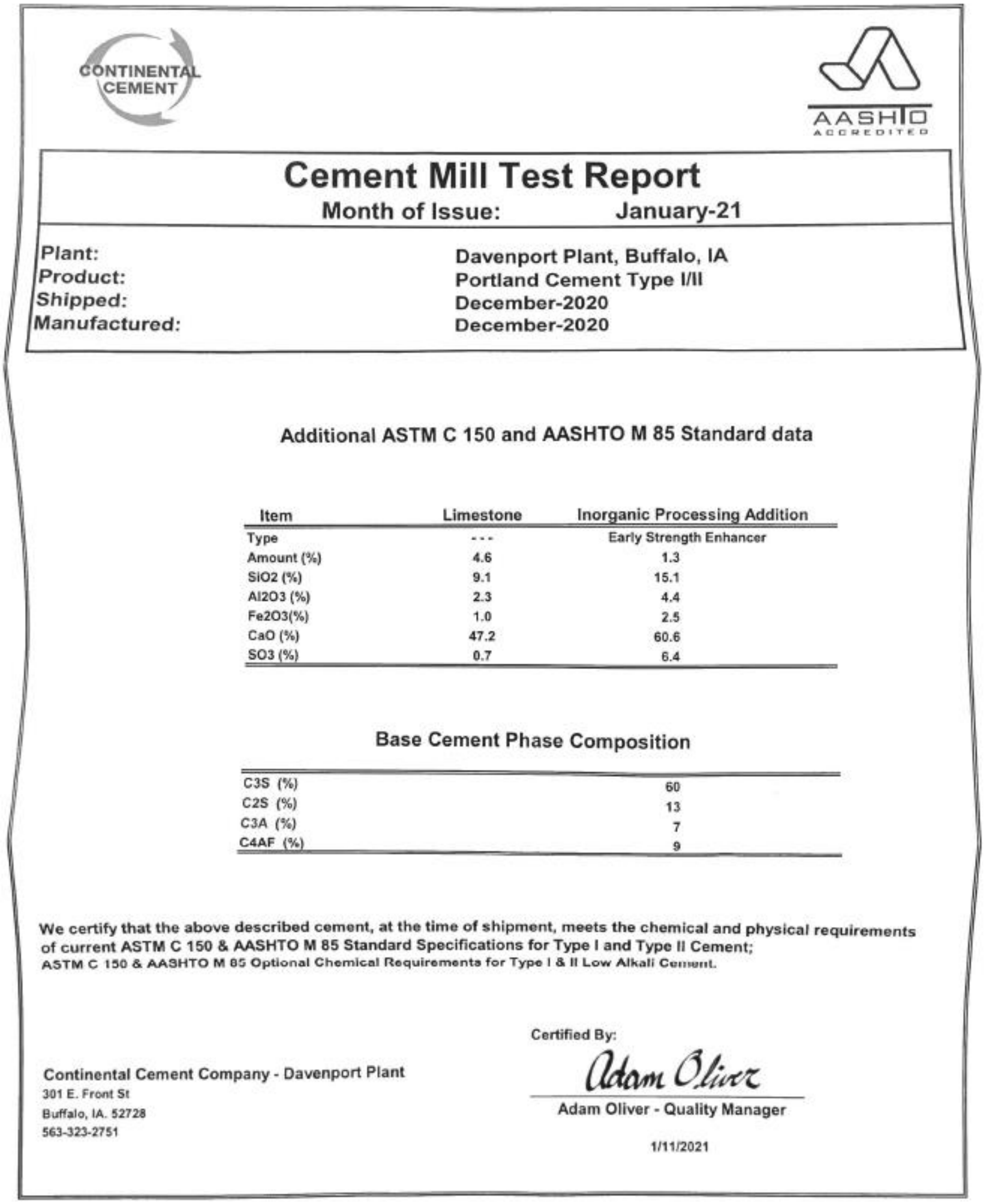
Certified By:

Adam Oliver

Adam Oliver - Quality Manager
1/11/2021

Continental Cement Company - Davenport Plant
301 E. Front St
Buffalo, IA. 52728
563-328-2751

(a)



CONTINENTAL CEMENT

AASHTO ACCREDITED

Cement Mill Test Report

Month of Issue: January-21

Plant:	Davenport Plant, Buffalo, IA
Product:	Portland Cement Type I/II
Shipped:	December-2020
Manufactured:	December-2020

Additional ASTM C 150 and AASHTO M 85 Standard data

Item	Limestone	Inorganic Processing Addition
Type	---	Early Strength Enhancer
Amount (%)	4.6	1.3
SiO2 (%)	9.1	15.1
Al2O3 (%)	2.3	4.4
Fe2O3(%)	1.0	2.5
CaO (%)	47.2	60.6
SO3 (%)	0.7	6.4

Base Cement Phase Composition

C3S (%)	60
C2S (%)	13
C3A (%)	7
C4AF (%)	9

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 150 & AASHTO M 85 Standard Specifications for Type I and Type II Cement;
ASTM C 150 & AASHTO M 85 Optional Chemical Requirements for Type I & II Low Alkali Cement.

Certified By:

Adam Oliver

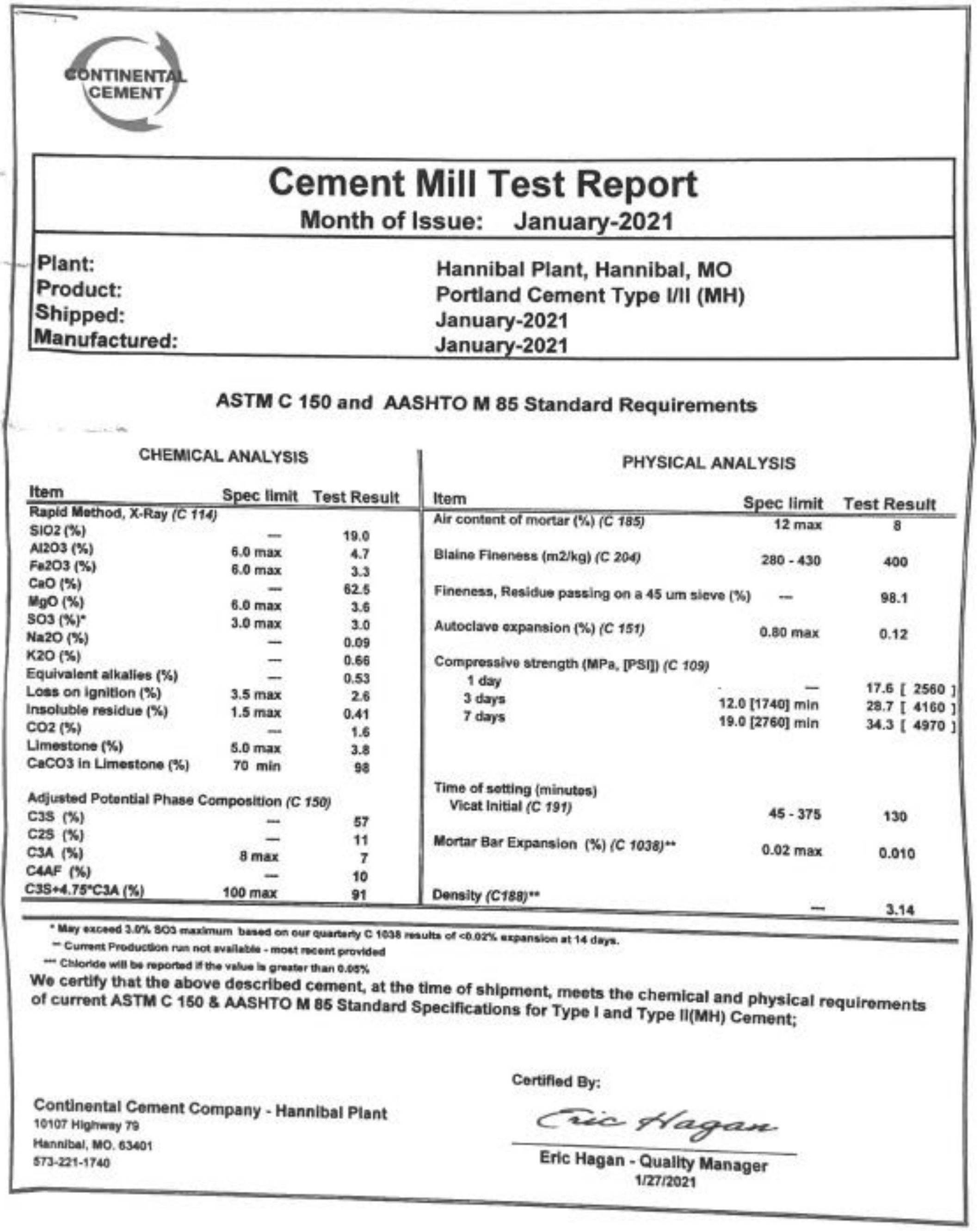
Adam Oliver - Quality Manager

1/11/2021

Continental Cement Company - Davenport Plant
301 E. Front St
Buffalo, IA. 52728
563-323-2751

(b)

Figure C.2 Mix 2 Mill Cert



CONTINENTAL CEMENT

Cement Mill Test Report

Month of Issue: January-2021

Plant:	**Hannibal Plant, Hannibal, MO**
Product:	**Portland Cement Type I/II (MH)**
Shipped:	**January-2021**
Manufactured:	**January-2021**

ASTM C 150 and AASHTO M 85 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C 114)*		
SIO2 (%)	—	19.0
Al2O3 (%)	6.0 max	4.7
Fe2O3 (%)	6.0 max	3.3
CaO (%)	—	62.5
MgO (%)	6.0 max	3.6
SO3 (%)*	3.0 max	3.0
Na2O (%)	—	0.09
K2O (%)	—	0.66
Equivalent alkalies (%)	—	0.53
Loss on ignition (%)	3.5 max	2.6
Insoluble residue (%)	1.5 max	0.41
CO2 (%)	—	1.6
Limestone (%)	5.0 max	3.8
CaCO3 in Limestone (%)	70 min	98
Adjusted Potential Phase Composition *(C 150)*		
C3S (%)	—	57
C2S (%)	—	11
C3A (%)	8 max	7
C4AF (%)	—	10
C3S+4.75*C3A (%)	100 max	91

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%) *(C 185)*	12 max	8
Blaine Fineness (m2/kg) *(C 204)*	280 - 430	400
Fineness, Residue passing on a 45 um sieve (%)	—	98.1
Autoclave expansion (%) *(C 151)*	0.80 max	0.12
Compressive strength (MPa, [PSI]) *(C 109)*		
1 day	—	17.6 [2560]
3 days	12.0 [1740] min	28.7 [4160]
7 days	19.0 [2760] min	34.3 [4970]
Time of setting (minutes)		
Vicat Initial *(C 191)*	45 - 375	130
Mortar Bar Expansion (%) *(C 1038)***	0.02 max	0.010
Density *(C188)***	—	3.14

* May exceed 3.0% SO3 maximum based on our quarterly C 1038 results of <0.02% expansion at 14 days.

** Current Production run not available - most recent provided

*** Chloride will be reported if the value is greater than 0.05%

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 150 & AASHTO M 85 Standard Specifications for Type I and Type II(MH) Cement;

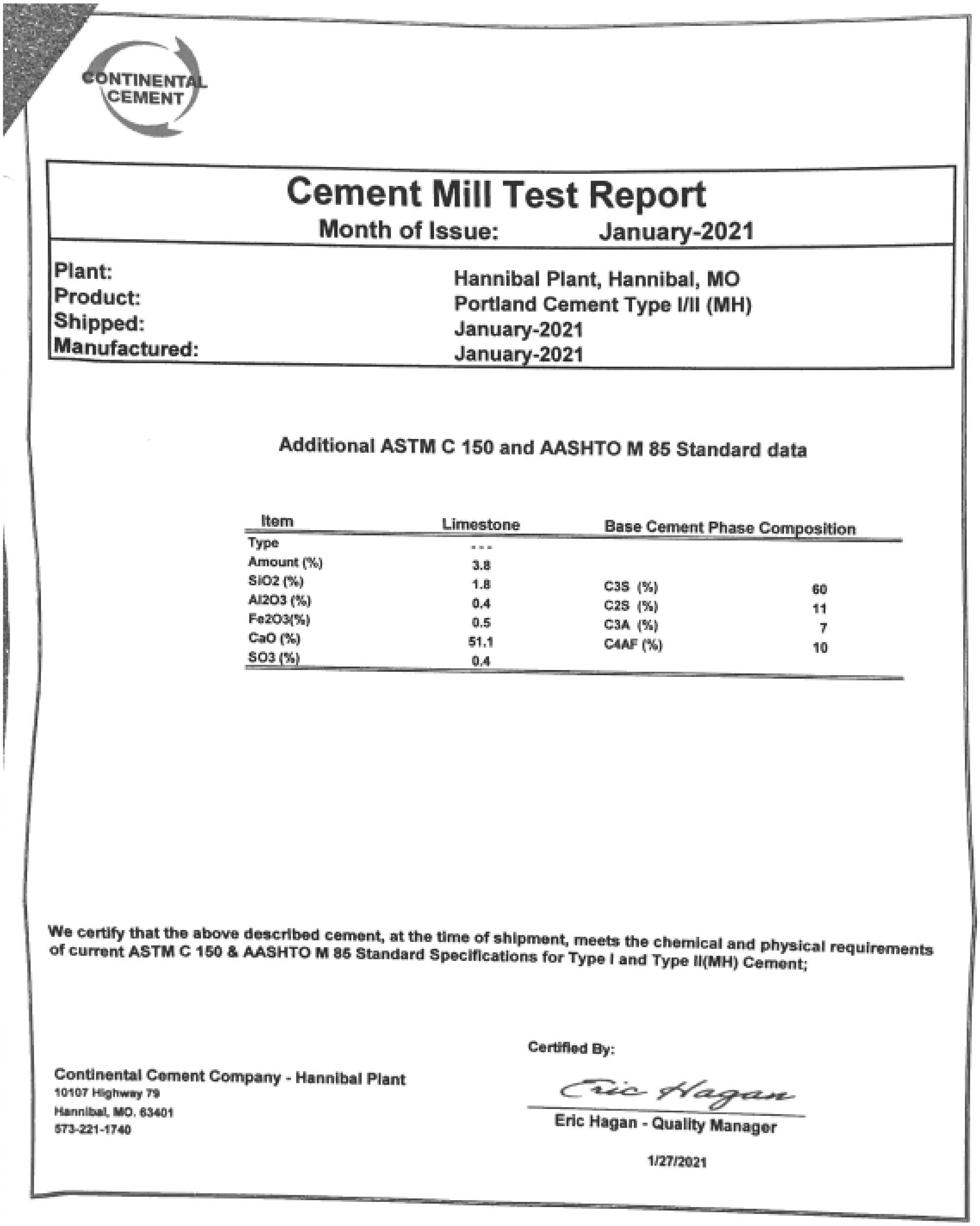
Continental Cement Company - Hannibal Plant
10107 Highway 79
Hannibal, MO. 63401
573-221-1740

Certified By:

Eric Hagan

Eric Hagan - Quality Manager
1/27/2021

(a)



CONTINENTAL CEMENT

Cement Mill Test Report

Month of Issue: January-2021

Plant:	Hannibal Plant, Hannibal, MO
Product:	Portland Cement Type I/II (MH)
Shipped:	January-2021
Manufactured:	January-2021

Additional ASTM C 150 and AASHTO M 85 Standard data

Item	Limestone	Base Cement Phase Composition	
Type	- - -		
Amount (%)	3.8		
SIO2 (%)	1.8	C3S (%)	60
Al2O3 (%)	0.4	C2S (%)	11
Fe2O3(%)	0.5	C3A (%)	7
CaO (%)	51.1	C4AF (%)	10
SO3 (%)	0.4		

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 150 & AASHTO M 85 Standard Specifications for Type I and Type II(MH) Cement;

Certified By:

Eric Hagan

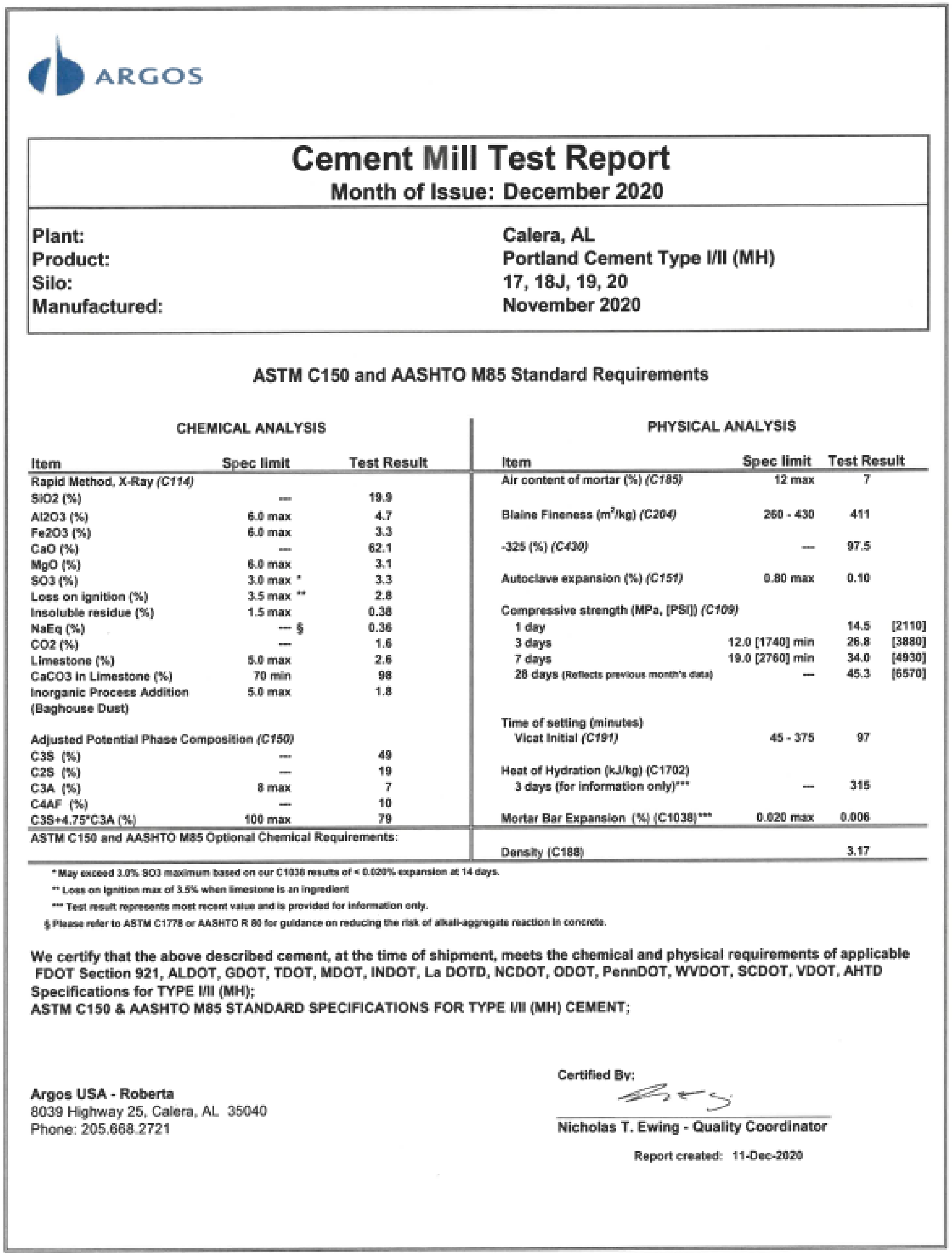
Eric Hagan - Quality Manager

1/27/2021

Continental Cement Company - Hannibal Plant
10107 Highway 79
Hannibal, MO. 63401
573-221-1740

(b)

Figure C.3 Mix 3 Mill Cert



ARGOS

Cement Mill Test Report

Month of Issue: December 2020

Plant:	**Calera, AL**
Product:	**Portland Cement Type I/II (MH)**
Silo:	**17, 18J, 19, 20**
Manufactured:	**November 2020**

ASTM C150 and AASHTO M85 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C114)*		
SiO2 (%)	---	19.9
Al2O3 (%)	6.0 max	4.7
Fe2O3 (%)	6.0 max	3.3
CaO (%)	---	62.1
MgO (%)	6.0 max	3.1
SO3 (%)	3.0 max *	3.3
Loss on ignition (%)	3.5 max **	2.8
Insoluble residue (%)	1.5 max	0.38
NaEq (%)	--- §	0.36
CO2 (%)	---	1.6
Limestone (%)	5.0 max	2.6
CaCO3 in Limestone (%)	70 min	98
Inorganic Process Addition (Baghouse Dust)	5.0 max	1.8
Adjusted Potential Phase Composition *(C150)*		
C3S (%)	---	49
C2S (%)	---	19
C3A (%)	8 max	7
C4AF (%)	---	10
C3S+4.75*C3A (%)	100 max	79
ASTM C150 and AASHTO M85 Optional Chemical Requirements:		

PHYSICAL ANALYSIS

Item	Spec limit	Test Result	
Air content of mortar (%) *(C185)*	12 max	7	
Blaine Fineness (m^2/kg) *(C204)*	260 - 430	411	
-325 (%) *(C430)*	---	97.5	
Autoclave expansion (%) *(C151)*	0.80 max	0.10	
Compressive strength (MPa, [PSI]) *(C109)*			
1 day		14.5	[2110]
3 days	12.0 [1740] min	26.8	[3880]
7 days	19.0 [2760] min	34.0	[4930]
28 days (Reflects previous month's data)	---	45.3	[6570]
Time of setting (minutes)			
Vicat Initial *(C191)*	45 - 375	97	
Heat of Hydration (kJ/kg) (C1702)			
3 days (for information only)***	---	315	
Mortar Bar Expansion (%) (C1038)***	0.020 max	0.006	
Density (C188)		3.17	

* May exceed 3.0% SO3 maximum based on our C1038 results of < 0.020% expansion at 14 days.

** Loss on ignition max of 3.5% when limestone is an ingredient

*** Test result represents most recent value and is provided for information only.

§ Please refer to ASTM C1778 or AASHTO R 80 for guidance on reducing the risk of alkali-aggregate reaction in concrete.

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of applicable FDOT Section 921, ALDOT, GDOT, TDOT, MDOT, INDOT, La DOTD, NCDOT, ODOT, PennDOT, WVDOT, SCDOT, VDOT, AHTD Specifications for TYPE I/II (MH);
ASTM C150 & AASHTO M85 STANDARD SPECIFICATIONS FOR TYPE I/II (MH) CEMENT;

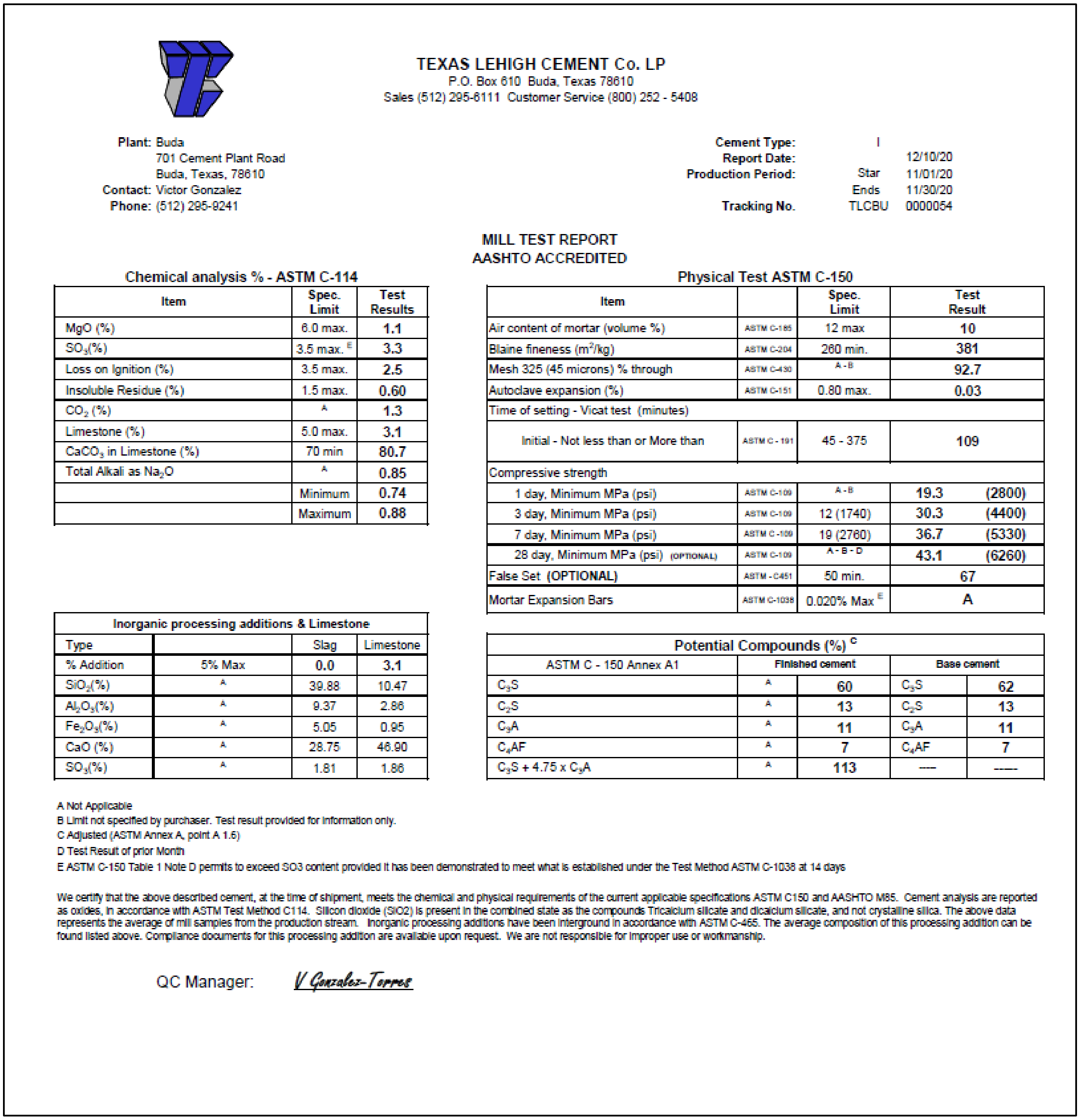
Argos USA - Roberta
8039 Highway 25, Calera, AL 35040
Phone: 205.668.2721

Certified By:

Nicholas T. Ewing - Quality Coordinator

Report created: 11-Dec-2020

Figure C.4 Mix 4 Mill Cert



TEXAS LEHIGH CEMENT Co. LP
P.O. Box 610 Buda, Texas 78610
Sales (512) 295-6111 Customer Service (800) 252 - 5408

Plant: Buda
701 Cement Plant Road
Buda, Texas, 78610
Contact: Victor Gonzalez
Phone: (512) 295-9241

Cement Type: I
Report Date: 12/10/20
Production Period: Star 11/01/20
Ends 11/30/20
Tracking No. TLCBU 0000054

MILL TEST REPORT
AASHTO ACCREDITED

Chemical analysis % - ASTM C-114

Item	Spec. Limit	Test Results
MgO (%)	6.0 max.	1.1
SO_3(%)	3.5 max. [E]	3.3
Loss on Ignition (%)	3.5 max.	2.5
Insoluble Residue (%)	1.5 max.	0.60
CO_2 (%)	[A]	1.3
Limestone (%)	5.0 max.	3.1
$CaCO_3$ in Limestone (%)	70 min	80.7
Total Alkali as Na_2O	[A]	0.85
	Minimum	0.74
	Maximum	0.88

Physical Test ASTM C-150

Item		Spec. Limit	Test Result	
Air content of mortar (volume %)	ASTM C-185	12 max	10	
Blaine fineness (m^2/kg)	ASTM C-204	260 min.	381	
Mesh 325 (45 microns) % through	ASTM C-430	[A - B]	92.7	
Autoclave expansion (%)	ASTM C-151	0.80 max.	0.03	
Time of setting - Vicat test (minutes)				
Initial - Not less than or More than	ASTM C - 191	45 - 375	109	
Compressive strength				
1 day, Minimum MPa (psi)	ASTM C-109	[A - B]	19.3	(2800)
3 day, Minimum MPa (psi)	ASTM C-109	12 (1740)	30.3	(4400)
7 day, Minimum MPa (psi)	ASTM C -109	19 (2760)	36.7	(5330)
28 day, Minimum MPa (psi) (OPTIONAL)	ASTM C-109	[A - B - D]	43.1	(6260)
False Set (OPTIONAL)	ASTM - C451	50 min.	67	
Mortar Expansion Bars	ASTM C-1038	0.020% Max [E]	A	

Inorganic processing additions & Limestone

Type		Slag	Limestone
% Addition	5% Max	0.0	3.1
SiO_2(%)	[A]	39.88	10.47
Al_2O_3(%)	[A]	9.37	2.86
Fe_2O_3(%)	[A]	5.05	0.95
CaO (%)	[A]	28.75	46.90
SO_3(%)	[A]	1.81	1.86

Potential Compounds (%) [C]

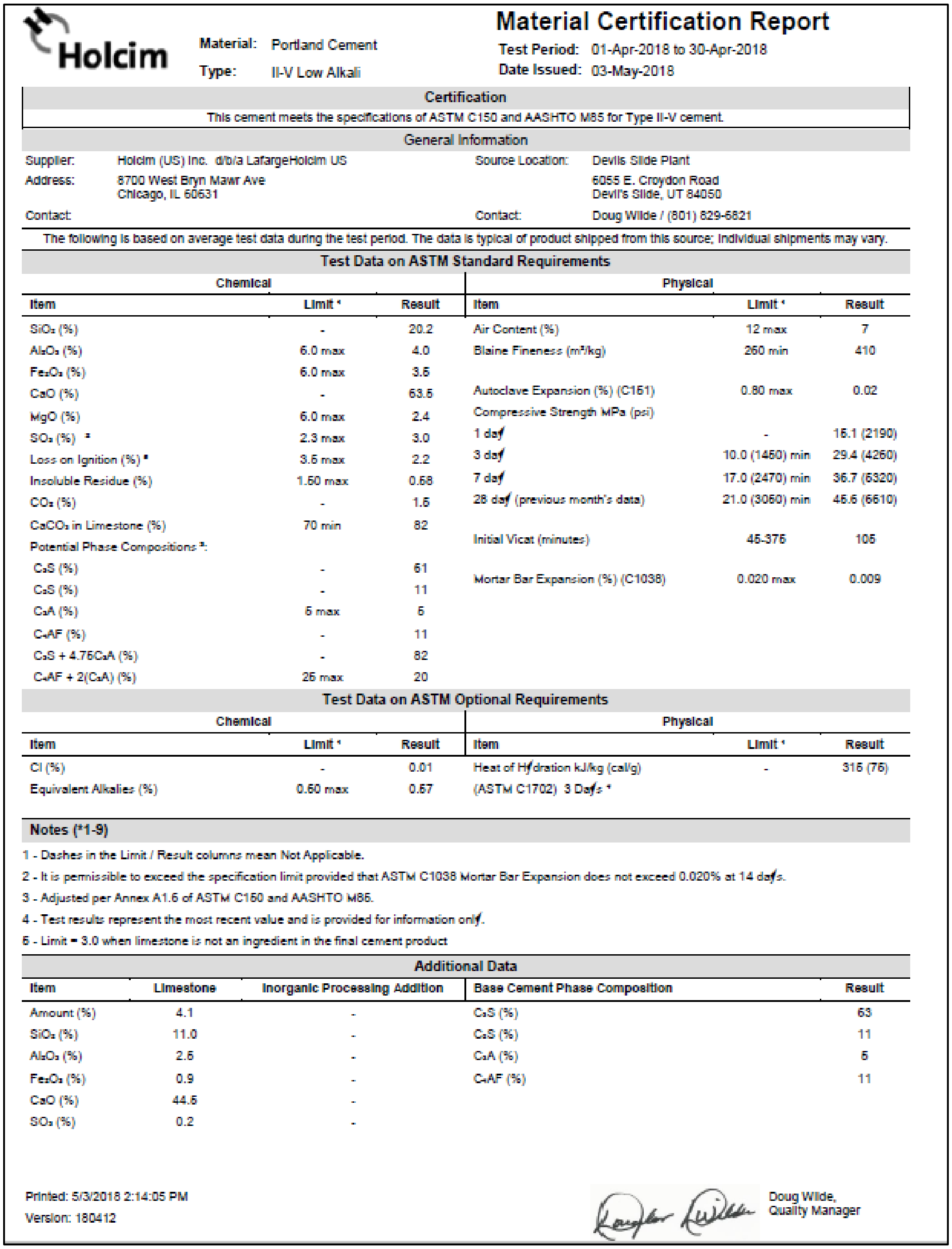
ASTM C - 150 Annex A1	Finished cement		Base cement	
C_3S	[A]	60	C_3S	62
C_2S	[A]	13	C_2S	13
C_3A	[A]	11	C_3A	11
C_4AF	[A]	7	C_4AF	7
C_3S + 4.75 x C_3A	[A]	113	----	-----

A Not Applicable
B Limit not specified by purchaser. Test result provided for information only.
C Adjusted (ASTM Annex A, point A 1.6)
D Test Result of prior Month
E ASTM C-150 Table 1 Note D permits to exceed SO3 content provided it has been demonstrated to meet what is established under the Test Method ASTM C-1038 at 14 days

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of the current applicable specifications ASTM C150 and AASHTO M85. Cement analysis are reported as oxides, in accordance with ASTM Test Method C114. Silicon dioxide (SiO2) is present in the combined state as the compounds Tricalcium silicate and dicalcium silicate, and not crystalline silica. The above data represents the average of mill samples from the production stream. Inorganic processing additions have been interground in accordance with ASTM C-465. The average composition of this processing addition can be found listed above. Compliance documents for this processing addition are available upon request. We are not responsible for improper use or workmanship.

QC Manager: V Gonzalez-Torres

Figure C.5 Mix 5 Mill Cert



Holcim

Material: Portland Cement

Type: II-V Low Alkali

Material Certification Report

Test Period: 01-Apr-2018 to 30-Apr-2018

Date Issued: 03-May-2018

Certification

This cement meets the specifications of ASTM C150 and AASHTO M85 for Type II-V cement.

General Information

Supplier: Holcim (US) Inc. d/b/a LafargeHolcim US

Address:
8700 West Bryn Mawr Ave
Chicago, IL 60631

Contact:

Source Location: Devils Slide Plant
6055 E. Croydon Road
Devil's Slide, UT 84050

Contact: Doug Wilde / (801) 829-6821

The following is based on average test data during the test period. The data is typical of product shipped from this source; individual shipments may vary.

Test Data on ASTM Standard Requirements

Chemical

Item	Limit [1]	Result
SiO_2 (%)	-	20.2
Al_2O_3 (%)	6.0 max	4.0
Fe_2O_3 (%)	6.0 max	3.5
CaO (%)	-	63.5
MgO (%)	6.0 max	2.4
SO_3 (%) [2]	2.3 max	3.0
Loss on Ignition (%) [5]	3.5 max	2.2
Insoluble Residue (%)	1.50 max	0.58
CO_2 (%)	-	1.5
$CaCO_3$ in Limestone (%)	70 min	82
Potential Phase Compositions [3]:		
C_3S (%)	-	61
C_2S (%)	-	11
C_3A (%)	5 max	5
C_4AF (%)	-	11
$C_3S + 4.75C_3A$ (%)	-	82
$C_4AF + 2(C_3A)$ (%)	25 max	20

Physical

Item	Limit [1]	Result
Air Content (%)	12 max	7
Blaine Fineness (m^2/kg)	260 min	410
Autoclave Expansion (%) (C151)	0.80 max	0.02
Compressive Strength MPa (psi)		
1 day	-	15.1 (2190)
3 day	10.0 (1450) min	29.4 (4260)
7 day	17.0 (2470) min	36.7 (5320)
28 day (previous month's data)	21.0 (3050) min	45.6 (6610)
Initial Vicat (minutes)	45-375	105
Mortar Bar Expansion (%) (C1038)	0.020 max	0.009

Test Data on ASTM Optional Requirements

Chemical

Item	Limit [1]	Result
Cl (%)	-	0.01
Equivalent Alkalies (%)	0.60 max	0.57

Physical

Item	Limit [1]	Result
Heat of Hydration kJ/kg (cal/g) (ASTM C1702) 3 Days [4]	-	315 (75)

Notes (*1-9)

1 - Dashes in the Limit / Result columns mean Not Applicable.

2 - It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020% at 14 days.

3 - Adjusted per Annex A1.6 of ASTM C150 and AASHTO M85.

4 - Test results represent the most recent value and is provided for information only.

5 - Limit = 3.0 when limestone is not an ingredient in the final cement product

Additional Data

Item	Limestone	Inorganic Processing Addition
Amount (%)	4.1	-
SiO_2 (%)	11.0	-
Al_2O_3 (%)	2.5	-
Fe_2O_3 (%)	0.9	-
CaO (%)	44.5	-
SO_3 (%)	0.2	-

Base Cement Phase Composition	Result
C_3S (%)	63
C_2S (%)	11
C_3A (%)	5
C_4AF (%)	11

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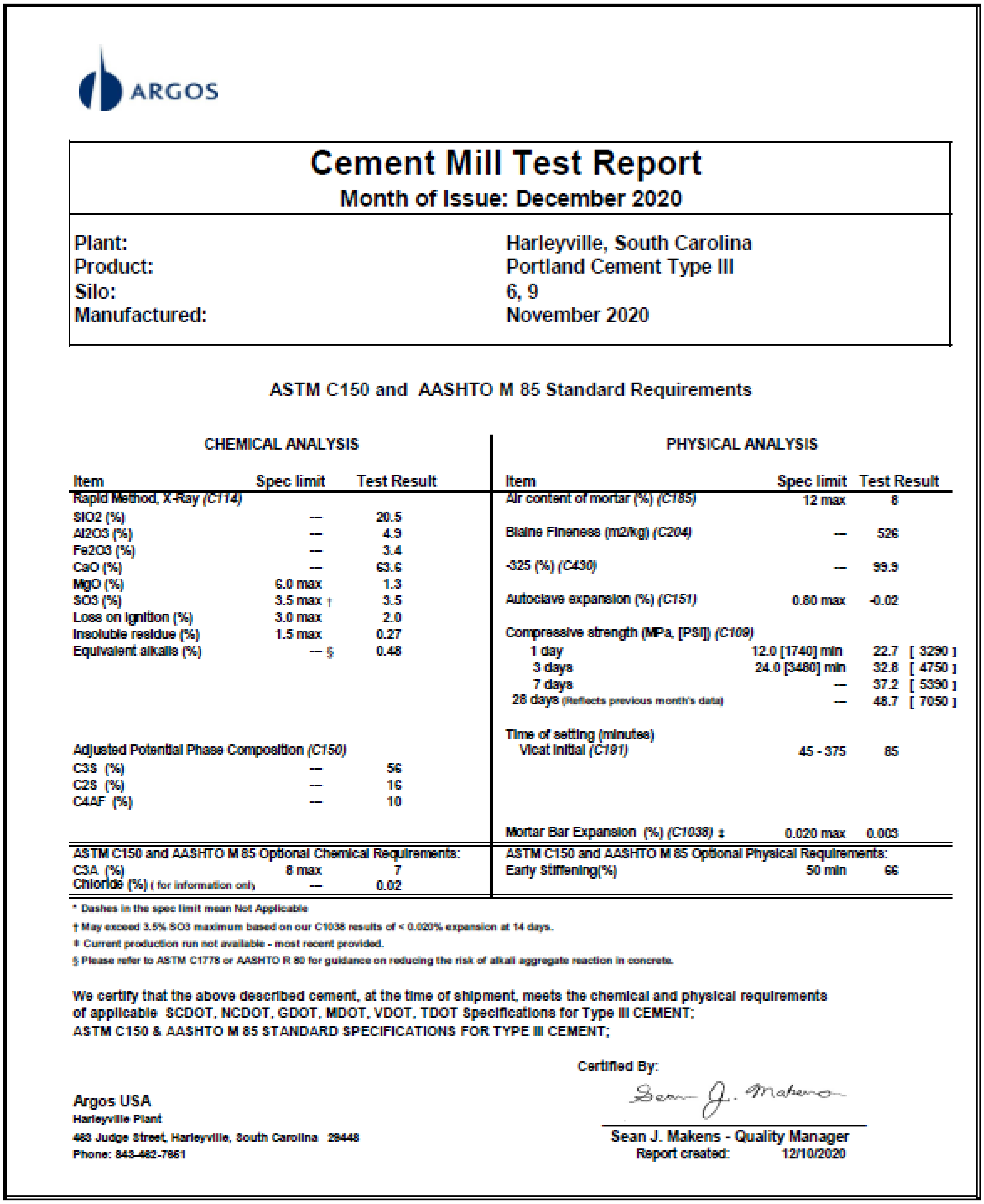
Version: 180412

Douglas Wilde

Doug Wilde,
Quality Manager

Figure C.6 Mix 6 Mill Cert



ARGOS

Cement Mill Test Report

Month of Issue: December 2020

Plant:	Harleyville, South Carolina
Product:	Portland Cement Type III
Silo:	6, 9
Manufactured:	November 2020

ASTM C150 and AASHTO M 85 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C114)*		
SiO2 (%)	—	20.5
Al2O3 (%)	—	4.9
Fe2O3 (%)	—	3.4
CaO (%)	—	63.6
MgO (%)	6.0 max	1.3
SO3 (%)	3.5 max †	3.5
Loss on ignition (%)	3.0 max	2.0
Insoluble residue (%)	1.5 max	0.27
Equivalent alkalis (%)	— §	0.48
Adjusted Potential Phase Composition *(C150)*		
C3S (%)	—	56
C2S (%)	—	16
C4AF (%)	—	10
ASTM C150 and AASHTO M 85 Optional Chemical Requirements:		
C3A (%)	8 max	7
Chloride (%) (for information only	—	0.02

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%) *(C185)*	12 max	8
Blaine Fineness (m2/kg) *(C204)*	—	526
-325 (%) *(C430)*	—	99.9
Autoclave expansion (%) *(C151)*	0.80 max	-0.02
Compressive strength (MPa, [PSI]) *(C109)*		
1 day	12.0 [1740] min	22.7 [3290]
3 days	24.0 [3480] min	32.8 [4750]
7 days	—	37.2 [5390]
28 days (Reflects previous month's data)	—	48.7 [7050]
Time of setting (minutes)		
Vicat Initial *(C191)*	45 - 375	85
Mortar Bar Expansion (%) *(C1038)* ‡	0.020 max	0.003
ASTM C150 and AASHTO M 85 Optional Physical Requirements:		
Early Stiffening(%)	50 min	66

* Dashes in the spec limit mean Not Applicable

† May exceed 3.5% SO3 maximum based on our C1038 results of < 0.020% expansion at 14 days.

‡ Current production run not available - most recent provided.

§ Please refer to ASTM C1778 or AASHTO R 80 for guidance on reducing the risk of alkali aggregate reaction in concrete.

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of applicable SCDOT, NCDOT, GDOT, MDOT, VDOT, TDOT Specifications for Type III CEMENT;
ASTM C150 & AASHTO M 85 STANDARD SPECIFICATIONS FOR TYPE III CEMENT;

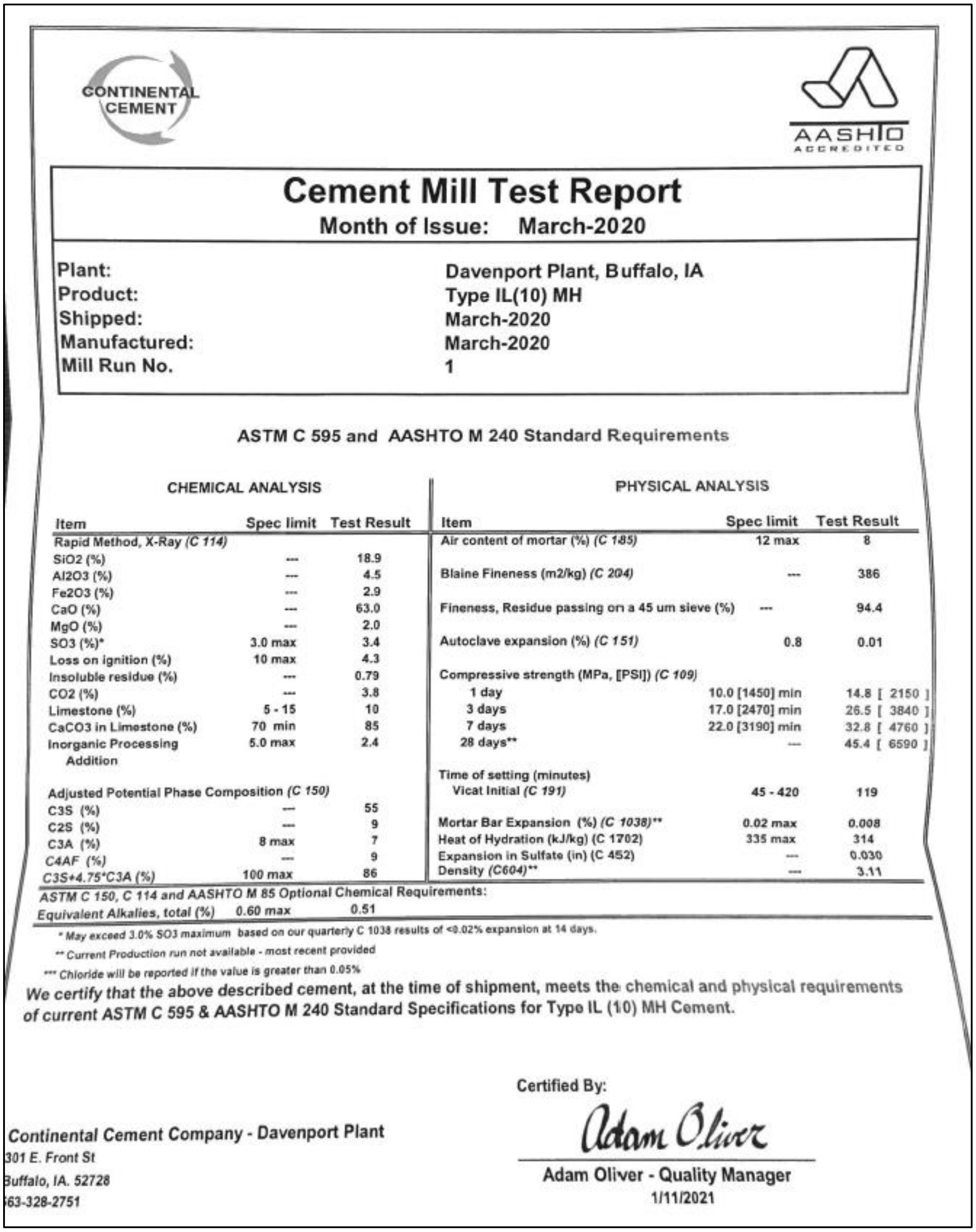
Certified By:

Sean J. Makens

Sean J. Makens - Quality Manager
Report created: 12/10/2020

Argos USA
Harleyville Plant
463 Judge Street, Harleyville, South Carolina 29448
Phone: 843-462-7861

Figure C.7 Mix 7 and Mix 8 Mill Cert



CONTINENTAL CEMENT

AASHTO ACCREDITED

Cement Mill Test Report

Month of Issue: March-2020

Plant:	Davenport Plant, Buffalo, IA
Product:	Type IL(10) MH
Shipped:	March-2020
Manufactured:	March-2020
Mill Run No.	1

ASTM C 595 and AASHTO M 240 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C 114)*		
SiO2 (%)	---	18.9
Al2O3 (%)	---	4.5
Fe2O3 (%)	---	2.9
CaO (%)	---	63.0
MgO (%)	---	2.0
SO3 (%)*	3.0 max	3.4
Loss on ignition (%)	10 max	4.3
Insoluble residue (%)	---	0.79
CO2 (%)	---	3.8
Limestone (%)	5 - 15	10
CaCO3 in Limestone (%)	70 min	85
Inorganic Processing Addition	5.0 max	2.4
Adjusted Potential Phase Composition *(C 150)*		
C3S (%)	---	55
C2S (%)	---	9
C3A (%)	8 max	7
C4AF (%)	---	9
*C3S+4.75*C3A (%)*	100 max	86

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%) *(C 185)*	12 max	8
Blaine Fineness (m2/kg) *(C 204)*	---	386
Fineness, Residue passing on a 45 um sieve (%)	---	94.4
Autoclave expansion (%) *(C 151)*	0.8	0.01
Compressive strength (MPa, [PSI]) *(C 109)*		
1 day	10.0 [1450] min	14.8 [2150]
3 days	17.0 [2470] min	26.5 [3840]
7 days	22.0 [3190] min	32.8 [4760]
28 days**	---	45.4 [6590]
Time of setting (minutes)		
Vicat Initial *(C 191)*	45 - 420	119
Mortar Bar Expansion (%) *(C 1038)***	0.02 max	0.008
Heat of Hydration (kJ/kg) (C 1702)	335 max	314
Expansion in Sulfate (in) (C 452)	---	0.030
Density *(C604)***	---	3.11

ASTM C 150, C 114 and AASHTO M 85 Optional Chemical Requirements:

Item	Spec limit	Test Result
Equivalent Alkalies, total (%)	0.60 max	0.51

** May exceed 3.0% SO3 maximum* based on our quarterly C 1038 results of <0.02% expansion at 14 days.

*** Current Production run not available - most recent provided*

**** Chloride will be reported if the value is greater than 0.05%*

***We certify** that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 595 & AASHTO M 240 Standard Specifications for Type IL (10) MH Cement.*

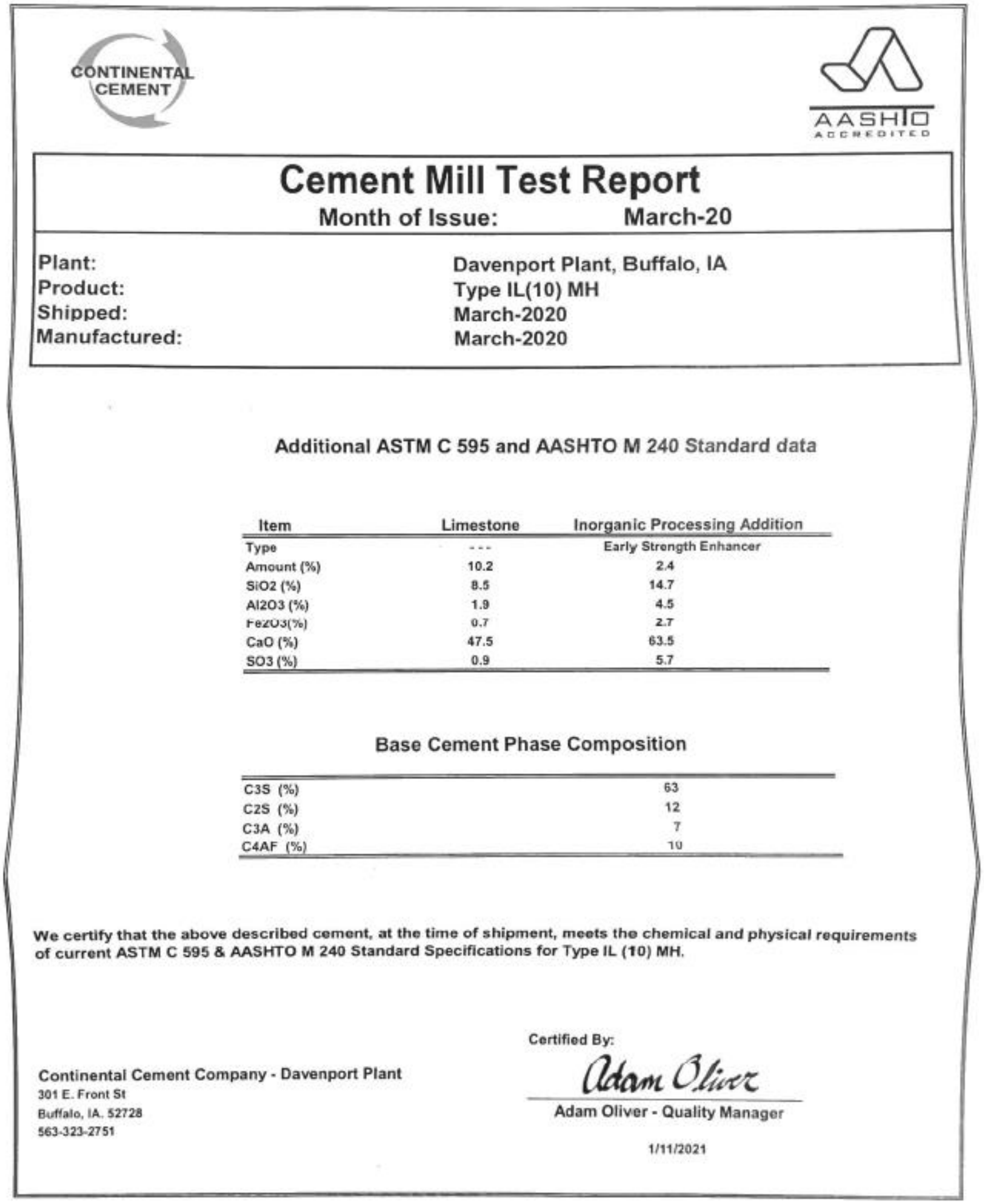
Certified By:

Adam Oliver

Adam Oliver - Quality Manager
1/11/2021

Continental Cement Company - Davenport Plant
301 E. Front St
Buffalo, IA. 52728
63-328-2751

(a)



CONTINENTAL CEMENT

AASHTO ACCREDITED

Cement Mill Test Report

Month of Issue: March-20

Plant:	Davenport Plant, Buffalo, IA
Product:	Type IL(10) MH
Shipped:	March-2020
Manufactured:	March-2020

Additional ASTM C 595 and AASHTO M 240 Standard data

Item	Limestone	Inorganic Processing Addition
Type	---	Early Strength Enhancer
Amount (%)	10.2	2.4
SiO2 (%)	8.5	14.7
Al2O3 (%)	1.9	4.5
Fe2O3(%)	0.7	2.7
CaO (%)	47.5	63.5
SO3 (%)	0.9	5.7

Base Cement Phase Composition

C3S (%)	63
C2S (%)	12
C3A (%)	7
C4AF (%)	10

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 595 & AASHTO M 240 Standard Specifications for Type IL (10) MH.

Certified By:

Adam Oliver

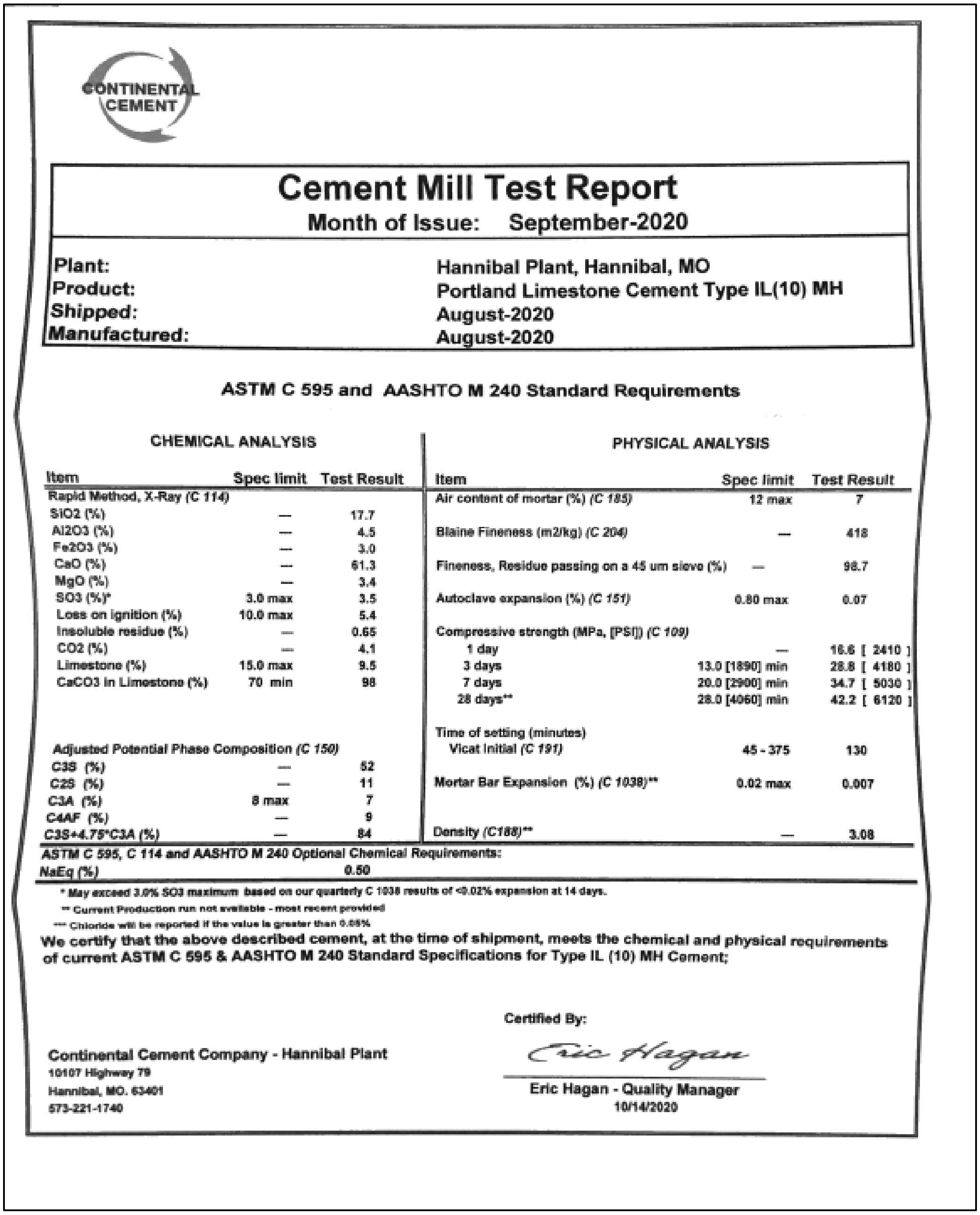
Adam Oliver - Quality Manager

1/11/2021

Continental Cement Company - Davenport Plant
301 E. Front St
Buffalo, IA. 52728
563-323-2751

(b)

Figure C.8 Mix 9 Mill Cert



CONTINENTAL CEMENT

Cement Mill Test Report

Month of Issue: September-2020

Plant:	**Hannibal Plant, Hannibal, MO**
Product:	**Portland Limestone Cement Type IL(10) MH**
Shipped:	**August-2020**
Manufactured:	**August-2020**

ASTM C 595 and AASHTO M 240 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C 114)*		
SiO_2 (%)	—	17.7
Al_2O_3 (%)	—	4.5
Fe_2O_3 (%)	—	3.0
CaO (%)	—	61.3
MgO (%)	—	3.4
SO_3 (%)*	3.0 max	3.5
Loss on ignition (%)	10.0 max	5.4
Insoluble residue (%)	—	0.65
CO_2 (%)	—	4.1
Limestone (%)	15.0 max	9.5
$CaCO_3$ in Limestone (%)	70 min	98
Adjusted Potential Phase Composition *(C 150)*		
C_3S (%)	—	52
C_2S (%)	—	11
C_3A (%)	8 max	7
C_4AF (%)	—	9
$C_3S+4.75{*}C_3A$ (%)	—	84

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%) *(C 185)*	12 max	7
Blaine Fineness (m2/kg) *(C 204)*	—	418
Fineness, Residue passing on a 45 um sieve (%)	—	98.7
Autoclave expansion (%) *(C 151)*	0.80 max	0.07
Compressive strength (MPa, [PSI]) *(C 109)*		
1 day	—	16.6 [2410]
3 days	13.0 [1890] min	28.8 [4180]
7 days	20.0 [2900] min	34.7 [5030]
28 days**	28.0 [4060] min	42.2 [6120]
Time of setting (minutes)		
Vicat Initial *(C 191)*	45 - 375	130
Mortar Bar Expansion (%) *(C 1038)***	0.02 max	0.007
Density *(C188)***	—	3.08

ASTM C 595, C 114 and AASHTO M 240 **Optional Chemical Requirements:**

NaEq (%) 0.50

* May exceed 3.0% SO_3 maximum based on our quarterly C 1038 results of <0.02% expansion at 14 days.

** Current Production run not available - most recent provided

*** Chloride will be reported if the value is greater than 0.05%

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 595 & AASHTO M 240 Standard Specifications for Type IL (10) MH Cement;

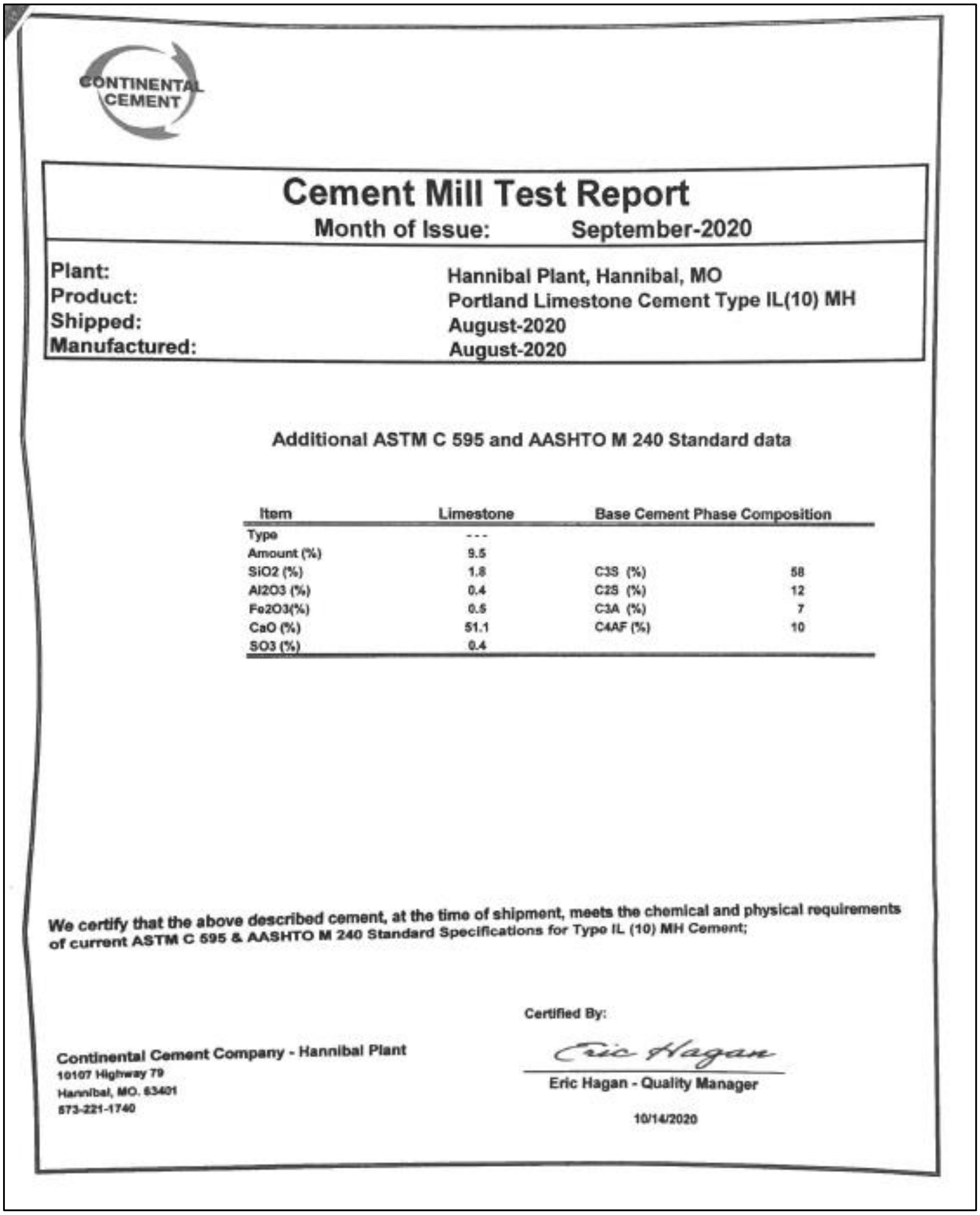
Certified By:

Eric Hagan

Eric Hagan - Quality Manager
10/14/2020

Continental Cement Company - Hannibal Plant
10107 Highway 79
Hannibal, MO. 63401
573-221-1740

(a)



CONTINENTAL CEMENT

Cement Mill Test Report

Month of Issue: September-2020

Plant: Hannibal Plant, Hannibal, MO
Product: Portland Limestone Cement Type IL(10) MH
Shipped: August-2020
Manufactured: August-2020

Additional ASTM C 595 and AASHTO M 240 Standard data

Item	Limestone	Base Cement Phase Composition	
Type	---		
Amount (%)	9.5		
SiO_2 (%)	1.8	C_3S (%)	58
Al_2O_3 (%)	0.4	C_2S (%)	12
Fe_2O_3(%)	0.5	C_3A (%)	7
CaO (%)	51.1	C_4AF (%)	10
SO_3 (%)	0.4		

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of current ASTM C 595 & AASHTO M 240 Standard Specifications for Type IL (10) MH Cement;

Certified By:

Eric Hagan

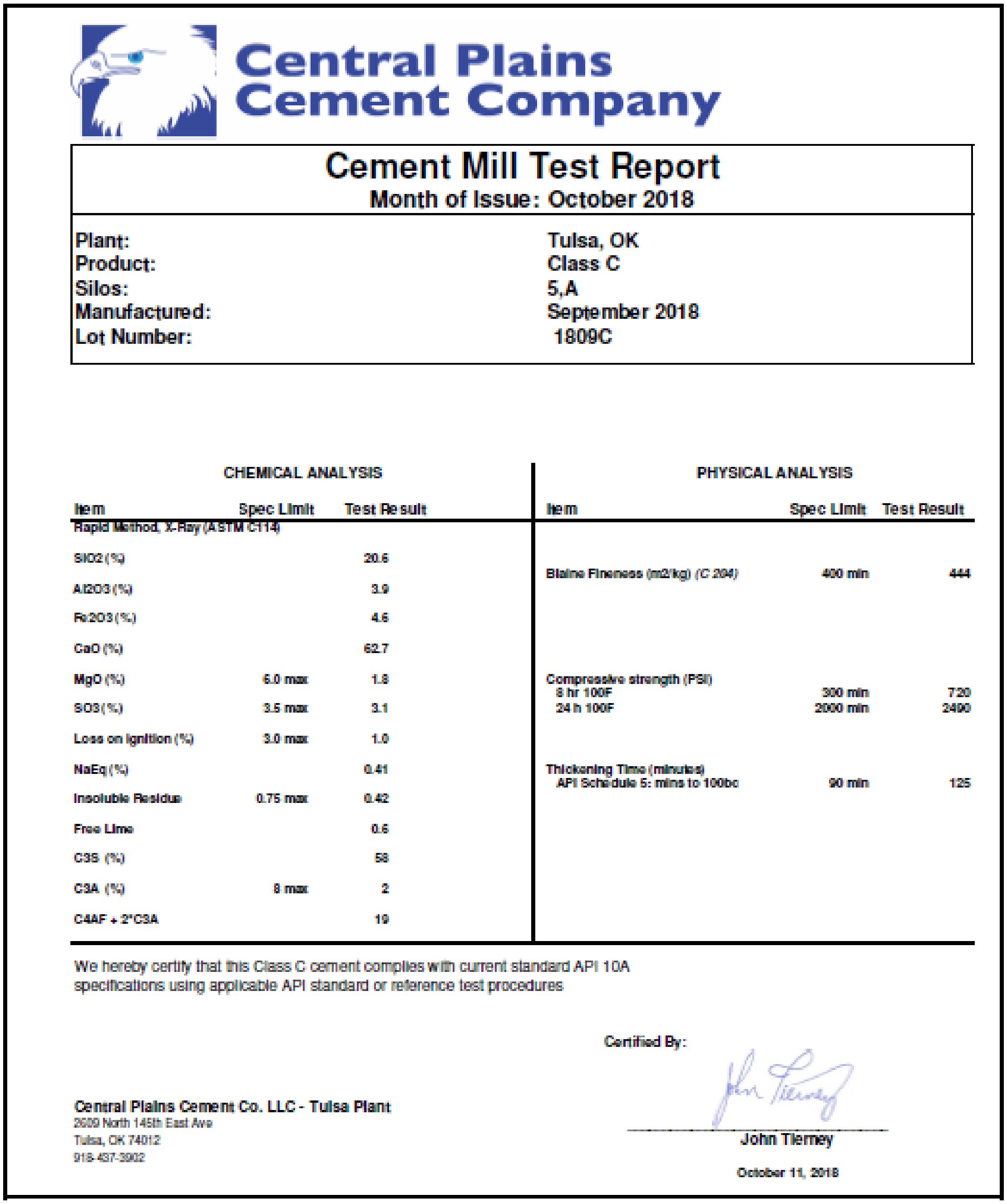
Eric Hagan - Quality Manager

10/14/2020

Continental Cement Company - Hannibal Plant
10107 Highway 79
Hannibal, MO. 63401
573-221-1740

(b)

Figure C.9 Mix 10 Mill Cert



Central Plains Cement Company

Cement Mill Test Report

Month of Issue: October 2018

Plant:	Tulsa, OK
Product:	Class C
Silos:	5,A
Manufactured:	September 2018
Lot Number:	1809C

CHEMICAL ANALYSIS

Item	Spec Limit	Test Result
Rapid Method, X-Ray (ASTM C114)		
SiO_2 (%)		20.6
Al_2O_3 (%)		3.9
Fe_2O_3 (%)		4.6
CaO (%)		62.7
MgO (%)	6.0 max	1.8
SO_3 (%)	3.5 max	3.1
Loss on ignition (%)	3.0 max	1.0
NaEq (%)		0.41
Insoluble Residue	0.75 max	0.42
Free Lime		0.6
C_3S (%)		58
C_3A (%)	8 max	2
$C_4AF + 2{*}C_3A$		19

PHYSICAL ANALYSIS

Item	Spec Limit	Test Result
Blaine Fineness (m2/kg) *(C 204)*	400 min	444
Compressive strength (PSI)		
8 hr 100F	300 min	720
24 h 100F	2000 min	2490
Thickening Time (minutes)		
API Schedule 5: mins to 100bc	90 min	125

We hereby certify that this Class C cement complies with current standard API 10A specifications using applicable API standard or reference test procedures

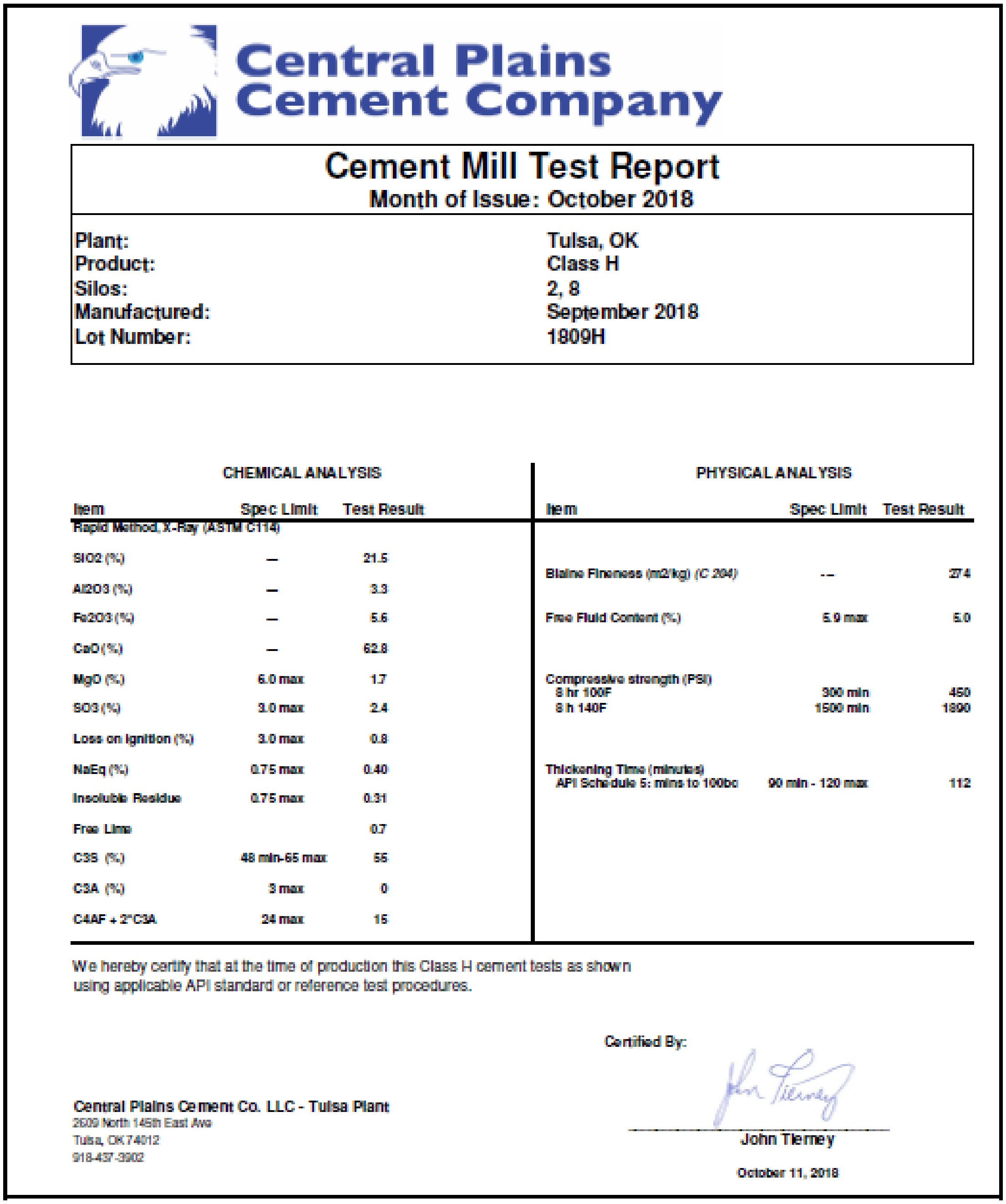
Certified By:

John Tierney

October 11, 2018

Central Plains Cement Co. LLC - Tulsa Plant
2609 North 145th East Ave
Tulsa, OK 74012
918-437-3902

Figure C.10 Mix 11 Mill Cert



Central Plains Cement Company

Cement Mill Test Report

Month of Issue: October 2018

Plant:	Tulsa, OK
Product:	Class H
Silos:	2, 8
Manufactured:	September 2018
Lot Number:	1809H

CHEMICAL ANALYSIS

Item	Spec Limit	Test Result
Rapid Method, X-Ray (ASTM C114)		
SiO2 (%)	—	21.5
Al2O3 (%)	—	3.3
Fe2O3 (%)	—	5.6
CaO (%)	—	62.8
MgO (%)	6.0 max	1.7
SO3 (%)	3.0 max	2.4
Loss on Ignition (%)	3.0 max	0.8
NaEq (%)	0.75 max	0.40
Insoluble Residue	0.75 max	0.31
Free Lime		0.7
C3S (%)	48 min-65 max	55
C3A (%)	3 max	0
C4AF + 2*C3A	24 max	15

PHYSICAL ANALYSIS

Item	Spec Limit	Test Result
Blaine Fineness (m2/kg) *(C 204)*	--	274
Free Fluid Content (%)	5.9 max	5.0
Compressive strength (PSI)		
8 hr 100F	300 min	450
8 h 140F	1500 min	1890
Thickening Time (minutes)		
API Schedule 5: mins to 100bc	90 min - 120 max	112

We hereby certify that at the time of production this Class H cement tests as shown using applicable API standard or reference test procedures.

Certified By:

John Tierney

October 11, 2018

Central Plains Cement Co. LLC - Tulsa Plant
2609 North 145th East Ave
Tulsa, OK 74012
918-437-3902

Figure C.11 Mix 12 Mill Cert