

DEVELOPMENT OF NON-PROPRIETARY  
ULTRA HIGH PERFORMANCE CONCRETE

by

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## ABSTRACT

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. Particularly, UHPC has compressive and post-cracking tensile strengths of around 20 ksi and 0.72 ksi, respectively. Thus, elements made with UHPC are thinner/lighter than elements made with conventional concrete. The enhanced durability properties of UHPC also allow for longer service lives and decreased maintenance costs. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing over 10 times conventional concrete mixes.

The overall objective of this research was to develop and characterize economical non-proprietary UHPC mixes made with materials readily available in Montana. This objective was achieved by first identifying and obtaining suitable/economical materials to be used in UHPC. Specifically, the materials identified and used in this research were simply Type I/II portland cement, class F fly ash, fine masonry sand, silica fume, and high range water reducer. UHPC mixes were then developed/characterized/optimized by using a statistical experimental design procedure (response surface methodology). The mixes developed as part of this research obtained compressive strengths of approximately 20 ksi with flows of 11 inches, and costs of \$300 per cubic yard (excluding freight of materials).

## INTRODUCTION

### Background

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. Thus, elements made with UHPC are thinner/lighter than elements made with conventional concrete. The enhanced durability properties of UHPC also allow for longer service lives and decreased maintenance costs. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes exceeding \$1,000 to \$2,000 per cubic yard, which is about 10 to 20 times the cost of conventional concrete.

### Research Objective

The overall objectives of this project were to develop and characterize non-proprietary UHPC mix designs made with materials readily available in Montana. These mixes are anticipated to be significantly less expensive than commercially available UHPC mixes, thus allowing for the use of UHPC in construction projects in Montana. In particular, the Montana Department of Transportation Bridge Bureau (MDT) is interested in using UHPC as a field-cast jointing material between precast concrete deck panels and girders and between the flanges of adjacent girders.

### Research Scope

These objectives were realized through the following tasks:

- Perform a literature review to summarize material behaviors documented in past UHPC studies.

- Develop suitable mixes for UHPC using response surface methodology (RSM). RSM was used to designate a test matrix of trial batches to be experimentally evaluated. Data from these trial batches were then used to create analytical models consisting of a set of regression equations to be used to investigate the effects of the various constituents on concrete performance, specifically, compressive strength, workability (flow), and cost. These models were ultimately used for optimization of mix designs. This task first consisted of an experimental design with four independent variables (e.g., water-to-cement ratio and sand-to-cement ratio) over a wide range of values. A follow-on experimental design was carried out with three independent variables over a refined range of values. The surfaces resulting from this 3-variable design were then used to obtain optimized mixes that met desired target parameters.

It should be noted that the overall project includes an additional task, which will characterize the long-term mechanical and durability performance of the mix designs.

This task will be completed at a later time.

Chapter 2 of this thesis provides a literature review of previous research conducted on UHPC. Chapter 3 discusses the materials used throughout this study, while Chapter 4 describes the testing methods used during this research. RSM was used to evaluate the effect of each constituent material on the performance of UHPC, and the design of the experiments conducted for this study is presented in detail in Chapter 5. Chapter 6 explains how the models developed in the RSM analyses were used to develop optimized UHPC mixes. Chapter 7 provides a summary of this research and the resultant conclusions.

## LITERATURE REVIEW

Previous research has focused on the development of UHPC mixes, the characterization of their mechanical properties, and the performance of structural elements produced with them. This chapter provides background on the basic material properties of UHPC, followed by a discussion of previous research conducted on the development of non-proprietary UHPC. This chapter concludes with a summary of research conducted specifically pertaining to the proposed application of joining precast concrete elements by MDT.

### Background

UHPC is a term used to describe concrete composites having compressive strengths of approximately 20 ksi, post-cracking tensile strength of at least 0.72 ksi, and a discontinuous pore structure that improves durability by limiting permeability. This material was initially introduced in the early 1990s and was referred to as reactive powder concrete (RPC). Early UHPC designs required the use of special mixing techniques, as well as steam curing. A significant amount of research has been conducted to develop UHPC that can be mixed and cured using more conventional methods (Graybeal & Tanesi, 2007; Wille, Naaman, El-Tawil, & Parra-Montesinos, 2012). The exceptional properties of UHPC are achieved with: (1) low water-to-cement ratios, (2) high particle packing density, (3) high quality aggregates and cements, (4) supplemental cementitious materials, (5) high particle dispersion during mixing, and (6) in some cases the incorporation of fiber reinforcement. High particle packing density (low porosity) is

one of the key principles surrounding UHPC design. Previous research has shown that there is a strong correlation between the mechanical performance of the cementitious paste and its rheological behavior, and changes in particle packing density can be indirectly evaluated with a spread test performed in accordance with ASTM C230 (Wille, Naaman, & Parra-Montesinos, 2011). Achieving the highest possible packing density of the granular constituents is one of the primary factors leading to the reduction of porosity in UHPC. This is achieved through the use of a combination of fine aggregates, silica fume, cement, and supplemental materials (Wille & Boisvert-Cotulio, 2015; Zdeb, 2013). Another important factor in the reduction of porosity of UHPC is a decrease in water-binder ratio. UHPC has a very low water-to-cement ratio ( $w/c$ ), generally ranging from 0.2 to 0.3 by weight. By increasing the particle packing density the volume of water-filled voids within the paste is reduced. By physically trapping less water in voids, more water is available to coat the surface of the particles, which leads to an overall reduction of paste viscosity. This improved rheological behavior allows the  $w/c$  ratio to be reduced while still maintaining adequate workability. This reduction in  $w/c$  is one of the key requirements for producing high-strength paste, and subsequently UHPC (Wille & Boisvert-Cotulio, 2015). Additionally, this low  $w/c$  helps to limit the amount of unreacted water found in the mix, thus decreasing the formation of capillary pores during the setting process and maintaining the necessary low porosity (Zdeb, 2013).

UHPC's high compressive strength, pre- and post-cracking tensile strength, and high durability make it a potentially desirable material for use in structures. Although the initial cost of UHPC far exceeds conventional concrete mixes, the use of UHPC has been

shown to reduce life-cycle costs (Piotrowski & Schmidt, 2012), as the increased durability of UHPC results in a longer service life and decreased maintenance costs. Further, the use of UHPC can result in smaller/lighter structural elements, thus using less material. Oftentimes, high strength steel fibers are required to achieve specified ductility and toughness requirements, and are commonly referred to as ultra-high performance fiber reinforced concrete (UHP-FRC) (Wille & Boisvert-Cotulio, 2015; Wille et al., 2012).

UHPC became commercially available in the U.S. through several proprietary sources around the year 2000. Since its introduction to the commercial market, the use of UHPC in various applications has been the focus of multiple research endeavors. Specifically, UHPC has been used in field-cast connections of prefabricated bridge components (Graybeal, 2010a, 2010b; Yuan & Graybeal, 2014), precast/prestressed girders (Rouse, Wipf, Phares, Fanous, & Berg, 2011), precast piles (Ng, Garder, & Sritharan, 2015; Wipf, Sritharan, Abu-Hawash, Phares, & Bierwagen, 2011), and waffle-type bridge decks (S. Aaleti & Sritharan, 2014; S. R. Aaleti, Sritharan, Bierwagen, & Wipf, 2011; Honarvar, Sritharan, Rouse, & Aaleti, 2016). Additionally, the seismic performance of UHPC elements/connections has been the subject of several research efforts (Lee, Huang, Song, & O'Connor, 2014; Zohrevand & Mirmiran, 2013). It should also be noted that the use of UHPC in transportation applications has been actively researched/promoted by the Federal Highway Administration (FHWA, 2013; Goodspeed, Vanikar, & Cook, 2013; Graybeal, 2006a, 2006b, 2011, 2012; Yuan & Graybeal, 2014, 2015). Of particular interest to the proposed use of UHPC by MDT, this research

included a study on the bond properties of UHPC (Yuan & Graybeal, 2014, 2015), and these findings are discussed below. Although the use of UHPC in these varied applications has been shown to be beneficial, a majority of this research has used commercially available/proprietary mixes, the cost of which has hindered its widespread use in infrastructure projects (as is the case in the proposed use discussed herein). These proprietary mixes range in cost from \$1,000-\$2,000 per cubic yard, which is 10 to 20 times the cost of conventional concrete.

While much of the material optimization of UHPC is done to improve its mechanical and structural behaviors, this optimization also leads to an improvement of its durability. Graybeal & Tanesi (2007) performed a comprehensive study focusing on the performance of UHPC subjected to standard durability tests. They found that the dynamic modulus of tested samples was 96% or greater after performing ASTM C 666 freeze-thaw cycles. After performing ASTM C 1260 tests, the results showed that there is little concern for alkali-silica reaction (ASR) problems in UHPC. Unintended curing of UHPC may take place during the testing process, but due to the low permeability and high silica fume content, UHPC is not susceptible to ASR. UHPC performed exceptionally well during ASTM C 672 scaling test, as well as AASHTO T259 chloride ion penetration tests. Untreated (traditionally cured) specimens showed chloride ion penetration that ranged from very low at 28 days to negligible at 56 days when subjected to ASTM C 1202 testing.

In addition to UHPC, a fair amount of research has been conducted on engineered cementitious composites (ECC). ECC are a class of high-performance fiber-reinforced

cementitious composites. They feature moderate compressive strengths (4.3 to 10.2 ksi) and high ductility while utilizing medium fiber contents. ECC can achieve tensile strain capacities from 3 to 6% compared to commercial UHPC with a tensile strain capacity of 0.1% (Ranade, Li, Stults, Heard, & Rushing, 2013). These large strain capacities are achieved by the development of multiple cracks rather than a continuous increase of crack widths (Folliard, Du, & Trejo, 2003; Wang & Li, 2007). ECC has been successfully utilized for dam repair, bridge deck overlays, coupling beams, and various structural elements (Li, 2004). Extensive research in the development of this material has been conducted by the University of Michigan, including the testing of a full-scale ECC link slab used to replace expansion joints on simply supported bridges (Lepech & Li, 2009).

#### Non-Proprietary UHPC Research

In 2011, Wille et al. (2011) performed research focused primarily on optimizing the proportions of UHPC constituents using materials commercially available in the U.S. In the first phase of the study, the compressive strengths and the rheological behavior of 38 paste mixtures were evaluated. These 38 mixes quantified the effects of various cement types (C), w/c ratio, silica fume (SF) types, as well as the type and dosage rate of high range water reducer (HRWR). Glass powder (GP) was also used as a supplementary cementitious material (SCM) in these mixes. From this study, it was found that a proportion of C:SF:GP of 1.0:0.25:0.25 provided optimum spread (flow) values. It was also noted that adjusting these proportions resulted in very little change of observed compressive strength, but did result in changes in spread, which indicated improved

particle packing density of the paste. Additionally, it was observed that by optimizing particle packing density of the powder constituents, acceptable flow values were observed with HRWR dosage rates of 1 to 8% by cement weight. Reducing the dosage rate to the lowest possible amount also resulted in higher compressive strengths. Once an optimized paste was determined, two types of fine silica sand were introduced at a proportion of 1.4:1.0 by cement weight. This ratio was used to keep the amount of cement low and therefore reduce shrinkage. Compressive strengths of 23.6 to 29.1 ksi were achieved during this phase of the study, with the largest compressive strength observed with the addition of high strength steel fibers at a ratio of 2.5% by volume. Additional research conducted by Wille et al. (2012) included more focused research on the performance of UHP-FRC. By utilizing twisted high strength steel fibers at a proportion of 8% by volume, the researchers were able to achieve compressive strengths up to 42 ksi and tensile stresses up to 5.4 ksi with a peak strain of 1.1%. These values were achieved without the use of any special curing or mixing techniques.

A research study recently completed by (FHWA, 2013) demonstrated promising advances in the development of non-proprietary UHPC mixes with material costs ranging from \$355 to \$500/yd<sup>3</sup> for non-fiber-reinforced mixes (adding fiber reinforcement increases the material costs by \$470/yd<sup>3</sup>). This study used a three-level approach to develop suitable UHPC mix designs for various regions in the U.S. Level 1 focused on optimization of the cementitious paste. This study considered mechanical performance, durability, rheological properties, and economy. The effects of various types of SCMs were also examined. The SCMs used in this study were GP, metakaolin, fly-ash (FA),

limestone powder, and ground granulated blast furnace slag (GGBS). The influences of the various SCMs were monitored using the spread value of the paste and compressive strength, and the pastes in this study were compared to the reference pastes developed by Wille et al. (2011). The second level of the study examined the performance of the cementitious matrix and the effects of different types of aggregates, the size of aggregates (fine and coarse), as well as the ratio of aggregate to cement by weight. Typical aggregate sources for three regions in the U.S. (Northeast, Upper Midwest, and Northwest) were considered, as well as pure quartz aggregate. Similar to the evaluation of the paste, spread values and compressive strengths were used to evaluate the performance of the cementitious matrix. Level 3 of this research examined the effects of five various commercially available fibers and their effect on the performance of the concrete composite. These fibers included both straight and deformed high strength steel fibers, straight polyvinyl alcohol fibers, and alkali resistant glass fibers. The performance of the fiber-reinforced composite was determined primarily by its tensile strength.

Additionally, stress-strain behavior under compressive loading was examined, as well as freeze-thaw resistance in accordance with ASTM C666. The best tensile performance was achieved with straight high strength steel fibers with a maximum tensile strength of 1.15 ksi, and after 108 freeze thaw cycles no visible deterioration was noticed. After completion of this study, four fine-aggregate and three coarse-aggregate UHPC mixes were recommended. The material costs of these composites ranged between \$360 and \$500 per cubic yard and \$355 and \$380 per cubic yard respectively (addition of steel fibers adds approximately \$470 per cubic yard). Compressive strengths of 22.5 to 29 ksi

were achieved with these recommended mixes, and all mixes exceeded the minimum requirement of 0.72 ksi tensile strength.

A recent study completed by the University of Michigan (El-Tawil, 2016) focused on the development of a cost-optimized non-proprietary UHPC and the evaluation of its mechanical and durability properties. Additionally, this study examined the possibility of using UHPC for field-cast joints used in prestressed bridge construction. Cost optimization was performed by investigating the relationship between the type and amount of the most expensive components (silica fume and silica powder) and the performance of the mix. Material performance was measured through compressive and tensile strength test, while durability was evaluated through freeze-thaw and chloride ion penetration testing. The developed mix used a 50:50 blend of Portland Type I cement and GGBS as the cementitious materials. This UHPC also varied from other non-proprietary UHPC developed through other research in that it used no inert or pozzolanic filler such as glass powder. By removing this expensive component from the composite, a 50% reduction in cost was achieved based on the reference mix developed by Wille et al. (Wille et al., 2011) while still obtaining 25.2 ksi compressive and 1.2 ksi post-cracking tensile strengths (1.5% steel fibers by volume). This study also examined bond length of reinforcing steel and joints between precast sections using UHPC, these results are discussed below.

#### Research Related to Proposed Application

Precast bridge elements are especially useful to facilitate accelerated construction schedules that are often desired for highway projects. One issue that arises from the use

of prefabricated bridge components is their reliance on the performance of field-cast connections. These types of connections often pose constructability, durability, and structural performance issues. The use of UHPC in these field cast connections may improve their performance due to its increased durability, and increased strength, which has been shown to improve bond strength.

Yuan & Graybeal (2014) performed research focused on evaluating the bond of reinforcing steel within UHPC concrete, and found that UHPC has enhanced bond performance when compared to conventional high strength concretes. However, it was determined that neither compressive strength ( $f'_c$ ) nor  $f'_c{}^{1/2}$  are effective for predicting the bond strength in UHPC. A comprehensive study on bond length was also performed at the University of Michigan (El-Tawil, 2016) on the UHPC blend that was developed during their research. It was determined that this UHPC blend required significantly less bond length than what is required for normal concrete; however the authors suggest additional research be conducted as their specific results differ from those reported by Yuan & Graybeal (2014) discussed above.

The research conducted by El-Tawil (2016) also included tests of field-cast joints between two pre-cast bridge deck sections using UHPC, and it was determined that a 6-inch joint length could be sufficient for load transfer between the two elements. Graybeal (Graybeal, 2010a, 2010b; Yuan & Graybeal, 2014) also tested field-cast connections and determined that the use of UHPC in such connections can mitigate some of their potential issues. Based on research conducted by Graybeal, full development of reinforcing steel can be achieved in a much shorter length when compared to traditional concrete and

grout mixtures. This allows a designer to specify shorter lap splices and connection details that reduce construction complexity and associated costs. The tensile capacity of UHPC as well as its ability to bond exceptionally well to previously cast concrete has also helped to facilitate the design of simpler connection details. The enhanced properties of UHPC can allow for precast bridge deck closure pours of 6 in. or less in length, allowing them to be effectively designed as narrow shear keys. Full-scale structural testing has shown that field-cast UHPC deck connections can perform equally as well or better than a monolithically cast bridge decks. This research also showed that reinforcement in both transverse and longitudinal UHPC-filled connections does not debond from UHPC, even under severe loading conditions. The results of these studies are particularly useful for the proposed application of non-proprietary UHPC by the MDT Bridge Bureau.

## MATERIALS

To meet the objective of developing cost effective UHPC, it was important to utilize materials that were readily available in Montana. Specifically, the materials used in this research were aggregate, cement, fly ash, silica fume, and HRWR. MDT requested a UHPC mix using only fine aggregate; therefore no coarse aggregates were examined in this research. This chapter discusses the mix ingredients that were chosen for use in this study.

### Aggregates

For this research, masonry sand processed and packaged by QUIKRETE near Billings, MT, was used as the sole aggregate in the UHPC mixes. This sand was chosen due to its fineness, favorable gradation, economy, and availability, all of which are key to the development of a cost-effective UHPC mix design for use in Montana. Additionally, this sand has been washed and dried; therefore no moisture content corrections were performed. As will be discussed in more detail in the following section, sands with more favorable gradations could be produced; however, this would increase the cost of the UHPC mix design.

### Material Characteristics

Previous research has shown that particle packing density of the aggregates can have a substantial impact on the workability of concrete. Research conducted on self-consolidating concrete (SCC) has shown that a standard s-shaped particle size

distribution (PSD) obtained by using the Fuller curve does not provide the proper particle packing density required for SCC, and subsequently UHPC. Use of the Fuller curve in these applications results in mixes with inadequate workability (Brouwers & Radix, 2005). This curve works best for particles sizes larger than 500 $\mu$ m, and therefore does not properly account for the amount of fine particles contained in UHPC mixes. Use of a modified Andreasen and Andersen (A&A) curve (Equation 1) has been found to provide a PSD that is more suited to the particle packing density required for UHPC (Brouwers & Radix, 2005; FHWA, 2013). A PSD that conforms to the following equation provides the optimum particle packing density:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q}$$

Equation 1

The parameter P is the percent of particles passing a sieve with diameter D.  $D_{min}$  and  $D_{max}$  are the minimum and maximum particle sizes respectively. The parameter q ranges from 0 to 1, and was found by Andreasen and Anderson to provide the optimum particle packing density when  $q \approx 0.37$  (Brouwers & Radix, 2005).

In order to keep costs at a minimum, the research team believed that using a fine aggregate conforming to an existing specification would be the best option for UHPC in Montana. Fine aggregate in accordance with ASTM C144 (Standard Specification for Aggregate for Masonry Mortar) was chosen for use in this experiment. The gradation requirements for both ASTM C144 and the modified A&A curve ( $D_{max}=1.18$ mm,

$D_{\min}=0.075\text{mm}$ , and  $q=0.37$ ) are shown below in Table 1. Figure 1 below shows the particle size distribution of the upper and lower limits of ASTM C144, the modified A&A curve, and the gradation curve of the fine aggregate (New Sand) used in the follow-on experimental design (discussed in a later section). It should be noted that the modified A&A curve for particle sizes in the specified range closely matches that of the upper limit provided by the standard specification.

Table 1. Fine Aggregate Gradation Specifications

Sieve Size	Percent Passing (ASTM C144)	Percent Passing (A & A Curve)
No. 4	100	NA
No. 8	95 to 100	NA
No. 16	70 to 100	99
No. 30	40 to 75	65
No. 50	20 to 40	37
No. 100	10 to 25	16
No. 200	0 to 10	0

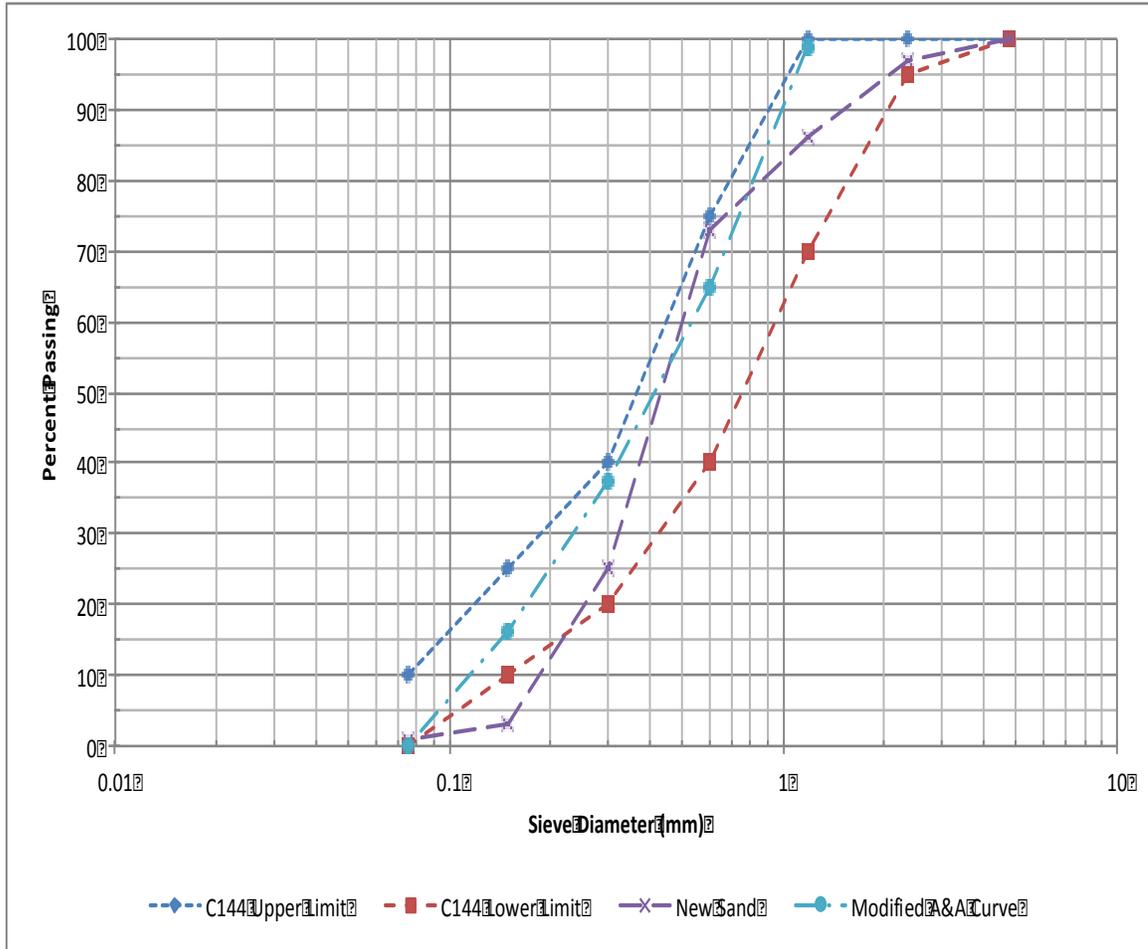


Figure 1. Gradation Limits and Fine Aggregate Gradation Curve

### Portland Cement

Type I/II Portland cement was used in this study, per MDT specifications. The cement was obtained from the CRH cement plant near Trident, MT. The chemical and physical properties of the cement used in this experiment conformed to ASTM C150, as can be seen in Table 2.

Table 2. Chemical and Physical Properties of Portland Cement, ASTM C150

<b>Chemical Properties</b>		
Item	Limit	Result
SiO <sub>2</sub> (%)	NA	20.6
Al <sub>2</sub> O <sub>3</sub> (%)	6.0 max	4.0
Fe <sub>2</sub> O <sub>3</sub> (%)	6.0 max	2.8
CaO (%)	NA	64.2
MgO (%)	6.0 max	2.5
SO <sub>3</sub> (%)	3.0 max	3.1
Loss on Ignition (%)	3.0 max	2.7
Insoluble Residue (%)	0.75 max	0.4
CO <sub>2</sub> (%)	NA	1.7
Limestone (%)	5.0 max	4.0
CaCO <sub>3</sub> in Limestone (%)	70 min	98.0
Inorganic Processing Addition (%)	5.0 max	1.2
<b>Potential Phase Compositions:</b>		
C <sub>3</sub> S (%)	NA	58.0
C <sub>2</sub> S (%)	NA	15.0
C <sub>3</sub> A (%)	8.0 max	6.0
C <sub>4</sub> AF (%)	NA	8.0
C <sub>3</sub> S + 4.75C <sub>3</sub> A (%)	NA	86.5
<b>Physical Properties</b>		
Air Content (%)	12.0 max	29.75
Blaine Fineness (m <sup>2</sup> /kg)	260 min	413
Autoclave Expansion	0.80 max	0.02
<b>Compressive Strength (Mpa) (psi):</b>		
3 days	12.0 (1740)	27.2 (3940)
7 days	19.0 (2760)	35.4 (5130)
Initial Vicat (minutes)	45 - 375	141
Mortar Bar Expansion (%) (C 1038)	NA	
<b>Heat of Hydration (kJ/kg) (cal/g)</b>		
7 days	NA	

### Silica Fume

The silica fume used for this study was MasterLife SF 100 from BASF. The research team chose this product because BASF materials are readily available throughout Montana. The chemical and physical properties of the silica fume used in this study conformed to ASTM C1240 and are given in Table 3.

Table 3. Chemical and Physical Properties of Silica Fume, ASTM C1240

Chemical Properties		
Item	Limit	Result
SiO <sub>2</sub> (%)	85.0 min	92.19
SO <sub>3</sub> (%)	NA	0.31
CL <sup>-</sup> (%)	NA	0.13
Total Alkali (%)	NA	0.85
Moisture Content (%)	3.0 max	0.45
Loss on Ignition (%)	6.0 max	3.07
pH	NA	7.94
Physical Properties		
Fineness (% retained on #325)	10.0 max	0.90
Density (specific gravity)	NA	2.26
Bulk Density (kg/m <sup>3</sup> )	NA	739.32
Specific Surface Area (m <sup>2</sup> /g)	15.0 min	22.42
Accelerated Pozzolanic Activity - w/ Portland Cement (%)	105 Min	140.41

### Fly Ash

Fly ash was selected as the SCM to be used in developing UHPC for this study because of its ease of availability throughout Montana, relatively low cost at approximately \$135 per ton compared to other SCM's such as silica powder at approximately \$800 per ton, as well as its potential to react pozzolanically with the byproducts of the cement hydration process. Additionally, the spherical particle shape can enhance the flow of the paste (FHWA, 2013). Initial trial mixes were conducted using a Class C fly ash. These initial mixes experienced an accelerated set time due to the self-cementing nature of that type of ash. A Class F fly ash from the Coal Creek Station power plant near Underwood, North Dakota was subsequently used throughout this study. The chemical and physical properties of the fly ash used in this experiment in conformed with the requirements of ASTM C618 as shown in Table 4.

Table 4. Chemical and Physical Properties of Fly Ash, ASTM C618

Chemical Properties		
Item	Limit	Result
SiO <sub>2</sub> (%)	NA	54.99
Al <sub>2</sub> O <sub>3</sub> (%)	NA	16.77
Fe <sub>2</sub> O <sub>3</sub> (%)	NA	6.00
Sum of Constituents	70.0 min	77.76
SO <sub>3</sub> (%)	5.0 max	0.5
CaO (%)	NA	11.4
Moisture (%)	3.0 max	0.03
Loss on Ignition (%)	6.0 max	0.06
Available Alkalis, as Na <sub>2</sub> O (%)	NA	0.94
Physical Properties		
Fineness (% retained on #325)	34% max	29.75
Strength Activity Index (% of control)		
7 days	75% min	78
28 days	75% min	93
Water Requirement (% control)	105 % max	95
Autoclave Soundness (%)	0.8% max	0
True Particle Density	NA	2.42

### High Range Water Reducer

As mentioned in Wille et al. (2011), HRWR has a large influence on the fresh properties of concrete. Polycarboxylate ether HRWRs are the most prevalent and readily available water reducers on the market. Three different HRWRs from two separate manufacturers were utilized in preliminary trial mix designs. Due to the similar chemical composition and cost (\$17 to \$26 per gallon), the HRWR providing the best workability and least amount of entrapped air was desirable. CHRYSO Fluid Premia 150 from CHRYSO, Inc. was selected as the HRWR admixture for the concrete mixtures examined in this study because it proved to provide the best release of entrapped air and workability in preliminary trial mixes.

Material Costs

Table 5 provides a summary of approximate material costs and specific manufacturers of the materials used throughout this study. It should be noted that the provided costs do not include freight/shipping or placement costs, as these costs can fluctuate based on market and location.

Table 5. Material Costs

<b>Material</b>	<b>Manufacturer</b>	<b>Cost (per ton)</b>
Fine Aggregate	QUIKRETE	\$26
Portland Cement, Type I/II	CRH	\$145
Silica Fume	BASF	\$840
Fly Ash, Type F	Coal Creek	\$135
HRWR (per gallon)	CHRYSO, Inc.	\$14

## METHODS

This chapter discusses the mix design proportioning method, mixing procedure, flow testing procedure, specimen preparation procedure (i.e. specimen casting, curing, and preparation), and compression strength-testing procedures used throughout this study.

### Mix Design Proportioning Method

The mixes performed during this investigation were proportioned using the absolute volume method utilizing selected values for w/c ratio, HRWR/c ratio, SCM/c ratio (includes silica fume and fly ash, and fixed at a value of 0.5), SF/FA ratio, and Sand/c ratio. This proportioning method was chosen because it accounts for variations in the specific gravities of the various concrete constituents. The specific gravities for materials used in this study are shown in Table 6. A typical mix proportioning sheet is shown in Figure 2. The mix proportioning sheets for all mixes performed in this study can be found in Appendices A-D.

Table 6. Material Specific Gravities

Material	Specific Gravity
Fine Aggregate	2.60
Portland Cement, Type I/II	3.15
Silica Fume	2.20
Fly Ash, Type F	2.00
HRWR	1.04

Mix Specifications		
Mix ID:		RSM 3-3
W/C	0.22	Unitless
HRWR Dosage Rate	0.06	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.50	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	225.5	\$ -	\$ -
HRWR (gallons)	8.73	\$ 14.00	\$ 122.23
Portland Cement	1262.4	\$ 145.00	\$ 91.52
Silica Fume	210.4	\$ 840.00	\$ 88.37
Fly Ash	420.8	\$ 135.00	\$ 28.40
Fine Aggregate	1767.3	\$ 26.00	\$ 22.98
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 353.49

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.65	0.1193
Fine Aggregate	40.35	0.0807
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.027	cu ft	1.67
HRWR	0.04	0.009	cu ft	0.56
Portland Cement	0.24	0.048	cu ft	9.35
Silica Fume	0.06	0.011	cu ft	1.56
Fly Ash	0.12	0.025	cu ft	3.12
Fine Aggregate	0.40	0.081	cu ft	13.09
Steel Fibers	0.00	0.000	cu ft	0.00

244.8 ml

Figure 2. Typical mix proportioning sheet

### Mixing Procedure

Compared to conventional concrete mixtures, UHPC contains a much larger amount of fine particles. To ensure proper particle dispersion and high packing density, special mixing techniques were required to breakup clumps that can develop when mixing these fine materials. The following section discusses the mixing technique used in this research.

A Hobart A200 bench top mixer was used for mixing UHPC in this research. The A200 is a ½ horsepower mixer with a 20-quart capacity bowl. The actual mixer used during this experiment can be seen in Figure 3.

Based on recommendations in Wille et al. (2011) and FHWA (2013), all fine aggregate and silica fume were added to the mixer and dry mixed for 5 minutes. The fly ash and cement were then added and mixed for an additional five minutes. After the dry mixing was completed, one third of the required HRWR was added to the mix water. The water and HRWR mixture was slowly added to the bowl within one minute from the start of pouring. The remaining HRWR was then added within one minute. The UHPC was mixed on low speed until becoming fluid, typically 5-10 minutes depending on mix characteristics, and then the speed was increased and mixing continued until desired fluidity was achieved, typically an additional 5-10 minutes.

The summarized mixing procedure is as follows (FHWA, 2013):

- Mix fine aggregate and silica fume for 5 minutes
- Add fly ash and cement and mix an additional 5 minutes
- Add 1/3 of the HRWR to the mix water

- Add the water and HRWR mixture within 1 minute after pouring has started
- Add the remaining HRWR within 1 minute after pouring has started
- Increase mixing speed
- Continue mixing until desired fluidity is achieved (5-10 additional minutes).



Figure 3. Hobart A200 Mixer

### Flow Testing Procedure

The workability of UHPC mixtures was determined using a spread cone mold in accordance with ASTM C230/C230M (Standard Specification for Flow Table for Use in Tests of Hydraulic Cement), as shown in Figure 4. The spread cone and base plate were both moistened with water prior to testing. The spread cone was then filled and lifted from the base. The remaining material in the cone was scraped off onto the base plate. The material on the base plate was allowed to spread until no more movement was detected. The diameter of the spread was measured in two directions and the average value recorded as the spread value to the nearest  $\frac{1}{4}$  inch.

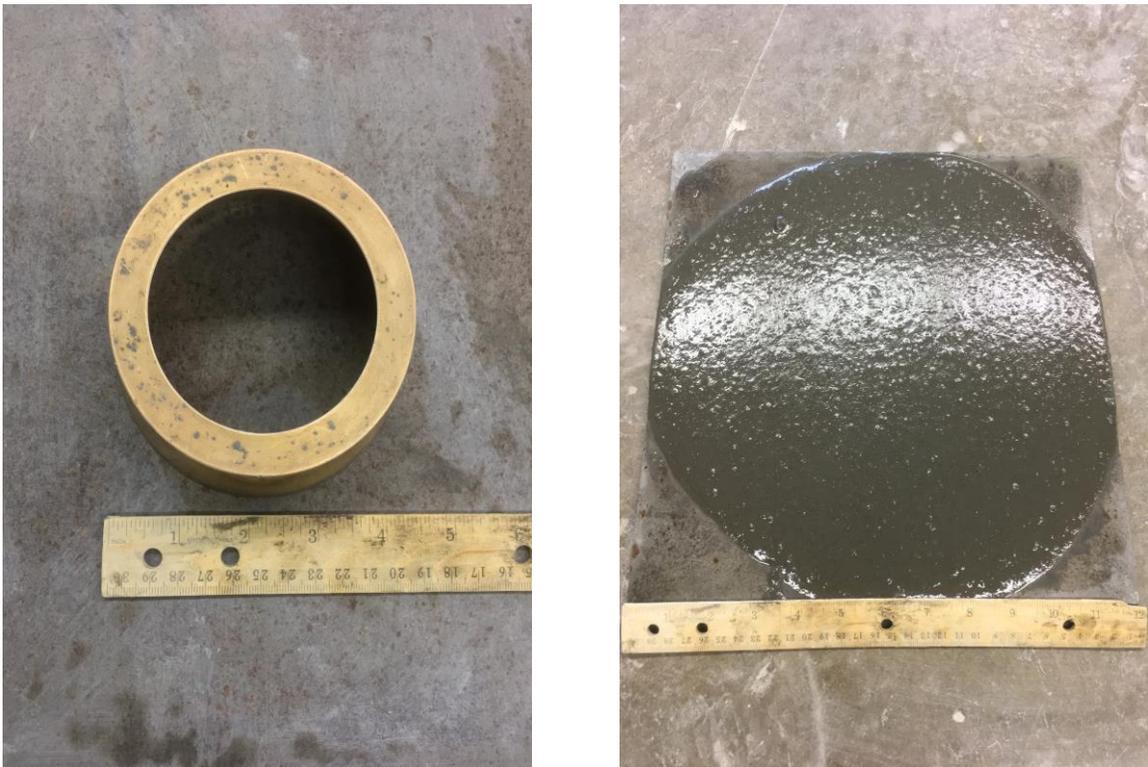


Figure 4. Spread Cone Mold and spread measurement

### Specimen Casting, Curing, Preparation, and Compression Testing Procedures

After performing the flow test, the UHPC was placed into six 3-by-6 inch plastic single-use cylinder molds. The material was added to the molds in two lifts of approximately equal volume. The cylinders were consolidated using a vibration table, and then the plastic covers were placed on the molds. The cylinders were de-molded after approximately 24 hours and placed in a temperature controlled cure room at 100% humidity until compression testing. No special curing methods were used during this experiment.

Before compressive testing, the ends of the cylinders were ground using an automatic cylinder end grinder, shown below in Figure 5, to planeness in accordance with ASTM C39 (Compressive Strength of Cylindrical Concrete Specimens). After preparing the cylinder ends, volume and mass measurements were taken and recorded.



Figure 5. Cylinder end grinder and prepared test specimen

The prepared cylinders were then placed in a Test Mark CM Series hydraulic compression load frame with a 400,000-pound capacity. The cylinders were loaded at a rate of 840 to 1050 lbs/second (approximately 120 to 150 psi/second) until failure based on recommendations from FHWA (2013). Two cylinders from each mix were tested at 7 and 28 days of age respectively. The maximum load at failure was recorded and used to determine the maximum average compressive strength of the UHPC mix at the specified testing intervals. All of the UHPC samples in this experiment were non-fiber reinforced, and due to the sudden and explosive nature of specimen failure, no strain data was collected. Figure 6 below shows a sample before and after failure.

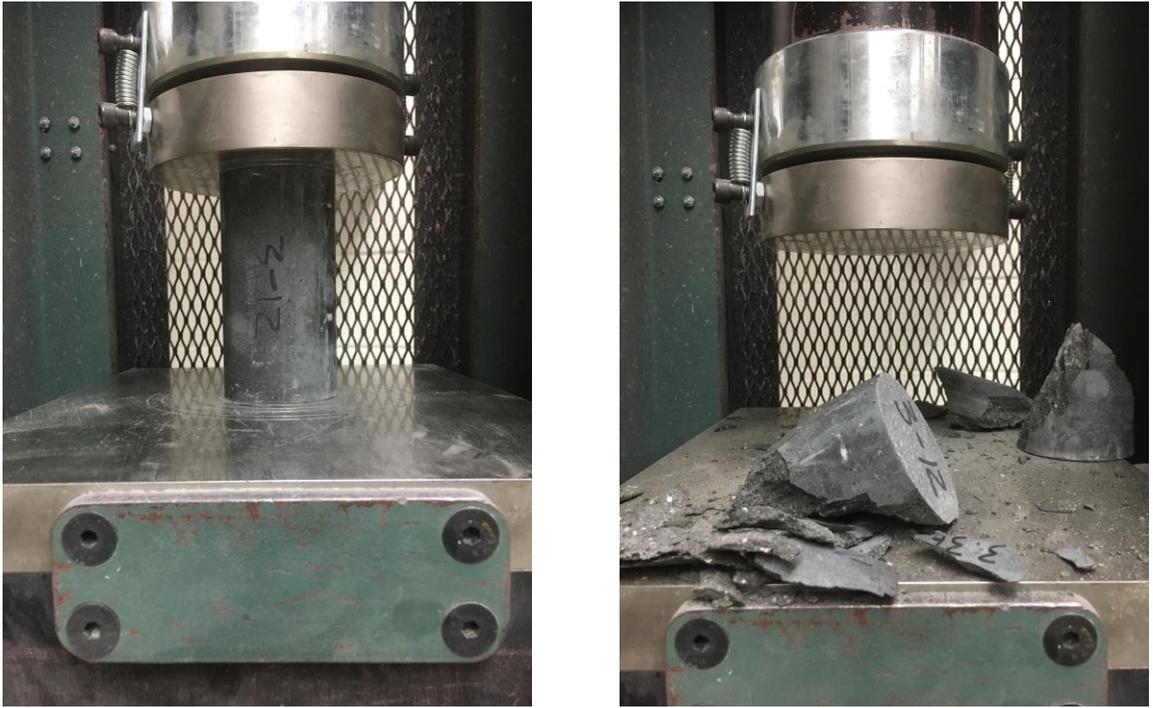


Figure 6. UHPC specimen before and after testing

## EXPERIMENTAL DESIGNS

A statistical experimental design procedure—response surface methodology (RSM)—was used to evaluate the effects of key constituents on concrete performance and then to optimize the mix designs. RSM is a collection of techniques useful for developing, improving, and optimizing processes and mixtures. RSM is commonly used in many applications in which the relationship between input variables and responses are not exactly known, and therefore mechanistic models are not available (Myers & Montgomery, 2002).

Although RSM has been commonly used in the industrial-engineering world for years, it has only been used in concrete mixture design in a limited number of projects over the past decade. The United States Federal Highway Administration (FHWA) conducted an extensive study on the use of statistical methods in concrete mixture design (including RSM) in 2004 (Simon, 2003), and found RSM to be a valuable and effective tool for use in concrete mixture design. Their study concluded with the development and deployment of an internet-based software program to develop and optimize concrete mixtures employing this methodology. RSM was also used successfully by Cihan et al. (Cihan, Guner, & Yuzer, 2013) to evaluate the effect of conventional concrete constituents on concrete compressive strength. Additionally, RSM has proven particularly beneficial in the development and evaluation of non-conventional concrete mixtures. For example, several studies have focused on using RSM for the development and evaluation of self-consolidating (Alqadi, Bin Mustapha, Naganathan, & Al-Kadi, 2012; Ghezal & Khayat, 2002; Khayat, Ghezal, & Hadriche, 2000; Long, Lemieux,

Hwang, & Khayat, 2012), pervious (Sonebi & Bassuoni, 2013), and foamed (Nambiar & Ramamurthy, 2006) concrete mixtures. Furthermore, it has proven useful in concrete mixtures containing alternate materials, such as paper mill residuals (Mohammed, Fang, Hossain, & Lachemi, 2012), recycled aggregate concrete (Lovato, Possan, Coitinho Dal Molin, Masuero, & Ribeiro, 2012), fly ash aggregate concrete (Kockal & Ozturan, 2011), and recycled asphalt pavement aggregate concrete (Berry, Kappes, & Kappes, 2015).

In RSM, the *response* is a performance measure or quality characteristic of the process or of the resulting product from that process. For example, in the case of UHPC mixtures, flow and compressive strength are considered responses. *Input variables* or *independent variables* are subject to the control of the engineer and potentially influence the responses. In UHPC, these input variables could be water-to-cement ratio and HRWR-to-cement ratio.

The procedure of fitting a response surface to a given process involves designating a set of trial batches that encompasses a range of input variables using a statistical experimental design procedure. These trial batches are then carried out, and the various responses are measured. Data from the trial batches are then compiled to create a model consisting of a set of complex regression equations that can accurately depict the behaviors and interactions of the mix ingredients and the specified end responses (Simon, 2003). This model can then ultimately be used for mixture optimization. The experimental design procedure used in this research was the Central Composite Design (CCD). CCD is an augmented factorial design, which is capable of estimating second-order models for each of the responses of interest without requiring the

completion of a three-level factorial experiment. Thus, a reduced number of trial batches, in comparison to other experimental designs, are used to obtain the same statistically verified results (Simon, 2003). In addition to factorial points, this experimental design includes several center point runs to provide an estimate of the pure error, which is associated with the testing procedures. Axial points (outside the region of interest) are also included to allow for efficient estimation of pure quadratic terms in the regression equations.

The experimental design was implemented in multiple phases in this research. First, initial screening mixes were carried out to identify the general effects of proportions of UHPC constituents, and to determine appropriate independent variables and ranges for these variables. An initial CCD-based investigation was then conducted using four independent variables. A follow-on CCD-based study was then carried out for three selected variables over a refined region of interest suggested by the initial and broader CCD investigation. This chapter discusses the responses and independent variables used in this study, the initial 4-variable CCD experiment, and lastly the follow-on 3-variable CCD experiment. Key findings from both studies are presented in this chapter.

### Responses and Variables

The UHPC mixture responses chosen for this experiment were flow, compressive strength, and cost. The target values for these responses were determined by the research team based on recommendations found during the literature review, and are shown in Table 7.

Table 7. Responses and Target Values

<b>Response</b>	<b>Specification</b>
Flow	11 to 13 inches
28-Day Compressive Strength	20 ksi
Cost	Maximum of \$500 per yd <sup>3</sup>

Before moving forward with the experimental design, several “trial” mixes were performed to qualitatively determine how each constituent would generally effect the overall performance of UHPC mixtures. From these trial mixes and knowledge gained during the literature review, the important mix parameters and their subsequent testing ranges were determined.

The selected independent variables were water-to-cement ratio (w/c), sand-to-cement ratio (Sand/c), silica fume-to-fly ash ratio (SF/FA), and HRWR-to-cement ratio (HRWR/c). It should also be noted that 69% of the weight of HRWR was considered as mix water when calculating w/c ratio, as the remaining 31% consisted of solids (per manufacturer specifications).

The initial experimental design used all four of these independent variables over the ranges specified in Table 8. As previously mentioned, a follow on experimental design was carried out over a refined region of interest. For this second experiment, the Sand/c ratio was fixed at 1.40, and the ranges of the remaining variables are provided in Table 8. The fixing of the Sand/c ratio is discussed in detail in a later section.

Table 8. Independent Variables and Ranges

Variable	Initial Design	Follow-on Design
w/c Ratio	0.2 to 0.25	0.22 to 0.26
Sand/c Ratio	1.25 to 1.50	1.40 (fixed)
Silica Fume/Fly Ash Ratio	0.85 to 1.15	0.50 to 1.00
HRWR/c Ratio	0.0275 to 0.0625	0.02 to 0.06

#### 4-Variable CCD

An initial experimental design was carried out for all four independent variables presented in the previous section over the shown range. For four variables, the CCD methodology used in this research designates a total of 27 trial batches, which consist of 16 factorial runs, eight one-factor-at-a-time runs at the axial points, and three center point runs. The design points for this CCD are provided in Table 9, while the 27 trial batches resulting from these design points are provided in Table 10. The factorial points in Table 9 are the bounds of the factorial runs, and designate the *region of interest*, which corresponds to the region in which the resulting response surface models are most applicable.

#### Experimental Design and Measured Responses

Once designated, these mixes were performed in a laboratory setting, and the responses were recorded. The resulting responses are included in Table 10, with the summary statistics for these responses provided in Table 11. Regression equations were then fit to this data, and the resulting response surfaces were evaluated for statistically

significant variables and goodness of fit. The response surfaces for each response have the following general form (Equation 2).

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2^2 + \beta_3x_2 + \beta_4x_2^2 + \dots \beta_8x_4^2 + \beta_9x_1x_2 + \beta_{10}x_1x_3 + \dots \beta_{14}x_3x_4$$

Equation 2

Where  $y$  is the particular response of interest,  $x_1 \dots x_4$  are the independent variables, and  $\beta_0 \dots \beta_{20}$  are coefficients obtained via regression for each response. A similar equation was used for the follow-on 3-variable CCD discussed in a later section. The variables that were determined to be statistically significant (shaded) and the  $R^2$  values for each response surface are also included in Table 11. Statistical significance was assessed by analysis of variance (ANOVA) calculations; in particular, variables with  $p$  values less than 0.05 were designated “significant”. The  $R^2$  values quantify the goodness of fit of the resulting response surface model to the collected data: an  $R^2$  equal to 1.0 corresponds to a perfect fit, while a value close to 0 corresponds to a poor fit. As can be seen in the table, the resulting response surface models for each response had  $R^2$  values greater than 0.85, indicating a good fit for each response.

Table 9. Design Points for Initial Experimental Design

Independent Variable	Axial Low	Axial High	Factorial Low	Center	Factorial High
w/c Ratio	0.2	0.3	0.250	0.250	0.275
Sand/c Ratio	0.75	1.75	1.25	1.00	1.50
Silica Fume/Fly Ash Ratio	0.70	1.30	0.85	1.00	1.15
HRWR/c Ratio	0.0100	0.0800	0.0275	0.045	0.0625

Despite the good fit for each response, the response surface models were found to be difficult to use to develop an optimum UHPC mix (i.e., a mixture with target properties given in Table 7), as the observed properties of the trial mixes were generally too distant from the targeted response values. Most notably, the target responses for flow and compressive strength were 11 to 13 inches and approximately 20 ksi, while the average observed responses from the initial experimental design were 7.2 and 13.2 respectively. This initial study however, provided key insight into the effects of the independent variables on all the responses for the larger region of interest.

Table 10. Summary of Mixes and Measured Results for Initial Experimental Design

Mix ID	Independent Variables				Measured Responses			
	w/c Ratio	Sand/c Ratio	SF/FA Ratio	HRWR/c Ratio	Flow (inches)	28-Day $f'_c$ (ksi)	Cost/yd <sup>3</sup>	Unit Wt. (lb/ft <sup>3</sup> )
27 C	0.250	1.25	1.00	0.0450	8.50	18.05	\$367	140.7
25 C	0.250	1.25	1.00	0.0450	7.00	17.19	\$367	142.7
12	0.275	1.50	1.15	0.0275	4.00	11.29	\$315	139.9
14	0.275	1.00	1.15	0.0625	12.25	17.52	\$430	138.5
16	0.275	1.50	1.15	0.0625	10.25	14.48	\$380	140.5
4	0.225	1.50	1.15	0.0275	4.00	1.67	\$326	n/a
23	0.250	1.25	0.70	0.0450	7.00	14.96	\$347	141.5
17	0.200	1.25	1.00	0.0450	4.00	11.67	\$382	n/a
6	0.225	1.00	1.15	0.0625	7.25	17.36	\$448	140.9
15	0.275	1.50	0.85	0.0625	8.75	16.91	\$363	143.0
1	0.225	1.00	0.85	0.0275	4.00	6.61	\$351	n/a
26 C	0.250	1.25	1.00	0.0450	7.50	17.03	\$367	142.5
20	0.250	1.25	1.00	0.0800	9.50	16.28	\$437	141.0
19	0.250	1.25	1.00	0.0100	4.00	0.41	\$296	n/a
11	0.275	1.50	0.85	0.0275	4.00	3.36	\$299	n/a
24	0.250	1.25	1.30	0.0450	7.75	17.03	\$383	141.7
5	0.225	1.00	0.85	0.0625	11.00	17.57	\$429	142.2
8	0.225	1.50	1.15	0.0625	5.00	16.82	\$393	144.0
2	0.225	1.00	1.15	0.0275	4.00	5.57	\$371	133.6
22	0.250	1.75	1.00	0.0450	5.25	14.26	\$327	142.4
21	0.250	0.75	1.00	0.0450	12.50	18.89	\$421	138.7
13	0.275	1.00	0.85	0.0625	11.50	17.40	\$411	139.6
3	0.225	1.50	0.85	0.0275	4.00	2.66	\$310	n/a
7	0.225	1.50	0.85	0.0625	9.25	18.49	\$377	144.9
9	0.275	1.50	0.85	0.0275	4.00	8.37	\$299	137.8
10	0.275	1.00	1.15	0.0275	5.75	16.32	\$355	139.7
18	0.300	1.25	1.00	0.0450	13.00	18.16	\$354	139.3
Min.	0.200	0.75	0.70	0.0100	4.00	0.41	\$296	133.6
Max.	0.300	1.75	1.30	0.0800	13.00	18.89	\$448	144.9
Average	0.250	1.27	1.00	0.0450	7.22	13.20	\$367	140.7
CV	-	-	-	-	0.43	0.45	0.12	0.02

Table 11. Response Statistics for Initial Experimental Design

Variable	Flow (in)		28-Day $f'c$ (MPa)	
	$R^2 = 0.85$		$R^2 = 0.95$	
	Beta	p	Beta	p
Intercept	18.84	-	-185.35	-
w/c	-113.88	0.003	932.16	0.001
w/c <sup>2</sup>	96.10	0.877	-1408.41	0.050
HRWR/c	206.44	0.000	2116.88	0.000
HRWR/c <sup>2</sup>	-1232.45	0.341	-8237.58	0.000
SF/FA	-18.59	0.562	22.49	0.458
SF/FA <sup>2</sup>	-9.83	0.572	-27.12	0.156
Sand/c	3.01	0.009	26.07	0.003
Sand/c <sup>2</sup>	2.46	0.693	-7.44	0.271
w/c*HRWR/c	819.13	0.448	-4767.87	0.001
w/c*Sf/FA	153.90	0.231	181.08	0.186
w/c*Sand/c	-56.26	0.466	-104.26	0.212
HRWR/c*Sf/FA	-112.71	0.530	-272.02	0.166
HRWR/c*Sand/c	-55.34	0.613	272.37	0.033
SF/FA*Sand/c	2.71	0.831	0.58	0.966

Note: Shaded p-values indicate statistical significance

### Response Surfaces

To evaluate the effects of the independent variables further, response surfaces were plotted as a function of two independent variables (with the other two variables held constant at their center point values).

Figure 7 shows the flow plotted as a function of HRWR/c ratio and w/c ratio, while Figure 8 shows cross-sections of the surface at various HRWR/c ratio values. As can be seen in these figures, as expected, an increase in both HRWR/c ratio and w/c ratio resulted in an increased flow.

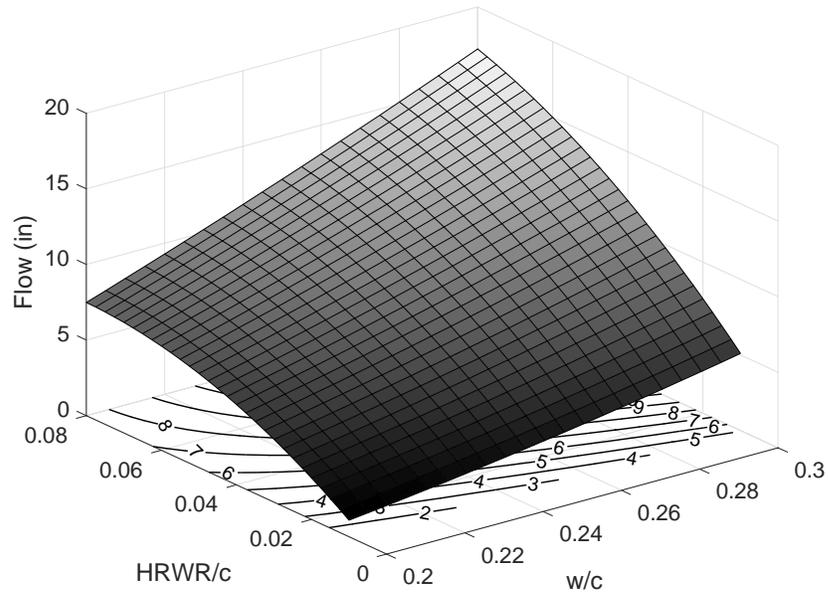


Figure 7. Flow vs. HRWR/c Ratio and w/c Ratio

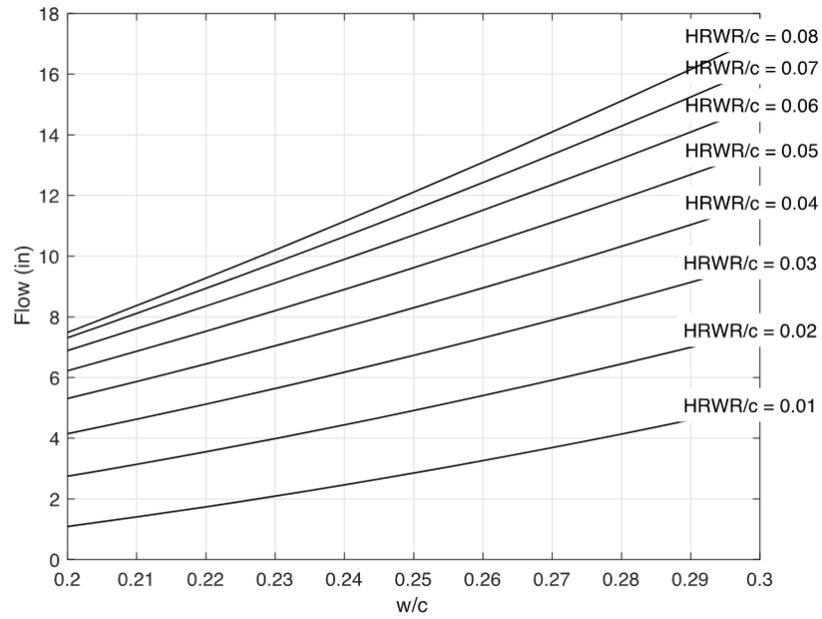


Figure 8. Effect of HRWR/c Ratio and w/c Ratio on Flow

Shown below in Figure 9 is the flow plotted as a function of Sand/c ratio and SF/FA ratio. Figure 10 shows cross-sections of this surface for various values of SF/FA ratio. As can be seen on the surface plot, an increase in both Sand/c ratio and SF/FA ratio resulted in a decrease in flow. The reduction in flow due to an increase of Sand/c ratio is contrary to the observed behavior reported in FHWA (2013) and Wille et al. (2011), which showed no substantial reduction in workability for Sand/c ratios between 0.7 and 1.5. Further, this trend was contrary to behaviors observed in the initial trial batches carried out in the research discussed herein. This observation/result will be discussed in greater detail in the following section.

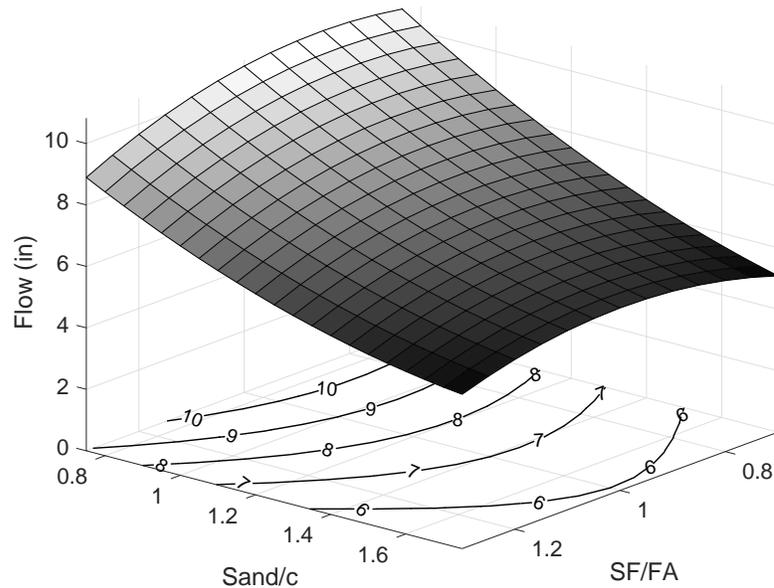


Figure 9. Flow vs. Sand/c Ratio and SF/FA Ratio

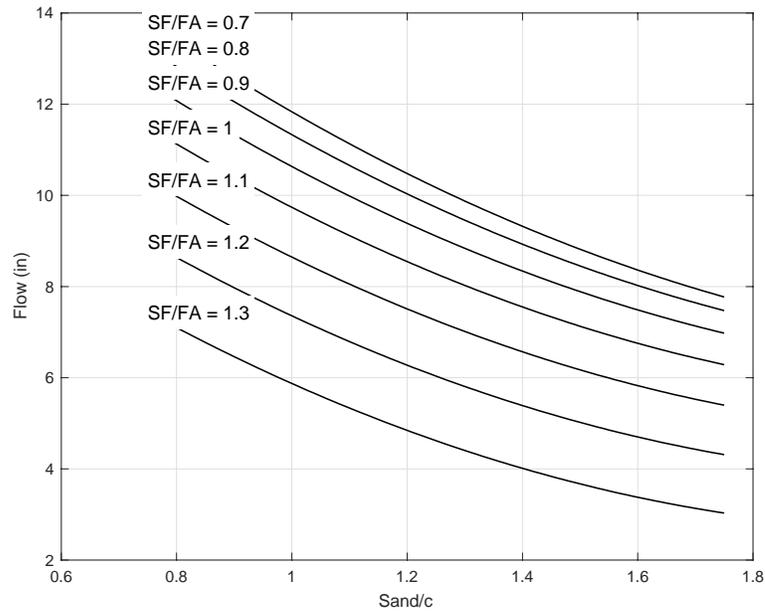


Figure 10. Effect of SF/FA Ratio and Sand/c Ratio on Flow

Figure 11 shows 28-day compressive strength plotted as a function of HRWR/c ratio and w/c ratio, and again cross-sections for this surface are shown in Figure 12. These figures show that both a reduction in HRWR/c ratio or w/c ratio generally results in a decrease in compressive strength. However, this trend is reversed at high HRWR/c and w/c ratios. These trends can be explained by the decreased workability and subsequently decreased consolidation that would result from decreasing the w/c ratio and/or amount of HRWR. This is of particular interest when considering the trend observed for decreasing strength with decreasing w/c ratio, as this trend is contrary to conventional concrete knowledge.

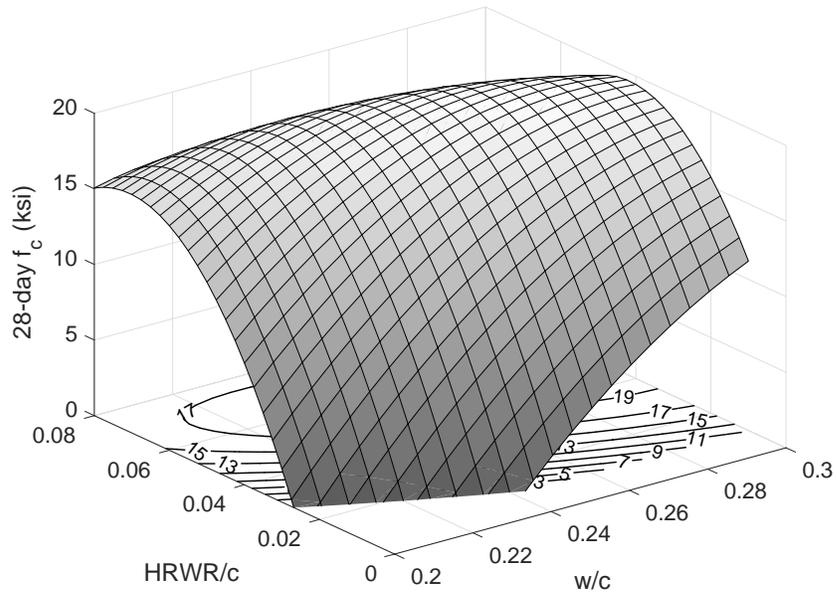


Figure 11. 28-day Compressive Strength vs. HRWR/c Ratio and w/c Ratio

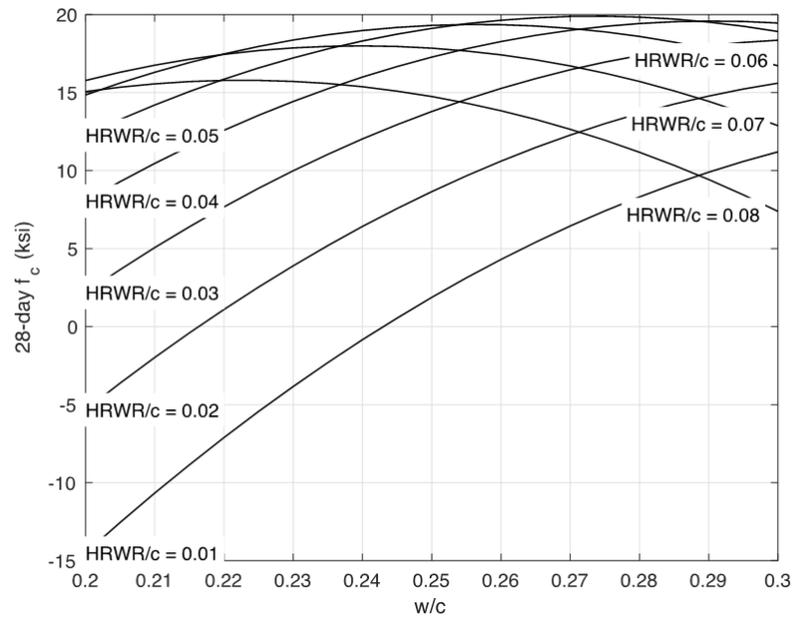


Figure 12. Effect of HRWR/c Ratio and w/c Ratio on 28-day Compressive Strength

Shown in Figure 13 is the 28-day compressive strength surface plotted against Sand/c ratio and SF/FA ratio. The surface cross-sections for various values of SF/FA ratio are shown in Figure 14. These figures show primarily that an increase in the Sand/c ratio results in a decrease in compressive strength. This trend is again contrary to the results observed in FHWA (2013) and Wille et al. (2011), which showed only a small reduction in compressive strength due to an increase in Sand/c ratio. This too will be discussed in the following section.

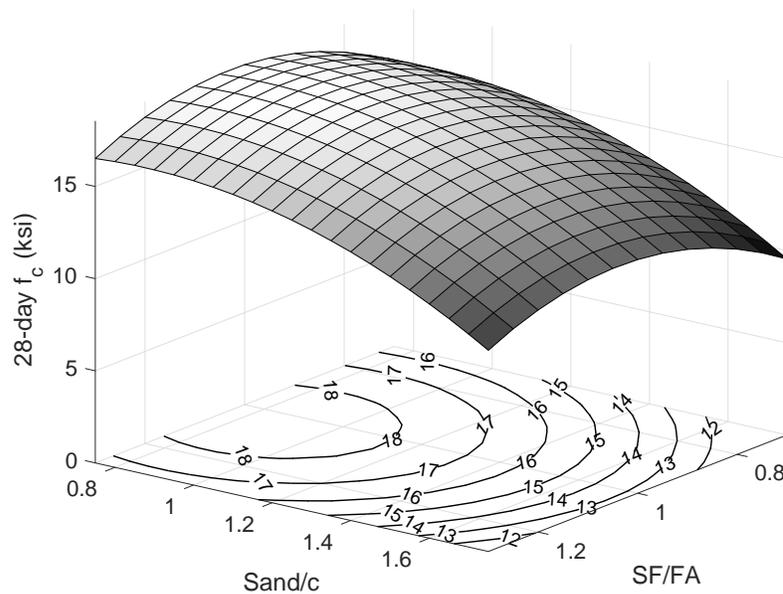


Figure 13. 28-day Compressive Strength vs. Sand/c Ratio and SF/FA Ratio

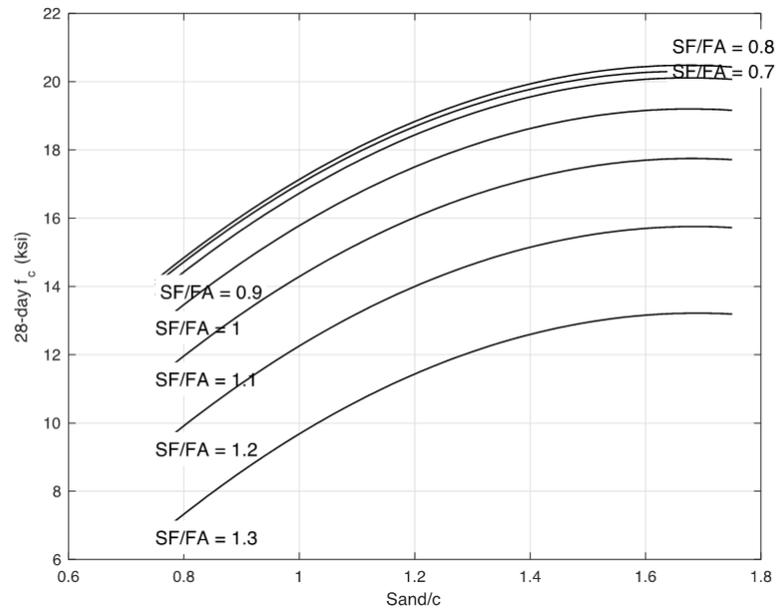


Figure 14. Effect of SF/FA Ratio and Sand/c Ratio on 28-day Compressive strength

### Discussion

As indicated above, the Sand/c ratio was observed to have a significant effect on the workability and compressive strength of UHPC mixes. This finding was contrary to what was found in the literature review and contrary to what was observed in initial trial mixes performed by the research team. This discrepancy was investigated further by (1) comparing the sand used in the 4-variable CCD to a newly obtained sand, and (2) performing additional trial batches to further characterize the effects.

The 4-variable sand is shown in Figure 15, while the newly obtained sand is shown in Figure 16. The physical difference between these two sands can be observed in these figures, with the 4-variable sand appearing to be significantly finer than the new sand.



Figure 15. 4-Variable Sand



Figure 16. New Sand

In addition to this qualitative comparison, an additional sieve analysis (ASTM C136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates) was performed on both sands by a third-party materials testing laboratory. The results of this analysis for the 4-variable and new sand are provided in Figure 17 and Figure 18 respectively. This analysis determined that the 4-variable sand contained 12 percent particles passing the #200 sieve compared to 0.9 percent for the new variable sand. The fineness modulus for the 4-variable and new sand was calculated to be 1.68 and 2.17, respectively. Fine sands typically have a fineness modulus between 2.2 and 2.6. This index number provides a metric to compare the average particle size of the two sands, and shows that the 4-variable sand was, in general, made up of finer particles than the new sand. The smaller average particle size of the 4-variable sand is consistent with the increased water demand of the trial mixes performed with that sand. Additionally, when attempting to perform a specific gravity analysis on the 4-variable sand, the technician reported that the sample “hydrated” at approximately 6% moisture content, suggesting that the aggregate source may have been contaminated or may contain clay particles. This finding prompted the research team to determine the absorption of the aggregate in accordance with ASTM C128 (Specific Gravity and Absorption of Fine Aggregate). The results of that test showed that the 4-variable sand had an absorption of 5.73% by weight versus 1.87% for the new sand.

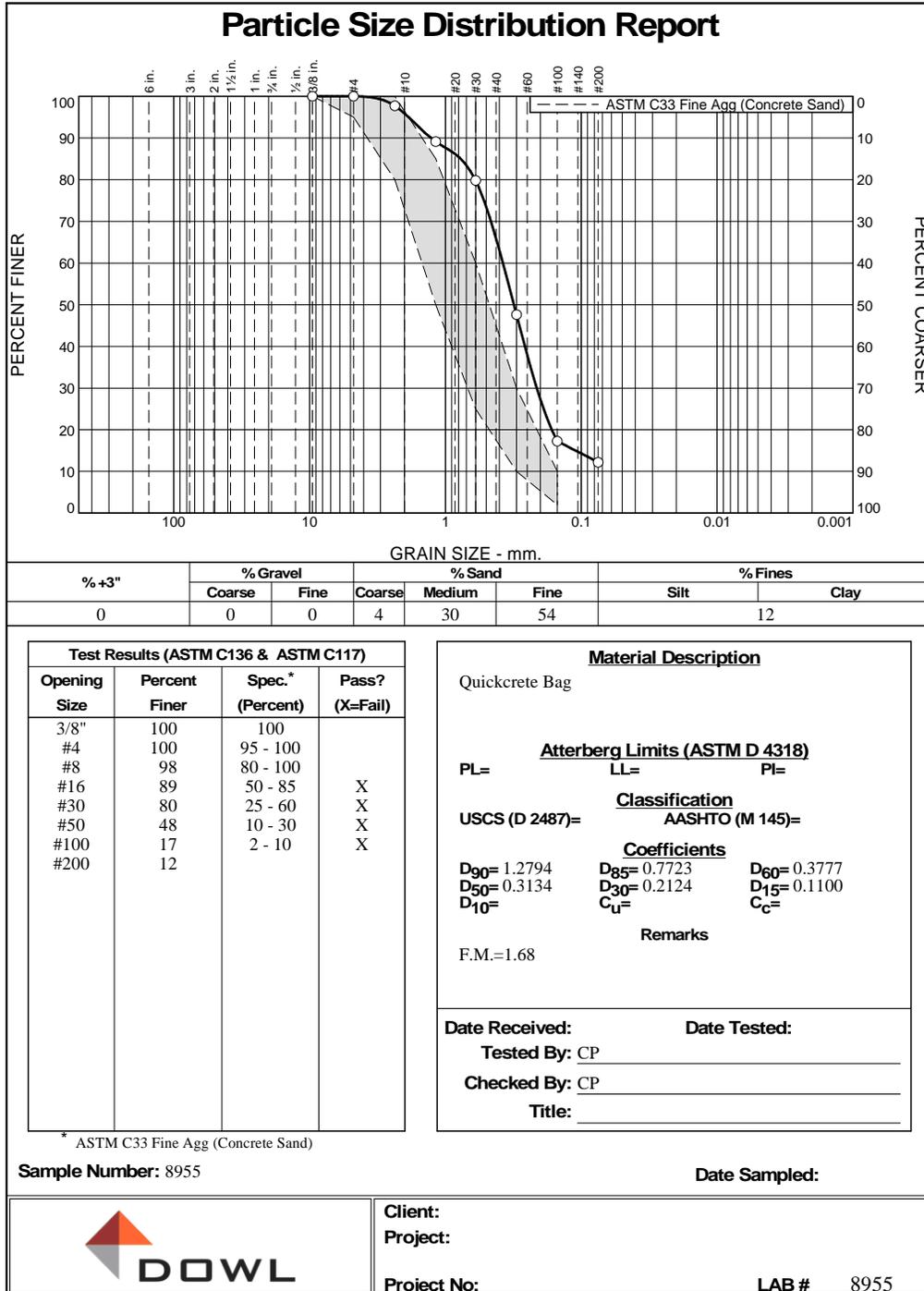


Figure 17. 4-Variable Sand Sieve Analysis

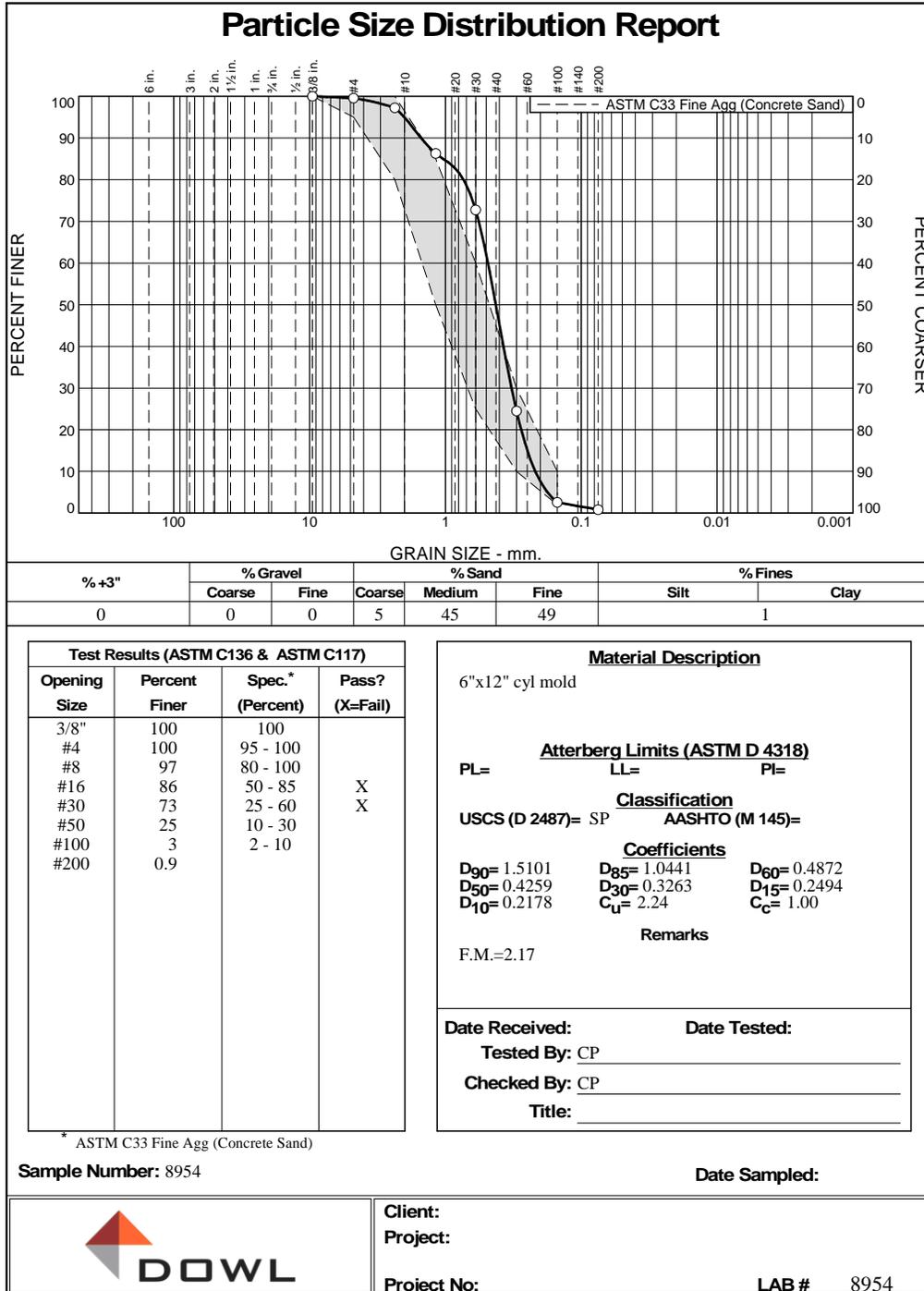


Figure 18. New Sand Sieve Analysis

In addition to comparing the two sands directly, additional trial mixes were performed to more directly examine the effects that varying the Sand/c ratio and varying sand source would have on flow and compressive strength. The results of these mixes are shown in Table 12. As can be observed in this table, the sand source was isolated for two pairs of mix designs: S1-S2, and S3-S4. That is, in these mix pairs the only variable between mixes was sand source. By comparing these mix pairs, it can be observed that the 4-variable sand significantly reduced the workability of the mixes. This would again indicate that the 4-variable sand was both finer and potentially more absorbent.

Table 12. Additional Trial Mix Results

Mix ID	Sand Type	w/c Ratio	Sand/c Ratio	SF/FA Ratio	HRWR/c Ratio	Flow (inches)	28-Day $f'_c$ (ksi)
S1	4-var	0.240	1.00	1.00	0.040	6.75	18.57
S2	New Sand	0.240	1.00	1.00	0.040	11.00	16.95
S3	4-var	0.262	1.50	1.00	0.037	5.75	17.52
S4	New Sand	0.262	1.50	1.00	0.037	12.00	16.62
S5	New Sand	0.262	0.70	1.00	0.037	12.50	16.22
S6	New Sand	0.262	1.00	1.00	0.037	12.50	16.14
S7	New Sand	0.262	1.50	1.00	0.037	12.00	18.98

Because of these findings, the research team determined that the newly obtained sand was more suitable for use in UHPC mixes. However, before moving forward with this new sand, several trial batches were performed to determine if varying Sand/c ratio with this sand would have any impact on workability and/or compressive strength. The results of these trial batches (S5-S7) are provided in Table 12. As can be observed, Sand/c ratio had nearly no effect on flow, and only a moderate effect on strength. A finding that is consistent with previous research and initial trial batches.

It should be noted, that while both sands were packaged by QUICKCRETE and obtained at Lowes in Bozeman, they were acquired at different times. Prior to commencing this project, it was confirmed that the masonry sand carried by Lowes in Bozeman originates from the QUICKCRETE plant in Billings, MT. Upon further investigation, the research team believes that the sand used in the 4-variable CCD most likely came from another source, as it appears to have been transferred from another store.

These findings highlight the importance of selecting an appropriate sand for use in UHPC mixes. The remainder of this research was conducted using this newly obtained sand, and care will be given to confirm the consistency of the sand as the research progresses.

#### Follow-on 3-Variable CCD

Upon completion of the initial 4-variable CCD, a second CCD analysis was carried out with a modified region of interest, a more appropriate/representative sand, and a fixed Sand/c ratio of 1.4. This Sand/c ratio is based on suggestions made in Wille et al. (2011) and FHWA (2013) to provide adequate strength and protection against shrinkage, and was shown in initial trial batches to be adequate. This follow-on CCD produced mixtures with properties more consistent with target responses the research team desired for UHPC.

### Experimental Design and Measured Responses

The design points for this CCD are provided in Table 13. A total of 16 trial batches, which consisted of eight factorial runs, six one-factor-at-a-time runs at the axial points, and two center point runs. The mix parameters for these 16 trial batches are provided in Table 14, along with the resulting measured responses for each mix. Summary statistics for these mixes are provided in Table 15, with the statistically significant variables shaded. The responses used in this experimental design were: flow, 28-day compressive strength, 56-day compressive strength, and cost. 56-day compressive strength was added as a response to further evaluate the strength gain of the UHPC mixtures over time, as it was believed that the high level of supplementary cementitious materials was retarding the strength gains of the UHPC mixes in this research.

Table 13. Design Points for Follow-on Experimental Design

<b>Independent Variable</b>	<b>Axial Low</b>	<b>Axial High</b>	<b>Factorial Low</b>	<b>Center</b>	<b>Factorial High</b>
w/c Ratio	0.206	0.274	0.220	0.240	0.260
Silica Fume/Fly Ash Ratio	0.330	1.17	0.50	0.75	1.00
HRWR/c Ratio	0.011364	0.078636	0.02	0.045	0.06

Table 14. Summary of Mixes and Measured Results for Follow-On Experimental Design

Mix ID	Independent Variables			Measured Responses			
	w/c Ratio	SF/FA Ratio	HRWR/c Ratio	Flow (inches)	28-Day $f_c$ (ksi)	56-Day $f_c$ (ksi)	Cost/yd <sup>3</sup>
3-12	0.240	0.75	0.079	12.00	17.4	17.4	\$405.69
3-9	0.206	0.75	0.045	9.50	21.1	21.1	\$349.33
3-11	0.240	0.75	0.011	4.00	4.3	8.0	\$274.65
3-13	0.240	0.33	0.045	12.50	20.2	20.5	\$299.91
3-8	0.260	1.00	0.060	12.75	19.7	21.3	\$380.26
3-3	0.220	0.50	0.060	10.50	17.3	19.7	\$353.49
3-14	0.240	1.17	0.045	11.25	18.3	20.2	\$365.65
3-15 C	0.240	0.75	0.045	13.00	19.5	20.1	\$340.61
3-6	0.260	1.00	0.020	4.00	12.8	14.9	\$303.33
3-16 C	0.240	0.75	0.045	13.00	17.9	18.8	\$340.61
3-2	0.220	1.00	0.020	4.00	16.2	16.2	\$312.52
3-10	0.274	0.75	0.045	13.50	17.8	19.1	\$332.32
3-4	0.220	1.00	0.060	10.50	18.0	18.6	\$391.69
3-5	0.260	0.50	0.020	4.00	15.8	15.8	\$266.20
3-7	0.260	0.50	0.060	13.50	18.5	20.1	\$343.21
3-1	0.220	0.50	0.020	4.00	14.1	15.4	\$274.24
Min.	0.206	0.330	0.011	4.00	4.3	8.0	\$266.20
Max.	0.274	1.170	0.079	13.50	21.1	21.3	\$405.69
Average	0.240	0.750	0.043	9.50	16.8	18.0	\$333.36
CV	-	-	-	0.42	0.3	0.2	0.13

As can be seen in Table 15, the resulting response surface models for each response had  $R^2$  values greater than 0.83, indicating a good fit for each response. In particular, the  $R^2$  values of 0.96 and 0.90 for flow and 56-day compressive strength, respectively, indicates the ability of the statistical model to accurately predict performance of UHPC mixtures.

Table 15. Response Statistics for Follow-on Experimental Design

Variable	Flow (in)		7-Day $f'_c$ (ksi)		28-Day $f'_c$ (ksi)		56-Day $f'_c$ (ksi)	
	$R^2 = 0.96$		$R^2 = 0.83$		$R^2 = 0.84$		$R^2 = 0.90$	
	Beta	p	Beta	p	Beta	p	Beta	p
Intercept	-138.78	-	-13.10	-	62.57	0.000	94.82	-
w/c	1078.03	0.065	50.55	0.899	-455.85	0.529	-643.80	0.783
w/c <sup>2</sup>	-2277.38	0.073	102.38	0.944	998.30	0.561	1221.25	0.392
HRWR/c	225.66	0.000	413.28	0.004	172.40	0.003	281.55	0.001
HRWR/c <sup>2</sup>	-5415.42	0.002	-4170.38	0.021	-4383.73	0.032	-4793.73	0.010
Sand/c	24.05	0.602	30.52	0.658	16.58	0.744	-18.06	0.935
Sand/c <sup>2</sup>	-12.92	0.109	0.61	0.949	5.39	0.629	9.46	0.317
w/c*HRWR/c	1731.61	0.179	-38.89	0.980	1114.51	0.550	997.55	0.514
w/c*Sand/c	-18.75	0.846	-135.00	0.313	-115.00	0.451	15.00	0.902
HRWR/c*San								
d/c	-23.89	0.802	46.01	0.717	54.31	0.713	3.07	0.980

Note: shaded p-values indicate statistical significance

From this 3-variable CCD, it was determined that only HRWR had a statistically significant effect on the flow and compressive strength of UHPC over the targeted range. This finding was somewhat unexpected, as w/c ratio is known to significantly affect workability and strength in conventional concrete mixtures.

### Response Surfaces

As was done in the 4-variable CCD, the resulting response surfaces are plotted as a function of two independent variables below. In these figures, the third variable was held constant at its center point value.

Shown in Figure 19 is the 56-day compressive strength plotted against SF/FA ratio and w/c ratio. As can be observed in this figure, SF/FA ratio and w/c ratio had little effect on the compressive strength within the region of interest of this study, and much of the surface sits above the target compressive strength of 20 ksi.

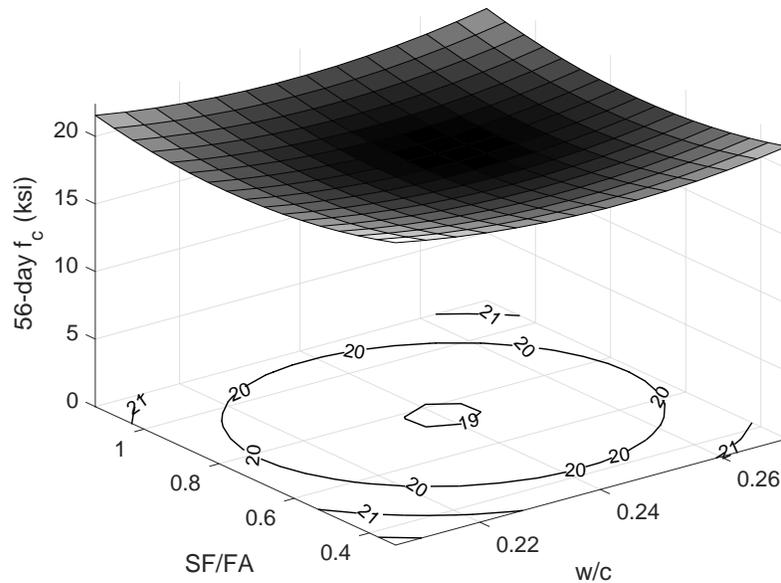


Figure 19. 56-day Compressive Strength vs. SF/FA Ratio and w/c Ratio

Figure 20 shows 56-day compressive strength plotted as a function of HRWR/c ratio and SF/FA ratio. Like the trend observed in Figure 19, SF/FA ratio appears to have a relatively low impact on the compressive strength of the UHPC mixture. It can also be observed in this figure that HRWR/c ratio has a significant effect on compressive strength at values above 0.06. This trend is also observed for HRWR/c ratios less than 0.04. This behavior might be expected, as HRWR/c ratio directly affects the workability of the mix, which subsequently affects consolidation.

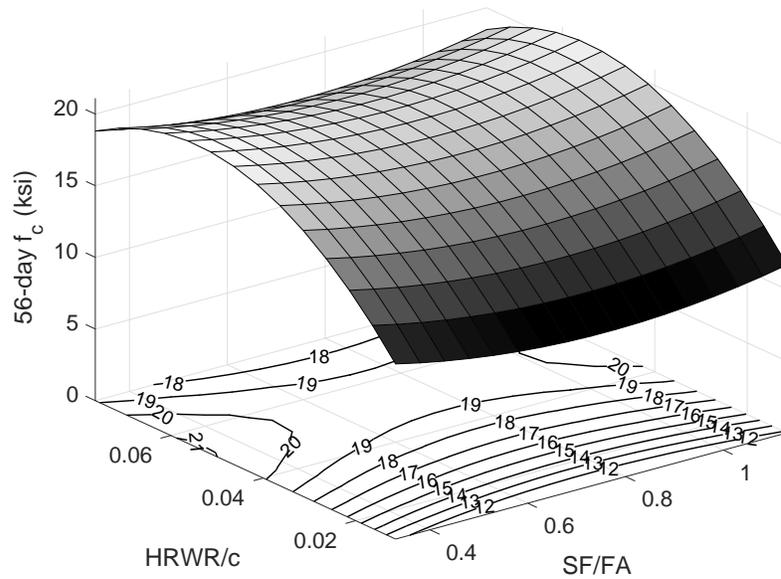


Figure 20. 56-day Compressive Strength vs. HRWR/c Ratio and SF/FA Ratio

56-day compressive strength is plotted as a function of HRWR/c ratio and w/c ratio in Figure 21. As can be observed, w/c had little impact on compressive strength, while HRWR/c ratio values below 0.04 can be observed to have a significant effect (decreasing strength with decrease in HRWR/c ratio).

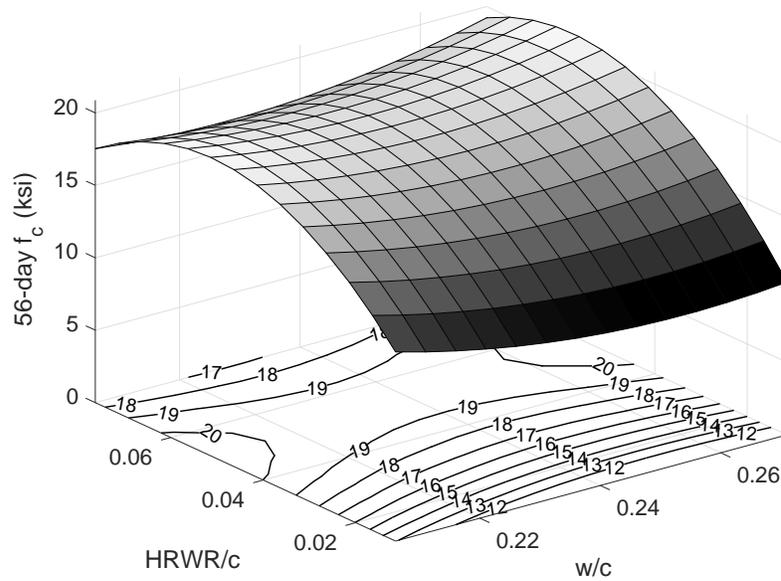


Figure 21. 56-day Compressive Strength vs. HRWR/c Ratio and w/c Ratio

Figure 22 shows the flow surface plotted as a function of SF/FA ratio and w/c ratio. SF/FA ratio can be observed to have little impact on the flow of the UHPC mixture within the range examined, while an increase w/c ratio generally resulted in an increase in flow (consistent with conventional understanding).

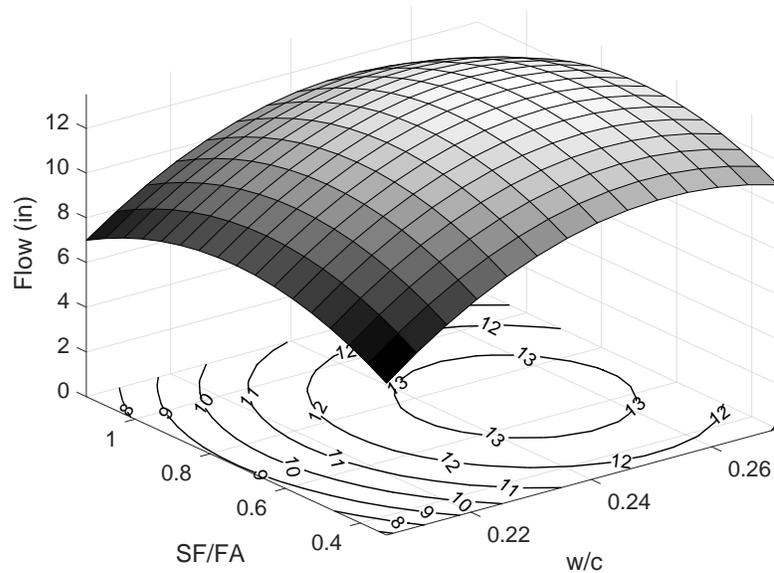


Figure 22. Flow vs. SF/FA Ratio and w/c Ratio

Flow is plotted as a function of HRWR/c ratio and SF/FA ratio in Figure 23. As previously observed, SF/FA ratio had little impact on UHPC flow within the range examined. However, HRWR/c ratio values below 0.04 had a significant impact on the workability of the mix, with decreasing HRWR/c ratio resulting in decreased flow, as might be expected. A reduction in flow was also observed for HRWR/c ratios greater than 0.06.

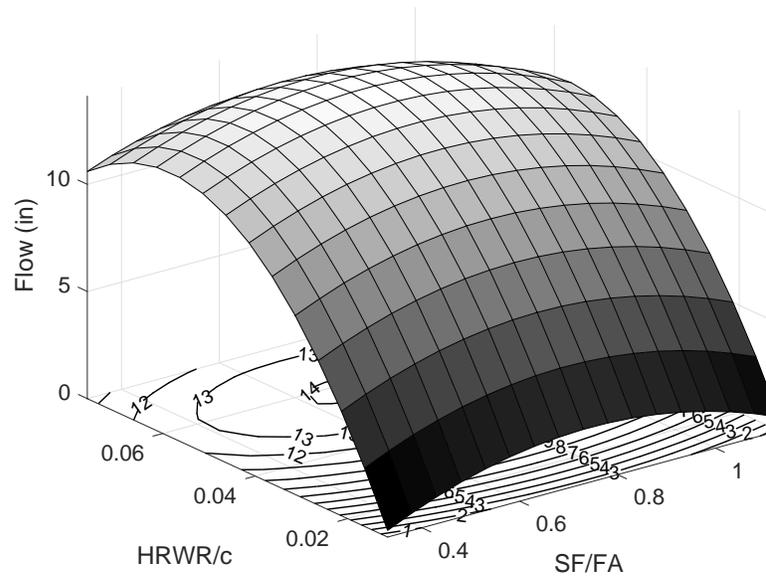


Figure 23. Flow vs. HRWR/c Ratio and SF/FA Ratio

Figure 24 shows flow plotted as a function of HRWR/c ratio and w/c ratio. As can be seen in the figure, both of these independent variables had a significant impact on the workability of the mixture. A HRWR/c ratio was observed to have a substantial effect on flow at values greater than 0.06 and less than 0.04.

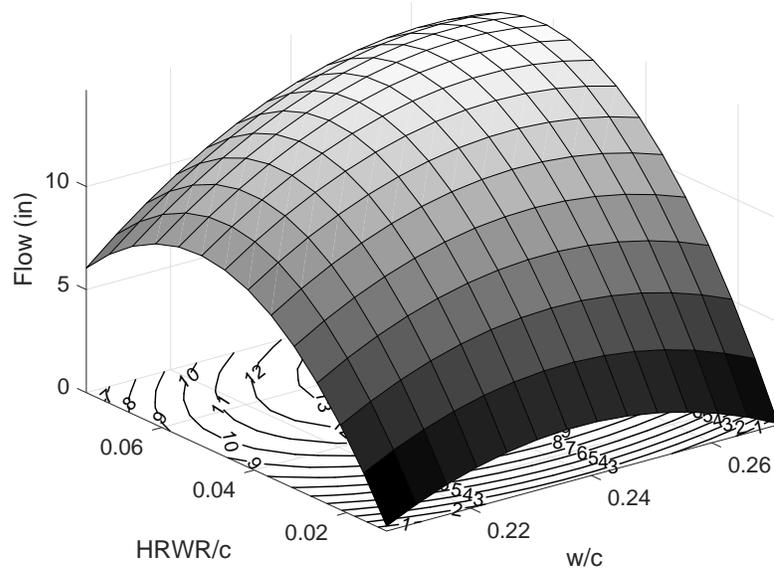


Figure 24. Flow vs. HRWR/c Ratio and w/c Ratio

The 7-, 28-, and 56-day compressive strength surfaces (bottom, middle, and top respectively) are plotted vs. the various concrete mix parameters in Figures 25 through 27 to provide a general comparison between the surfaces and to investigate whether or not predicted effects vary over time. Generally speaking, the observed trends do not appear to vary over time, with the exception of the trends observed in Figure 25, where the effects of SF/FA ratio and w/c ratio observed at 7-days vary from those observed at 28 and 56 days. This variation may be associated with the high levels of SCMs used in these mixes, and the effects that these SCMs may be having on strength gain.

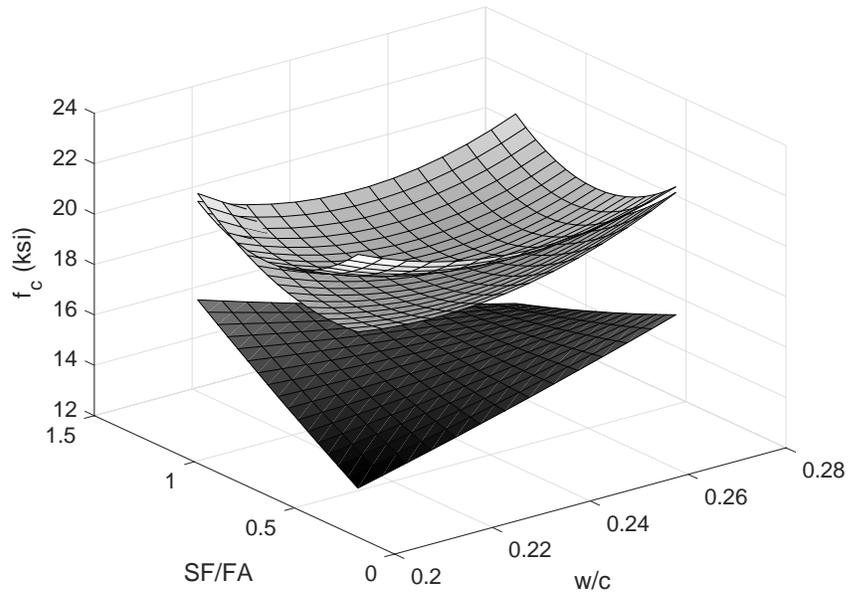


Figure 25. Compressive Strength vs. SF/FA Ratio and w/c Ratio

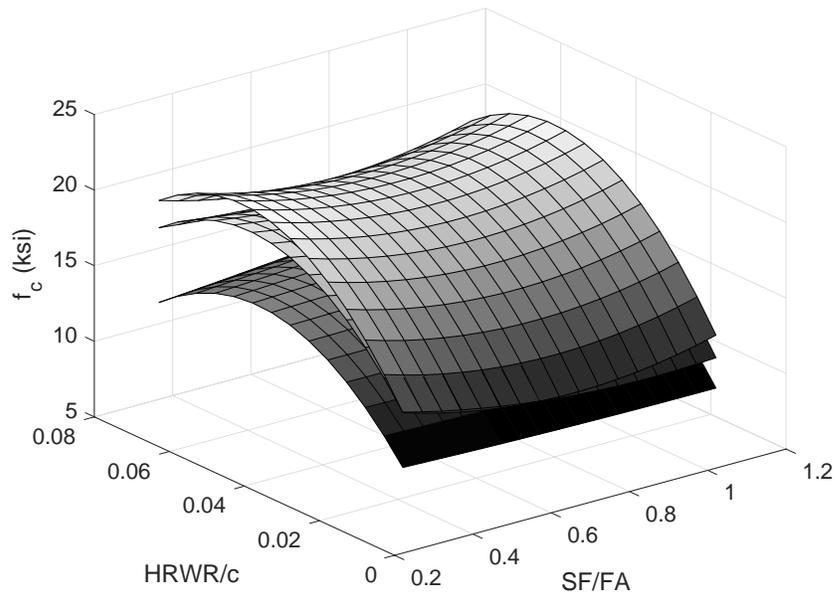


Figure 26. Compressive Strength vs. HRWR/c Ratio and SF/FA Ratio

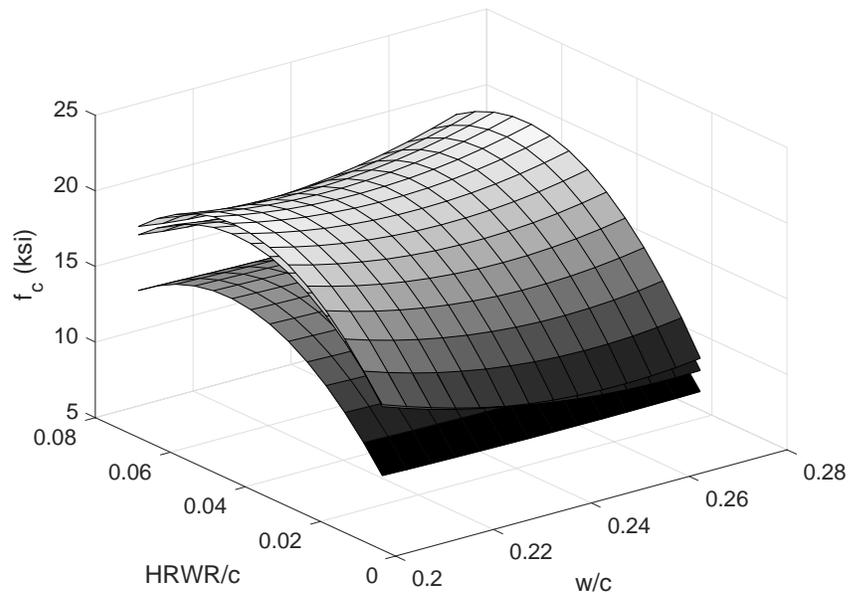


Figure 27. Compressive Strength vs. HRWR/c Ratio and w/c Ratio

Figure 28 shows cost response surface as a function of HRWR/c ratio and SF/FA ratio. Silica fume and HRWR are the most expensive components (by weight) used in these UHPC mixes. It should be noted that the cost response has a direct relationship to the mix parameters, and therefore has a perfect fit ( $R^2 = 1.0$ ). This response was used as a mechanism for developing low-cost economical mixes, as will be discussed in the following chapter.

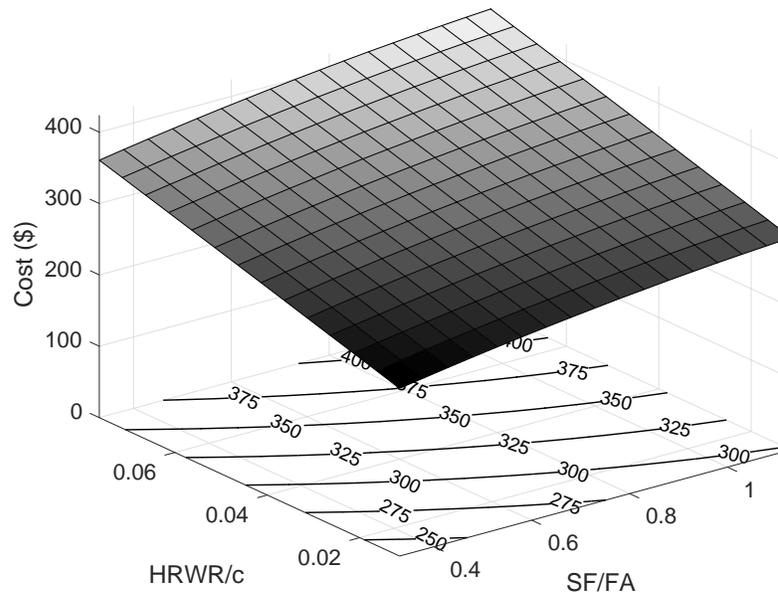


Figure 28. Cost vs. HRWR/c Ratio and SF/FA Ratio

### Discussion

The response surfaces generated from this 3-variable CCD fit the data well, and were determined to be appropriate for optimization, as target responses were achievable within or near the prescribed region of interest (no extrapolation). The process used and the results of this optimization are discussed in the following chapter.

## OPTIMIZATION AND SELECTION OF MIXES

In the previous chapter, response surfaces were developed for flow, compressive strength, and cost, as functions of the independent variables: w/c ratio, HRWR/c ratio, and SF/FA ratio. In this chapter, these surfaces are used to obtain mixes that meet target response parameters. Specifically, UHPC mixes with flows of 11 inches, 56-day compressive strengths of 20-21 ksi, and costs of \$300-350 were targeted.

To obtain targeted results for numerous responses, RSM analyses often employ the use of desirability functions. These functions allow the analyst to prioritize the response values during the optimization procedure (Myers & Montgomery, 2002). A separate desirability function is created for each response, and then the geometric mean of the desirability functions is calculated to obtain a single optimized composite response (Myers & Montgomery, 2002).

A simpler and more robust process was used in this research to obtain mixes that met the desired response parameters. The response surface equations were simultaneously solved for the unknown independent variables for a targeted set of response values. For example, the three response surface equations for the follow-on 3-variable CCD (flow, compressive strength, and cost) were solved for the three independent variables (w/c ratio, HRWR/c ratio, and SF/FA ratio) to yield the specified response values. The developed response surfaces are nonlinear, and thus it should be noted that multiple solutions for the targeted values might exist. During the analyses, only solutions that fell within or near the designated region of interest were considered to be valid. Additionally, in cases where an exact solution does not exist, this methodology

does not allow the analyst to compromise between the target responses, whereas the use of desirability functions allows for this compromise.

### Mix Development and Trial Mixes

The second approach described above was used to develop several mixes with similar targeted response parameters. The first mix (3M1) was developed by targeting specified values for flow (11 inches), 56-day compressive strength (20 ksi), and material cost (\$300 per cubic yard). 3M2 and 3M3 were developed by targeting the same flow and cost (11 inches and \$300, respectively) but a higher 56-day compressive strength of 21 ksi. A fourth mix (3M4) was developed using a higher targeted material cost of \$350 per cubic yard while still targeting a flow of 11 inches and 56-day compressive strength of 20 ksi. It should be noted that these trial mixes utilized the same Sand/c ratio ratio of 1.4 that was used in the follow-on experimental design. Table 16 shows a summary of the 4 mixes resulting from these targeted responses. Included in this table are the predicted responses and their respective 95% confidence intervals (CI).

Table 16. Optimized Mix Summary and Results

Variable/Response	3M1		3M2		3M3		3M4	
w/c Ratio	0.236		0.237		0.274		0.216	
SF/FA Ratio	0.38		0.31		0.43		0.68	
HRWR/c Ratio	0.042		0.046		0.043		0.049	
	Predicted (95% CI)	Measured						
Flow (inches)	11.00 (8.9 to 13.1)	12.00	11.00 (8.2 to 13.8)	11.25	11.00 (7.0 to 15.0)	12.50	11.0 (9.2 to 12.9)	10.50
7-day $f'_c$ (ksi)	14.4 (11.6 to 17.3)	13.0	14.6 (10.9 to 18.3)	14.1	16.3 (11.0 to 21.6)	14.4	15.2 (12.7 to 17.6)	11.2
28-day $f'_c$ (ksi)	18.7 (15.5 to 22.0)	16.2	19.4 (15.1 to 23.7)	18.2	20.7 (14.6 to 26.9)	18.2	19.1 (16.2 to 22.0)	-
56-day $f'_c$ (ksi)	20.0 (17.3 to 22.7)	-	21.0 (17.5 to 24.5)	-	21.0 (15.9 to 26.0)	-	20.0 (17.6 to 22.3)	-

Note: "-" denotes measured response that was not available at time of writing

It should be noted that the low target cost of \$300/cubic yard used in 3M1-3M3 resulted in mixes with fairly low silica fume content. In mix 3M4, the cost was increased to \$350/cubic yard, which yielded a mix with significantly more silica fume. This result was specifically targeted, as silica fume is known to reduce porosity and thus increase durability. It should also be noted that all four of these mixes fall just outside of the designated region of interest used in the 3-variable CCD. 3M1, 3M2, and 3M3 have SF/FA ratios that fall just outside the factorial low and factorial high points shown previously in Table 13. Similarly, 3M3 and 3M4 have w/c ratios that again fall just outside of the factorial points. The relatively large bounds on the 95% confidence intervals provided in Table 16 can be attributed to this fact.

To validate the parameters obtained in Table 16 for the various mixes, and to visualize these solutions, the flow, cost, and 28-day compressive strength response surface contours are overlaid in Figures 29-32. In these figures, the SF/FA ratios are set at their optimum values. The figures indicate the target responses with solid red lines, and the intersection of these contours occurs at the optimum w/c ratio and HRWR/c ratios.

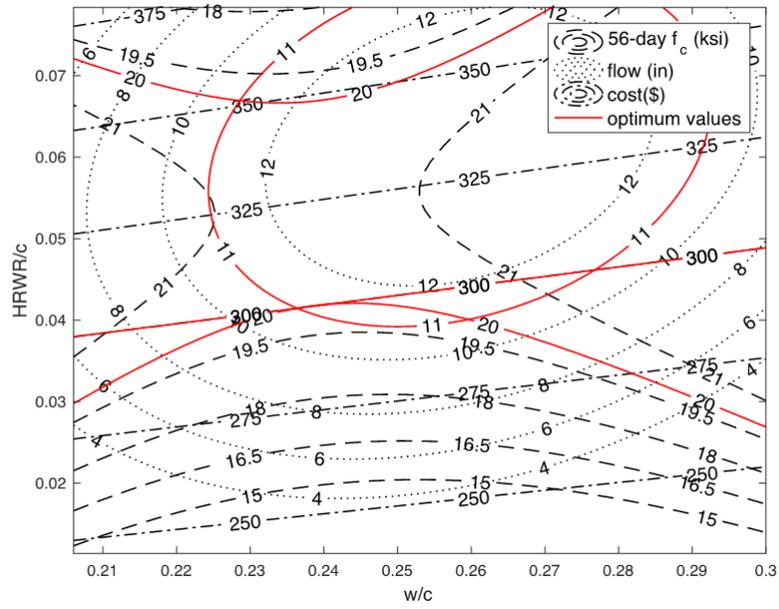


Figure 29. 3M1 Optimization Contour Lines

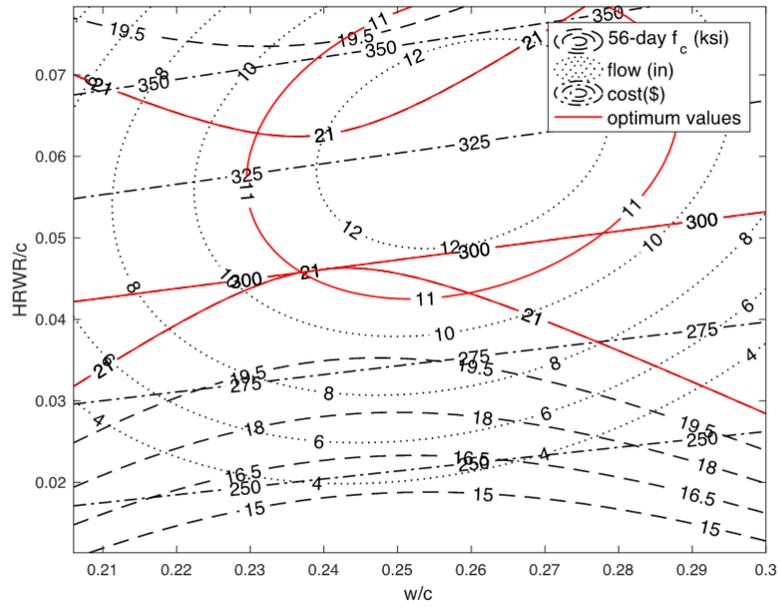


Figure 30. 3M2 Optimization Contour Lines

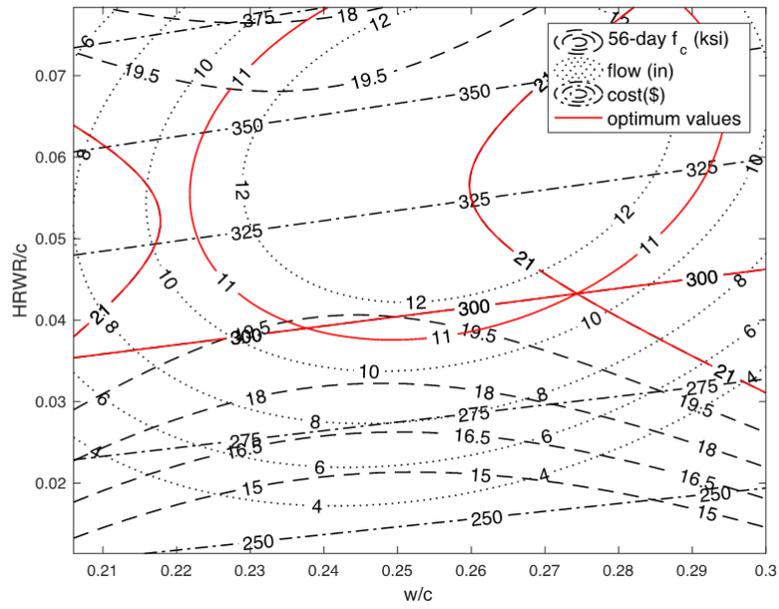


Figure 31. 3M3 Optimization Contour Lines

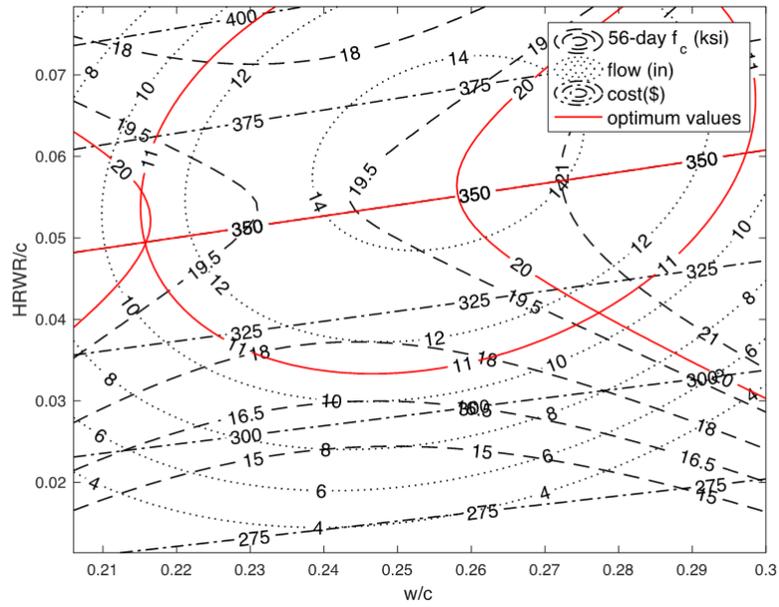


Figure 32. 3M4 Optimization Contour Lines

After development, the aforementioned mixes were carried out in a laboratory setting to verify their performance against the predicted values, and also to validate the effectiveness of this mix design methodology. Overall, the response surface models developed in this study reasonably predicted the responses and served as an efficient tool for developing mix designs. Included in Table 16 are the measured response obtained from these mixes. As can be observed in this table, all measured responses fell easily within the 95% confidence interval, with the exception of the 7-day compressive strength of 3M4, which is slightly below the lower bound. However, it is worth noting that all of the measured compressive strengths were lower than the predicted values. For 3M1, the measured flow was within 1.0 inch of the predicted value, and the measured 7- and 28-day compressive strengths are within 10 and 14 percent of the predicted strengths, respectively. 3M2 had a measured flow within 0.25 inches of the predicted value, while the 7- and 28-day strengths were within 4 and 7 percent of the respective predicted values. 3M3 had a measured flow within 1.5 inches of the predicted flow, and measured 7- and 28-day compressive strengths within 12 percent of their predicted values. 3M4 had a measured flow within 0.5 inches of the predicted value, and a 7-day compressive strength within 26 percent of the predicted value. As mentioned previously, this was the only measured response to fall outside of the 95% CI. It should be noted that this table is not complete, as at the time of writing, the research team was waiting for 28-day compressive strengths for 3M4 and 56-day compressive strengths for 3M1-3M4.

It should be noted that inaccuracies in the statistical model as well as the inherent variability in standard concrete sampling and testing methods are responsible for the discrepancy between the measured and predicted responses in these mixes.

## SUMMARY AND CONCLUSIONS

The primary objective of this research was to develop economical, non-proprietary UHPC mixes with materials readily available in Montana. In this research, suitable materials for use in UHPC were first obtained and characterized. Initial trial mixes were then prepared and tested to determine a suitable range of mix parameters, followed by a characterization of individual material properties through the completion of numerous trial mixes. A 4-variable CCD was then carried out to characterize the effects of materials and mix parameters on UHPC performance. A follow-on 3-variable CCD was then carried out using a more appropriate sand and a refined region of interest determined from the results of the 4-variable CCD. Results of the 3-variable CCD were then used to determine optimized mixes that met specified performance criteria. These optimization mixes were then carried out, and resulting responses were compared to the predicted responses from the 3-variable CCD response surfaces. Based on this investigation, the following conclusions can be made.

- Suitable materials for use in UHPC can be easily obtained in the state of Montana. Specifically, a Type I/II cement from the CRH plant in Trident, MT was used throughout this study, which proved to be acceptable for use in UHPC. Montana-sourced fine sand that meets standard masonry sand specifications worked well in mixes performed during this study, and has a particle size distribution similar to distributions recommended for SCC and UHPC mix designs. During this study, it was determined that UHPC performance can be very sensitive to the physical makeup of the sand, and potential contaminants within it. Therefore, care should be taken when selecting an appropriate sand for use in this application. A class F fly ash from the Coal Creek Station near Underwood, ND worked well as a SCM filler in the UHPC mixes. It was determined during this study that class C fly ashes may not be suitable for use in UHPC due to the self-cementitious nature of this ash, which resulted in greatly accelerated set times, and reduced workability. The silica fume and HRWR were the most expensive components used in the UHPC mixes developed in this research, and were the most difficult materials to obtain

in Montana. The silica fume was obtained from BASF, and the HRWR was obtained from CHRYSO, Inc., both of which can be obtained in bulk from these companies.

- The initial 4-variable CCD proved to be an efficient tool for characterizing the effect of the various concrete constituents on the performance of UHPC. The resulting surfaces fit the data well, with  $R^2$  values of at least 0.85 for all responses. Despite the good fit, the response surfaces obtained from this this CCD were not suitable for optimization due to the fact that extrapolation was required to obtain the target responses. That being said, this analysis revealed an unexpected effect of Sand/c ratio on flow and compressive strength. This trend was later attributed to the physical nature and potential contamination of the sand used in this 4-variable CCD. This analysis also proved beneficial in determining the refined region of interest to be used in the follow-on 3-variable CCD.
- The follow-on 3-variable CCD also proved to be a very useful tool for characterizing the effects of the various concrete constituents on the performance of UHPC, and also proved useful for optimization. This CCD was carried out with a more appropriate sand over a refined region of interest, which was more suitable for optimizing mixes to meet the desired target responses. In this CCD, the resulting response surfaces again fit the data well, with  $R^2$  values of at least 0.83 for all responses. In regards to optimization, four mixes were obtained that will likely meet the desired performance criteria: \$300-\$350 cost, 11-inch flow, and 20-21 ksi strength at 56 days. The measured responses from these mixes were all within 12 percent of the predicted responses, and all easily within the 95% confidence interval
- Overall, this research demonstrated that self-consolidating, non-proprietary UHPC mixes can be made with materials readily available in the state of Montana.

Further research is currently being conducted to characterize the mechanical properties and durability of the mixes resulting from this investigation. In addition, the effects of including a chemical accelerator and steel fibers are being evaluated.

Accelerators are being investigated in an attempt to achieve higher strengths at 28 days, and steel fibers are being investigated as the increased tensile strength resulting from their use may be beneficial in the proposed use in field-cast joints. Investigation into the

field application of these aforementioned UHPC mixes (i.e. scaled up production/batching and placement) may be the focus of future research endeavors.

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APPENDICES

APPENDIX A

4 VARIABLE RSM MIX PROPORTIONS

Mix Specifications		
Mix ID:		1
W/C	0.225	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.67	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	295.6	\$ -	\$ -
HRWR (gallons)	4.55	\$ 14.00	\$ 63.68
Portland Cement	1435.0	\$ 145.00	\$ 104.04
Silica Fume	329.7	\$ 840.00	\$ 138.46
Fly Ash	387.8	\$ 135.00	\$ 26.18
Fine Aggregate	1435.0	\$ 26.00	\$ 18.65
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 351.01

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.24	0.1345
Fine Aggregate	32.76	0.0655
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.035	cu ft	2.19
HRWR	0.02	0.005	cu ft	0.29
Portland Cement	0.27	0.054	cu ft	10.63
Silica Fume	0.09	0.018	cu ft	2.44
Fly Ash	0.12	0.023	cu ft	2.87
Fine Aggregate	0.33	0.066	cu ft	10.63
Steel Fibers	0.00	0.000	cu ft	0.00

127.5 ml

Figure 33. Mix 1 Proportions

Mix Specifications		
Mix ID:		2
W/C	0.225	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.67	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	296.1	\$ -	\$ -
HRWR (gallons)	4.56	\$ 14.00	\$ 63.78
Portland Cement	1437.1	\$ 145.00	\$ 104.19
Silica Fume	384.3	\$ 840.00	\$ 161.42
Fly Ash	334.2	\$ 135.00	\$ 22.56
Fine Aggregate	1437.1	\$ 26.00	\$ 18.68
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 370.62

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.19	0.1344
Fine Aggregate	32.81	0.0656
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.035	cu ft	2.19
HRWR	0.02	0.005	cu ft	0.29
Portland Cement	0.27	0.054	cu ft	10.64
Silica Fume	0.10	0.021	cu ft	2.85
Fly Ash	0.10	0.020	cu ft	2.48
Fine Aggregate	0.33	0.066	cu ft	10.64
Steel Fibers	0.00	0.000	cu ft	0.00

127.7 ml

Figure 34. Mix 2 Proportions

Mix Specifications		
Mix ID:		3
W/C	0.225	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.58	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	254.0	\$ -	\$ -
HRWR (gallons)	3.91	\$ 14.00	\$ 54.72
Portland Cement	1233.0	\$ 145.00	\$ 89.39
Silica Fume	283.3	\$ 840.00	\$ 118.97
Fly Ash	333.2	\$ 135.00	\$ 22.49
Fine Aggregate	1849.5	\$ 26.00	\$ 24.04
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 309.62

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	57.78	0.1156
Fine Aggregate	42.22	0.0844
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.030	cu ft	1.88
HRWR	0.02	0.004	cu ft	0.25
Portland Cement	0.23	0.046	cu ft	9.13
Silica Fume	0.08	0.015	cu ft	2.10
Fly Ash	0.10	0.020	cu ft	2.47
Fine Aggregate	0.42	0.084	cu ft	13.70
Steel Fibers	0.00	0.000	cu ft	0.00

109.6 ml

Figure 35. Mix 3 Proportions

Mix Specifications		
Mix ID:		4
W/C	0.225	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.58	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	254.4	\$ -	\$ -
HRWR (gallons)	3.91	\$ 14.00	\$ 54.79
Portland Cement	1234.6	\$ 145.00	\$ 89.51
Silica Fume	330.2	\$ 840.00	\$ 138.67
Fly Ash	287.1	\$ 135.00	\$ 19.38
Fine Aggregate	1851.8	\$ 26.00	\$ 24.07
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 326.42

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	57.73	0.1155
Fine Aggregate	42.27	0.0845
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.030	cu ft	1.88
HRWR	0.02	0.004	cu ft	0.25
Portland Cement	0.23	0.047	cu ft	9.14
Silica Fume	0.09	0.018	cu ft	2.45
Fly Ash	0.09	0.017	cu ft	2.13
Fine Aggregate	0.42	0.085	cu ft	13.72
Steel Fibers	0.00	0.000	cu ft	0.00

109.7 ml

Figure 36. Mix 4 Proportions

Mix Specifications		
Mix ID:		5
W/C	0.225	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.68	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	258.9	\$ -	\$ -
HRWR (gallons)	10.25	\$ 14.00	\$ 143.57
Portland Cement	1423.4	\$ 145.00	\$ 103.20
Silica Fume	327.0	\$ 840.00	\$ 137.34
Fly Ash	384.7	\$ 135.00	\$ 25.97
Fine Aggregate	1423.4	\$ 26.00	\$ 18.50
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 428.59

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.50	0.1350
Fine Aggregate	32.50	0.0650
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.92
HRWR	0.05	0.010	cu ft	0.66
Portland Cement	0.27	0.054	cu ft	10.54
Silica Fume	0.09	0.018	cu ft	2.42
Fly Ash	0.11	0.023	cu ft	2.85
Fine Aggregate	0.32	0.065	cu ft	10.54
Steel Fibers	0.00	0.000	cu ft	0.00

287.6 ml

Figure 37. Mix 5 Proportions

Mix Specifications		
Mix ID:		6
W/C	0.225	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.67	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	259.3	\$ -	\$ -
HRWR (gallons)	10.27	\$ 14.00	\$ 143.78
Portland Cement	1425.5	\$ 145.00	\$ 103.35
Silica Fume	381.2	\$ 840.00	\$ 160.12
Fly Ash	331.5	\$ 135.00	\$ 22.38
Fine Aggregate	1425.5	\$ 26.00	\$ 18.53
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 448.16

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.46	0.1349
Fine Aggregate	32.54	0.0651
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.92
HRWR	0.05	0.010	cu ft	0.66
Portland Cement	0.27	0.054	cu ft	10.56
Silica Fume	0.10	0.021	cu ft	2.82
Fly Ash	0.10	0.020	cu ft	2.46
Fine Aggregate	0.33	0.065	cu ft	10.56
Steel Fibers	0.00	0.000	cu ft	0.00

288.0 ml

Figure 38. Mix 6 Proportions

Mix Specifications		
Mix ID:		7
W/C	0.225	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.58	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	222.7	\$ -	\$ -
HRWR (gallons)	8.82	\$ 14.00	\$ 123.50
Portland Cement	1224.5	\$ 145.00	\$ 88.78
Silica Fume	281.3	\$ 840.00	\$ 118.15
Fly Ash	330.9	\$ 135.00	\$ 22.34
Fine Aggregate	1836.7	\$ 26.00	\$ 23.88
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 376.64

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	58.07	0.1161
Fine Aggregate	41.93	0.0839
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.026	cu ft	1.65
HRWR	0.04	0.009	cu ft	0.57
Portland Cement	0.23	0.046	cu ft	9.07
Silica Fume	0.08	0.015	cu ft	2.08
Fly Ash	0.10	0.020	cu ft	2.45
Fine Aggregate	0.42	0.084	cu ft	13.61
Steel Fibers	0.00	0.000	cu ft	0.00

247.4 ml

Figure 39. Mix 7 Proportions

Mix Specifications		
Mix ID:		8
W/C	0.225	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.58	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	223.0	\$ -	\$ -
HRWR (gallons)	8.83	\$ 14.00	\$ 123.66
Portland Cement	1226.0	\$ 145.00	\$ 88.89
Silica Fume	327.9	\$ 840.00	\$ 137.71
Fly Ash	285.1	\$ 135.00	\$ 19.25
Fine Aggregate	1839.0	\$ 26.00	\$ 23.91
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 393.41

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	58.02	0.1160
Fine Aggregate	41.98	0.0840
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.026	cu ft	1.65
HRWR	0.04	0.009	cu ft	0.57
Portland Cement	0.23	0.046	cu ft	9.08
Silica Fume	0.09	0.018	cu ft	2.43
Fly Ash	0.08	0.017	cu ft	2.11
Fine Aggregate	0.42	0.084	cu ft	13.62
Steel Fibers	0.00	0.000	cu ft	0.00

247.7 ml

Figure 40. Mix 8 Proportions

Mix Specifications		
Mix ID:		9
W/C	0.275	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	304.5	\$ -	\$ -
HRWR (gallons)	3.77	\$ 14.00	\$ 52.79
Portland Cement	1189.5	\$ 145.00	\$ 86.24
Silica Fume	273.3	\$ 840.00	\$ 114.77
Fly Ash	321.5	\$ 135.00	\$ 21.70
Fine Aggregate	1784.2	\$ 26.00	\$ 23.20
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 298.69

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.27	0.1185
Fine Aggregate	40.73	0.0815
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.26
HRWR	0.02	0.004	cu ft	0.24
Portland Cement	0.22	0.045	cu ft	8.81
Silica Fume	0.07	0.015	cu ft	2.02
Fly Ash	0.10	0.019	cu ft	2.38
Fine Aggregate	0.41	0.081	cu ft	13.22
Steel Fibers	0.00	0.000	cu ft	0.00

105.7 ml

Figure 41. Mix 9 Proportions

Mix Specifications		
Mix ID:		10
W/C	0.275	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.69	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	352.9	\$ -	\$ -
HRWR (gallons)	4.37	\$ 14.00	\$ 61.17
Portland Cement	1378.3	\$ 145.00	\$ 99.93
Silica Fume	368.6	\$ 840.00	\$ 154.82
Fly Ash	320.5	\$ 135.00	\$ 21.64
Fine Aggregate	1378.3	\$ 26.00	\$ 17.92
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 355.46

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	68.54	0.1371
Fine Aggregate	31.46	0.0629
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.21	0.042	cu ft	2.61
HRWR	0.02	0.004	cu ft	0.28
Portland Cement	0.26	0.052	cu ft	10.21
Silica Fume	0.10	0.020	cu ft	2.73
Fly Ash	0.10	0.019	cu ft	2.37
Fine Aggregate	0.31	0.063	cu ft	10.21
Steel Fibers	0.00	0.000	cu ft	0.00

122.5 ml

Figure 42. Mix 10 Proportions

Mix Specifications		
Mix ID:		11
W/C	0.275	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	304.5	\$ -	\$ -
HRWR (gallons)	3.77	\$ 14.00	\$ 52.79
Portland Cement	1189.5	\$ 145.00	\$ 86.24
Silica Fume	273.3	\$ 840.00	\$ 114.77
Fly Ash	321.5	\$ 135.00	\$ 21.70
Fine Aggregate	1784.2	\$ 26.00	\$ 23.19
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 298.69

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.27	0.1185
Fine Aggregate	40.73	0.0815
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.26
HRWR	0.02	0.004	cu ft	0.24
Portland Cement	0.22	0.045	cu ft	8.81
Silica Fume	0.07	0.015	cu ft	2.02
Fly Ash	0.10	0.019	cu ft	2.38
Fine Aggregate	0.41	0.081	cu ft	13.22
Steel Fibers	0.00	0.000	cu ft	0.00

105.7 ml

Figure 43. Mix 11 Proportions

Mix Specifications		
Mix ID:		12
W/C	0.275	Unitless
HRWR Dosage Rate	0.0275	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.5	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	304.9	\$ -	\$ -
HRWR (gallons)	3.78	\$ 14.00	\$ 52.85
Portland Cement	1190.9	\$ 145.00	\$ 86.34
Silica Fume	318.5	\$ 840.00	\$ 133.77
Fly Ash	277.0	\$ 135.00	\$ 18.69
Fine Aggregate	1786.4	\$ 26.00	\$ 23.22
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 314.88

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2.75	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.22	0.1184
Fine Aggregate	40.78	0.0816
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.26
HRWR	0.02	0.004	cu ft	0.24
Portland Cement	0.22	0.045	cu ft	8.82
Silica Fume	0.09	0.017	cu ft	2.36
Fly Ash	0.08	0.016	cu ft	2.05
Fine Aggregate	0.41	0.082	cu ft	13.23
Steel Fibers	0.00	0.000	cu ft	0.00

105.9 ml

Figure 44. Mix 12 Proportions

Mix Specifications		
Mix ID:		13
W/C	0.275	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.69	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	316.7	\$ -	\$ -
HRWR (gallons)	9.84	\$ 14.00	\$ 137.75
Portland Cement	1365.8	\$ 145.00	\$ 99.02
Silica Fume	313.8	\$ 840.00	\$ 131.78
Fly Ash	369.1	\$ 135.00	\$ 24.92
Fine Aggregate	1365.8	\$ 26.00	\$ 17.75
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 411.21

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	68.82	0.1376
Fine Aggregate	31.18	0.0624
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.19	0.038	cu ft	2.35
HRWR	0.05	0.010	cu ft	0.63
Portland Cement	0.26	0.051	cu ft	10.12
Silica Fume	0.08	0.017	cu ft	2.32
Fly Ash	0.11	0.022	cu ft	2.73
Fine Aggregate	0.31	0.062	cu ft	10.12
Steel Fibers	0.00	0.000	cu ft	0.00

275.9 ml

Figure 45. Mix 13 Proportions

Mix Specifications		
Mix ID:		14
W/C	0.275	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.69	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	317.1	\$ -	\$ -
HRWR (gallons)	9.85	\$ 14.00	\$ 137.94
Portland Cement	1367.7	\$ 145.00	\$ 99.15
Silica Fume	365.8	\$ 840.00	\$ 153.62
Fly Ash	318.1	\$ 135.00	\$ 21.47
Fine Aggregate	1367.7	\$ 26.00	\$ 17.78
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 429.97

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	68.78	0.1376
Fine Aggregate	31.22	0.0624
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.19	0.038	cu ft	2.35
HRWR	0.05	0.010	cu ft	0.63
Portland Cement	0.26	0.052	cu ft	10.13
Silica Fume	0.10	0.020	cu ft	2.71
Fly Ash	0.09	0.019	cu ft	2.36
Fine Aggregate	0.31	0.062	cu ft	10.13
Steel Fibers	0.00	0.000	cu ft	0.00

276.3 ml

Figure 46. Mix 14 Proportions

Mix Specifications		
Mix ID:		15
W/C	0.275	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.85	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	274.0	\$ -	\$ -
HRWR (gallons)	8.51	\$ 14.00	\$ 119.17
Portland Cement	1181.6	\$ 145.00	\$ 85.66
Silica Fume	271.4	\$ 840.00	\$ 114.00
Fly Ash	319.3	\$ 135.00	\$ 21.56
Fine Aggregate	1772.3	\$ 26.00	\$ 23.04
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 363.44

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.54	0.1191
Fine Aggregate	40.46	0.0809
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.033	cu ft	2.03
HRWR	0.04	0.008	cu ft	0.55
Portland Cement	0.22	0.045	cu ft	8.75
Silica Fume	0.07	0.015	cu ft	2.01
Fly Ash	0.09	0.019	cu ft	2.37
Fine Aggregate	0.40	0.081	cu ft	13.13
Steel Fibers	0.00	0.000	cu ft	0.00

238.7 ml

Figure 47. Mix 15 Proportions

Mix Specifications		
Mix ID:		16
W/C	0.275	Unitless
HRWR Dosage Rate	0.0625	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.15	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	274.3	\$ -	\$ -
HRWR (gallons)	8.52	\$ 14.00	\$ 119.32
Portland Cement	1183.0	\$ 145.00	\$ 85.77
Silica Fume	316.4	\$ 840.00	\$ 132.88
Fly Ash	275.1	\$ 135.00	\$ 18.57
Fine Aggregate	1774.5	\$ 26.00	\$ 23.07
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 379.60

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6.25	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.49	0.1190
Fine Aggregate	40.51	0.0810
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.033	cu ft	2.03
HRWR	0.04	0.008	cu ft	0.55
Portland Cement	0.22	0.045	cu ft	8.76
Silica Fume	0.09	0.017	cu ft	2.34
Fly Ash	0.08	0.016	cu ft	2.04
Fine Aggregate	0.41	0.081	cu ft	13.14
Steel Fibers	0.00	0.000	cu ft	0.00

239.0 ml

Figure 48. Mix 16 Proportions

Mix Specifications		
Mix ID:		17
W/C	0.2	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.62	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	227.9	\$ -	\$ -
HRWR (gallons)	7.00	\$ 14.00	\$ 97.95
Portland Cement	1348.8	\$ 145.00	\$ 97.79
Silica Fume	337.2	\$ 840.00	\$ 141.63
Fly Ash	337.2	\$ 135.00	\$ 22.76
Fine Aggregate	1686.0	\$ 26.00	\$ 21.92
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 382.05

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	61.51	0.1230
Fine Aggregate	38.49	0.0770
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.14	0.027	cu ft	1.69
HRWR	0.03	0.007	cu ft	0.45
Portland Cement	0.25	0.051	cu ft	9.99
Silica Fume	0.09	0.018	cu ft	2.50
Fly Ash	0.10	0.020	cu ft	2.50
Fine Aggregate	0.38	0.077	cu ft	12.49
Steel Fibers	0.00	0.000	cu ft	0.00

196.2 ml

Figure 49. Mix 17 Proportions

Mix Specifications		
Mix ID:		18
W/C	0.3	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.64	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	335.9	\$ -	\$ -
HRWR (gallons)	6.48	\$ 14.00	\$ 90.69
Portland Cement	1248.8	\$ 145.00	\$ 90.54
Silica Fume	312.2	\$ 840.00	\$ 131.13
Fly Ash	312.2	\$ 135.00	\$ 21.07
Fine Aggregate	1561.1	\$ 26.00	\$ 20.29
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 353.73

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	64.36	0.1287
Fine Aggregate	35.64	0.0713
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.20	0.040	cu ft	2.49
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.24	0.047	cu ft	9.25
Silica Fume	0.08	0.017	cu ft	2.31
Fly Ash	0.09	0.019	cu ft	2.31
Fine Aggregate	0.36	0.071	cu ft	11.56
Steel Fibers	0.00	0.000	cu ft	0.00

181.6 ml

Figure 50. Mix 18 Proportions

Mix Specifications		
Mix ID:		19
W/C	0.25	Unitless
HRWR Dosage Rate	0.01	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	317.6	\$ -	\$ -
HRWR (gallons)	1.51	\$ 14.00	\$ 21.08
Portland Cement	1306.5	\$ 145.00	\$ 94.72
Silica Fume	326.6	\$ 840.00	\$ 137.18
Fly Ash	326.6	\$ 135.00	\$ 22.05
Fine Aggregate	1633.1	\$ 26.00	\$ 21.23
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 296.26

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	1	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	62.72	0.1254
Fine Aggregate	37.28	0.0746
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.19	0.038	cu ft	2.35
HRWR	0.01	0.001	cu ft	0.10
Portland Cement	0.25	0.049	cu ft	9.68
Silica Fume	0.09	0.018	cu ft	2.42
Fly Ash	0.10	0.019	cu ft	2.42
Fine Aggregate	0.37	0.075	cu ft	12.10
Steel Fibers	0.00	0.000	cu ft	0.00

42.2 ml

Figure 51. Mix 19 Proportions

Mix Specifications		
Mix ID:		20
W/C	0.25	Unitless
HRWR Dosage Rate	0.08	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	250.8	\$ -	\$ -
HRWR (gallons)	11.87	\$ 14.00	\$ 166.22
Portland Cement	1287.5	\$ 145.00	\$ 93.34
Silica Fume	321.9	\$ 840.00	\$ 135.19
Fly Ash	321.9	\$ 135.00	\$ 21.73
Fine Aggregate	1609.4	\$ 26.00	\$ 20.92
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 437.40

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	8	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	63.26	0.1265
Fine Aggregate	36.74	0.0735
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.030	cu ft	1.86
HRWR	0.06	0.012	cu ft	0.76
Portland Cement	0.24	0.049	cu ft	9.54
Silica Fume	0.09	0.017	cu ft	2.38
Fly Ash	0.10	0.019	cu ft	2.38
Fine Aggregate	0.37	0.073	cu ft	11.92
Steel Fibers	0.00	0.000	cu ft	0.00

332.9 ml

Figure 52. Mix 20 Proportions

Mix Specifications		
Mix ID:		21
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	0.75	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.74	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	333.3	\$ -	\$ -
HRWR (gallons)	7.90	\$ 14.00	\$ 110.55
Portland Cement	1522.3	\$ 145.00	\$ 110.36
Silica Fume	380.6	\$ 840.00	\$ 159.84
Fly Ash	380.6	\$ 135.00	\$ 25.69
Fine Aggregate	1141.7	\$ 26.00	\$ 14.84
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 421.28

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	73.94	0.1479
Fine Aggregate	26.06	0.0521
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.20	0.040	cu ft	2.47
HRWR	0.04	0.008	cu ft	0.51
Portland Cement	0.29	0.057	cu ft	11.28
Silica Fume	0.10	0.021	cu ft	2.82
Fly Ash	0.11	0.023	cu ft	2.82
Fine Aggregate	0.26	0.052	cu ft	8.46
Steel Fibers	0.00	0.000	cu ft	0.00

221.4 ml

Figure 53. Mix 21 Proportions

Mix Specifications		
Mix ID:		22
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.75	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.55	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	247.3	\$ -	\$ -
HRWR (gallons)	5.86	\$ 14.00	\$ 82.04
Portland Cement	1129.7	\$ 145.00	\$ 81.90
Silica Fume	282.4	\$ 840.00	\$ 118.62
Fly Ash	282.4	\$ 135.00	\$ 19.06
Fine Aggregate	1976.9	\$ 26.00	\$ 25.70
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 327.32

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	54.87	0.1097
Fine Aggregate	45.13	0.0903
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.029	cu ft	1.83
HRWR	0.03	0.006	cu ft	0.38
Portland Cement	0.21	0.043	cu ft	8.37
Silica Fume	0.08	0.015	cu ft	2.09
Fly Ash	0.08	0.017	cu ft	2.09
Fine Aggregate	0.45	0.090	cu ft	14.64
Steel Fibers	0.00	0.000	cu ft	0.00

164.3 ml

Figure 54. Mix 22 Proportions

Mix Specifications		
Mix ID:		23
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.70	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	283.5	\$ -	\$ -
HRWR (gallons)	6.72	\$ 14.00	\$ 94.04
Portland Cement	1294.9	\$ 145.00	\$ 93.88
Silica Fume	266.6	\$ 840.00	\$ 111.97
Fly Ash	380.9	\$ 135.00	\$ 25.71
Fine Aggregate	1618.6	\$ 26.00	\$ 21.04
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 346.64

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	63.05	0.1261
Fine Aggregate	36.95	0.0739
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.049	cu ft	9.59
Silica Fume	0.07	0.014	cu ft	1.97
Fly Ash	0.11	0.023	cu ft	2.82
Fine Aggregate	0.37	0.074	cu ft	11.99
Steel Fibers	0.00	0.000	cu ft	0.00

188.3 ml

Figure 55. Mix 23 Proportions

Mix Specifications		
Mix ID:		24
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.30	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	284.3	\$ -	\$ -
HRWR (gallons)	6.73	\$ 14.00	\$ 94.29
Portland Cement	1298.4	\$ 145.00	\$ 94.13
Silica Fume	366.9	\$ 840.00	\$ 154.11
Fly Ash	282.3	\$ 135.00	\$ 19.05
Fine Aggregate	1623.0	\$ 26.00	\$ 21.10
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 382.69

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	62.95	0.1259
Fine Aggregate	37.05	0.0741
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.11
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.049	cu ft	9.62
Silica Fume	0.10	0.020	cu ft	2.72
Fly Ash	0.08	0.017	cu ft	2.09
Fine Aggregate	0.37	0.074	cu ft	12.02
Steel Fibers	0.00	0.000	cu ft	0.00

188.8 ml

Figure 56. Mix 24 Proportions

Mix Specifications		
Mix ID:		25 C
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	284.0	\$ -	\$ -
HRWR (gallons)	6.73	\$ 14.00	\$ 94.18
Portland Cement	1296.9	\$ 145.00	\$ 94.03
Silica Fume	324.2	\$ 840.00	\$ 136.18
Fly Ash	324.2	\$ 135.00	\$ 21.89
Fine Aggregate	1621.1	\$ 26.00	\$ 21.07
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 367.34

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	62.99	0.1260
Fine Aggregate	37.01	0.0740
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.049	cu ft	9.61
Silica Fume	0.09	0.017	cu ft	2.40
Fly Ash	0.10	0.019	cu ft	2.40
Fine Aggregate	0.37	0.074	cu ft	12.01
Steel Fibers	0.00	0.000	cu ft	0.00

188.6 ml

Figure 57. Mix 25 C Proportions

Mix Specifications		
Mix ID:		26 C
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	284.0	\$ -	\$ -
HRWR (gallons)	6.73	\$ 14.00	\$ 94.18
Portland Cement	1296.9	\$ 145.00	\$ 94.03
Silica Fume	324.2	\$ 840.00	\$ 136.18
Fly Ash	324.2	\$ 135.00	\$ 21.89
Fine Aggregate	1621.1	\$ 26.00	\$ 21.07
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 367.34

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	62.99	0.1260
Fine Aggregate	37.01	0.0740
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.049	cu ft	9.61
Silica Fume	0.09	0.017	cu ft	2.40
Fly Ash	0.10	0.019	cu ft	2.40
Fine Aggregate	0.37	0.074	cu ft	12.01
Steel Fibers	0.00	0.000	cu ft	0.00

188.6 ml

Figure 58. Mix 26 C Proportions

Mix Specifications		
Mix ID:		27 C
W/C	0.25	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.25	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.63	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	284.0	\$ -	\$ -
HRWR (gallons)	6.73	\$ 14.00	\$ 94.18
Portland Cement	1296.9	\$ 145.00	\$ 94.03
Silica Fume	324.2	\$ 840.00	\$ 136.18
Fly Ash	324.2	\$ 135.00	\$ 21.89
Fine Aggregate	1621.1	\$ 26.00	\$ 21.07
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 367.34

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	62.99	0.1260
Fine Aggregate	37.01	0.0740
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.049	cu ft	9.61
Silica Fume	0.09	0.017	cu ft	2.40
Fly Ash	0.10	0.019	cu ft	2.40
Fine Aggregate	0.37	0.074	cu ft	12.01
Steel Fibers	0.00	0.000	cu ft	0.00

188.6 ml

Figure 59. Mix 27 C Proportions

APPENDIX B

TRIAL MIX PROPORTIONS

Mix Specifications		
Mix ID:		S1
W/C	0.24	Unitless
HRWR Dosage Rate	0.04	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.68	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	300.3	\$ -	\$ -
HRWR (gallons)	6.52	\$ 14.00	\$ 91.27
Portland Cement	1413.9	\$ 145.00	\$ 102.51
Silica Fume	353.5	\$ 840.00	\$ 148.46
Fly Ash	353.5	\$ 135.00	\$ 23.86
Fine Aggregate	1413.9	\$ 26.00	\$ 18.38
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 384.48

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.72	0.1354
Fine Aggregate	32.28	0.0646
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.22
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.27	0.053	cu ft	10.47
Silica Fume	0.10	0.019	cu ft	2.62
Fly Ash	0.10	0.021	cu ft	2.62
Fine Aggregate	0.32	0.065	cu ft	10.47
Steel Fibers	0.00	0.000	cu ft	0.00

182.8 ml

Figure 60. Mix S1Proportions

Mix Specifications		
Mix ID:		S2
W/C	0.24	Unitless
HRWR Dosage Rate	0.04	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.68	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	300.3	\$ -	\$ -
HRWR (gallons)	6.52	\$ 14.00	\$ 91.27
Portland Cement	1413.9	\$ 145.00	\$ 102.51
Silica Fume	353.5	\$ 840.00	\$ 148.46
Fly Ash	353.5	\$ 135.00	\$ 23.86
Fine Aggregate	1413.9	\$ 26.00	\$ 18.38
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 384.48

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	67.72	0.1354
Fine Aggregate	32.28	0.0646
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.22
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.27	0.053	cu ft	10.47
Silica Fume	0.10	0.019	cu ft	2.62
Fly Ash	0.10	0.021	cu ft	2.62
Fine Aggregate	0.32	0.065	cu ft	10.47
Steel Fibers	0.00	0.000	cu ft	0.00

182.8 ml

Figure 61. Mix S2 Proportions

Mix Specifications		
Mix ID:		S3
W/C	0.262	Unitless
HRWR Dosage Rate	0.0366	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	283.9	\$ -	\$ -
HRWR (gallons)	5.06	\$ 14.00	\$ 70.83
Portland Cement	1199.2	\$ 145.00	\$ 86.94
Silica Fume	299.8	\$ 840.00	\$ 125.91
Fly Ash	299.8	\$ 135.00	\$ 20.24
Fine Aggregate	1798.8	\$ 26.00	\$ 23.38
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 327.30

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	3.66	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	58.94	0.1179
Fine Aggregate	41.06	0.0821
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.005	cu ft	0.33
Portland Cement	0.23	0.045	cu ft	8.88
Silica Fume	0.08	0.016	cu ft	2.22
Fly Ash	0.09	0.018	cu ft	2.22
Fine Aggregate	0.41	0.082	cu ft	13.32
Steel Fibers	0.00	0.000	cu ft	0.00

141.9 ml

Figure 62. Mix S3 Proportions

Mix Specifications		
Mix ID:		S4
W/C	0.262	Unitless
HRWR Dosage Rate	0.0366	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	283.9	\$ -	\$ -
HRWR (gallons)	5.06	\$ 14.00	\$ 70.83
Portland Cement	1199.2	\$ 145.00	\$ 86.94
Silica Fume	299.8	\$ 840.00	\$ 125.91
Fly Ash	299.8	\$ 135.00	\$ 20.24
Fine Aggregate	1798.8	\$ 26.00	\$ 23.38
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 327.30

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	3.66	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	58.94	0.1179
Fine Aggregate	41.06	0.0821
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.005	cu ft	0.33
Portland Cement	0.23	0.045	cu ft	8.88
Silica Fume	0.08	0.016	cu ft	2.22
Fly Ash	0.09	0.018	cu ft	2.22
Fine Aggregate	0.41	0.082	cu ft	13.32
Steel Fibers	0.00	0.000	cu ft	0.00

141.9 ml

Figure 63. Mix S4 Proportions

Mix Specifications		
Mix ID:		S5
W/C	0.262	Unitless
HRWR Dosage Rate	0.0366	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	0.70	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.75	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	363.5	\$ -	\$ -
HRWR (gallons)	6.48	\$ 14.00	\$ 90.69
Portland Cement	1535.5	\$ 145.00	\$ 111.32
Silica Fume	383.9	\$ 840.00	\$ 161.22
Fly Ash	383.9	\$ 135.00	\$ 25.91
Fine Aggregate	1074.8	\$ 26.00	\$ 13.97
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 403.12

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	3.66	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	75.46	0.1509
Fine Aggregate	24.54	0.0491
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.22	0.043	cu ft	2.69
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.29	0.058	cu ft	11.37
Silica Fume	0.10	0.021	cu ft	2.84
Fly Ash	0.11	0.023	cu ft	2.84
Fine Aggregate	0.25	0.049	cu ft	7.96
Steel Fibers	0.00	0.000	cu ft	0.00

181.6 ml

Figure 64. Mix S5 Proportions

Mix Specifications		
Mix ID:		S6
W/C	0.262	Unitless
HRWR Dosage Rate	0.0366	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.00	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.68	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	328.9	\$ -	\$ -
HRWR (gallons)	5.86	\$ 14.00	\$ 82.06
Portland Cement	1389.4	\$ 145.00	\$ 100.73
Silica Fume	347.3	\$ 840.00	\$ 145.88
Fly Ash	347.3	\$ 135.00	\$ 23.45
Fine Aggregate	1389.4	\$ 26.00	\$ 18.06
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 370.18

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	3.66	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	68.28	0.1366
Fine Aggregate	31.72	0.0634
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.20	0.039	cu ft	2.44
HRWR	0.03	0.006	cu ft	0.38
Portland Cement	0.26	0.052	cu ft	10.29
Silica Fume	0.09	0.019	cu ft	2.57
Fly Ash	0.10	0.021	cu ft	2.57
Fine Aggregate	0.32	0.063	cu ft	10.29
Steel Fibers	0.00	0.000	cu ft	0.00

164.4 ml

Figure 65. Mix S6 Proportions

Mix Specifications		
Mix ID:		S7
W/C	0.262	Unitless
HRWR Dosage Rate	0.0366	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.50	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	283.9	\$ -	\$ -
HRWR (gallons)	5.06	\$ 14.00	\$ 70.83
Portland Cement	1199.2	\$ 145.00	\$ 86.94
Silica Fume	299.8	\$ 840.00	\$ 125.91
Fly Ash	299.8	\$ 135.00	\$ 20.24
Fine Aggregate	1798.8	\$ 26.00	\$ 23.38
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 327.30

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	3.66	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	58.94	0.1179
Fine Aggregate	41.06	0.0821
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.034	cu ft	2.10
HRWR	0.03	0.005	cu ft	0.33
Portland Cement	0.23	0.045	cu ft	8.88
Silica Fume	0.08	0.016	cu ft	2.22
Fly Ash	0.09	0.018	cu ft	2.22
Fine Aggregate	0.41	0.082	cu ft	13.32
Steel Fibers	0.00	0.000	cu ft	0.00

141.9 ml

Figure 66. Mix S7 Proportions

APPENDIX C

3 VARIABLE RSM MIX PROPORTIONS

Mix Specifications		
Mix ID:		RSM 3-1
W/C	0.22	Unitless
HRWR Dosage Rate	0.02	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.50	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	262.4	\$ -	\$ -
HRWR (gallons)	2.93	\$ 14.00	\$ 41.08
Portland Cement	1272.7	\$ 145.00	\$ 92.27
Silica Fume	212.1	\$ 840.00	\$ 89.09
Fly Ash	424.2	\$ 135.00	\$ 28.64
Fine Aggregate	1781.8	\$ 26.00	\$ 23.16
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 274.24

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.32	0.1186
Fine Aggregate	40.68	0.0814
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.031	cu ft	1.94
HRWR	0.01	0.003	cu ft	0.19
Portland Cement	0.24	0.048	cu ft	9.43
Silica Fume	0.06	0.011	cu ft	1.57
Fly Ash	0.13	0.025	cu ft	3.14
Fine Aggregate	0.41	0.081	cu ft	13.20
Steel Fibers	0.00	0.000	cu ft	0.00

82.3 ml

Figure 67. Mix 3-1 Proportions

Mix Specifications		
Mix ID:		RSM 3-2
W/C	0.22	Unitless
HRWR Dosage Rate	0.02	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	263.2	\$ -	\$ -
HRWR (gallons)	2.94	\$ 14.00	\$ 41.20
Portland Cement	1276.4	\$ 145.00	\$ 92.54
Silica Fume	319.1	\$ 840.00	\$ 134.02
Fly Ash	319.1	\$ 135.00	\$ 21.54
Fine Aggregate	1786.9	\$ 26.00	\$ 23.23
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 312.52

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.21	0.1184
Fine Aggregate	40.79	0.0816
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.031	cu ft	1.95
HRWR	0.01	0.003	cu ft	0.19
Portland Cement	0.24	0.048	cu ft	9.45
Silica Fume	0.09	0.017	cu ft	2.36
Fly Ash	0.09	0.019	cu ft	2.36
Fine Aggregate	0.41	0.082	cu ft	13.24
Steel Fibers	0.00	0.000	cu ft	0.00

82.5 ml

Figure 68. Mix 3-2 Proportions

Mix Specifications		
Mix ID:		RSM 3-3
W/C	0.22	Unitless
HRWR Dosage Rate	0.06	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.50	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	225.5	\$ -	\$ -
HRWR (gallons)	8.73	\$ 14.00	\$ 122.23
Portland Cement	1262.4	\$ 145.00	\$ 91.52
Silica Fume	210.4	\$ 840.00	\$ 88.37
Fly Ash	420.8	\$ 135.00	\$ 28.40
Fine Aggregate	1767.3	\$ 26.00	\$ 22.98
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 353.49

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.65	0.1193
Fine Aggregate	40.35	0.0807
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.027	cu ft	1.67
HRWR	0.04	0.009	cu ft	0.56
Portland Cement	0.24	0.048	cu ft	9.35
Silica Fume	0.06	0.011	cu ft	1.56
Fly Ash	0.12	0.025	cu ft	3.12
Fine Aggregate	0.40	0.081	cu ft	13.09
Steel Fibers	0.00	0.000	cu ft	0.00

244.8 ml

Figure 69. Mix 3-3 Proportions

Mix Specifications		
Mix ID:		RSM 3-4
W/C	0.22	Unitless
HRWR Dosage Rate	0.06	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	226.1	\$ -	\$ -
HRWR (gallons)	8.76	\$ 14.00	\$ 122.58
Portland Cement	1266.0	\$ 145.00	\$ 91.78
Silica Fume	316.5	\$ 840.00	\$ 132.93
Fly Ash	316.5	\$ 135.00	\$ 21.36
Fine Aggregate	1772.3	\$ 26.00	\$ 23.04
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 391.69

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.54	0.1191
Fine Aggregate	40.46	0.0809
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.027	cu ft	1.67
HRWR	0.04	0.009	cu ft	0.56
Portland Cement	0.24	0.048	cu ft	9.38
Silica Fume	0.09	0.017	cu ft	2.34
Fly Ash	0.09	0.019	cu ft	2.34
Fine Aggregate	0.40	0.081	cu ft	13.13
Steel Fibers	0.00	0.000	cu ft	0.00

245.5 ml

Figure 70. Mix 3-4 Proportions

Mix Specifications		
Mix ID:		RSM 3-5
W/C	0.26	Unitless
HRWR Dosage Rate	0.02	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.50	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.61	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	304.2	\$ -	\$ -
HRWR (gallons)	2.85	\$ 14.00	\$ 39.87
Portland Cement	1235.4	\$ 145.00	\$ 89.57
Silica Fume	205.9	\$ 840.00	\$ 86.48
Fly Ash	411.8	\$ 135.00	\$ 27.80
Fine Aggregate	1729.5	\$ 26.00	\$ 22.48
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 266.20

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.52	0.1210
Fine Aggregate	39.48	0.0790
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.25
HRWR	0.01	0.003	cu ft	0.18
Portland Cement	0.23	0.047	cu ft	9.15
Silica Fume	0.06	0.011	cu ft	1.53
Fly Ash	0.12	0.024	cu ft	3.05
Fine Aggregate	0.39	0.079	cu ft	12.81
Steel Fibers	0.00	0.000	cu ft	0.00

79.9 ml

Figure 71. Mix 3-5 Proportions

Mix Specifications		
Mix ID:		RSM 3-6
W/C	0.26	Unitless
HRWR Dosage Rate	0.02	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	305.0	\$ -	\$ -
HRWR (gallons)	2.86	\$ 14.00	\$ 39.98
Portland Cement	1238.8	\$ 145.00	\$ 89.82
Silica Fume	309.7	\$ 840.00	\$ 130.08
Fly Ash	309.7	\$ 135.00	\$ 20.91
Fine Aggregate	1734.4	\$ 26.00	\$ 22.55
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 303.33

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

From RSM Model

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	2	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.41	0.1208
Fine Aggregate	39.59	0.0792
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.036	cu ft	2.26
HRWR	0.01	0.003	cu ft	0.18
Portland Cement	0.23	0.047	cu ft	9.18
Silica Fume	0.08	0.017	cu ft	2.29
Fly Ash	0.09	0.018	cu ft	2.29
Fine Aggregate	0.40	0.079	cu ft	12.85
Steel Fibers	0.00	0.000	cu ft	0.00

80.1 ml

Figure 72. Mix 3-6 Proportions

Mix Specifications		
Mix ID:		RSM 3-7
W/C	0.26	Unitless
HRWR Dosage Rate	0.06	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.50	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.61	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	267.9	\$ -	\$ -
HRWR (gallons)	8.48	\$ 14.00	\$ 118.67
Portland Cement	1225.6	\$ 145.00	\$ 88.86
Silica Fume	204.3	\$ 840.00	\$ 85.79
Fly Ash	408.5	\$ 135.00	\$ 27.58
Fine Aggregate	1715.9	\$ 26.00	\$ 22.31
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 343.21

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.83	0.1217
Fine Aggregate	39.17	0.0783
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.032	cu ft	1.98
HRWR	0.04	0.008	cu ft	0.54
Portland Cement	0.23	0.046	cu ft	9.08
Silica Fume	0.06	0.011	cu ft	1.51
Fly Ash	0.12	0.024	cu ft	3.03
Fine Aggregate	0.39	0.078	cu ft	12.71
Steel Fibers	0.00	0.000	cu ft	0.00

237.7 ml

Figure 73. Mix 3-7 Proportions

Mix Specifications		
Mix ID:		RSM 3-8
W/C	0.26	Unitless
HRWR Dosage Rate	0.06	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.00	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.61	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	268.7	\$ -	\$ -
HRWR (gallons)	8.50	\$ 14.00	\$ 119.00
Portland Cement	1229.0	\$ 145.00	\$ 89.10
Silica Fume	307.3	\$ 840.00	\$ 129.05
Fly Ash	307.3	\$ 135.00	\$ 20.74
Fine Aggregate	1720.6	\$ 26.00	\$ 22.37
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 380.26

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	6	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.72	0.1214
Fine Aggregate	39.28	0.0786
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.032	cu ft	1.99
HRWR	0.04	0.008	cu ft	0.55
Portland Cement	0.23	0.046	cu ft	9.10
Silica Fume	0.08	0.017	cu ft	2.28
Fly Ash	0.09	0.018	cu ft	2.28
Fine Aggregate	0.39	0.079	cu ft	12.75
Steel Fibers	0.00	0.000	cu ft	0.00

238.3 ml

Figure 74. Mix 3-8 Proportions

Mix Specifications		
Mix ID: RSM 3-9		
W/C	0.206	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	224.7	\$ -	\$ -
HRWR (gallons)	6.65	\$ 14.00	\$ 93.06
Portland Cement	1281.4	\$ 145.00	\$ 92.90
Silica Fume	274.6	\$ 840.00	\$ 115.33
Fly Ash	366.1	\$ 135.00	\$ 24.71
Fine Aggregate	1794.0	\$ 26.00	\$ 23.32
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 349.33

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.05	0.1181
Fine Aggregate	40.95	0.0819
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.13	0.027	cu ft	1.66
HRWR	0.03	0.007	cu ft	0.43
Portland Cement	0.24	0.048	cu ft	9.49
Silica Fume	0.07	0.015	cu ft	2.03
Fly Ash	0.11	0.022	cu ft	2.71
Fine Aggregate	0.41	0.082	cu ft	13.29
Steel Fibers	0.00	0.000	cu ft	0.00

186.4 ml

Figure 75. Mix 3-9 Proportions

Mix Specifications		
Mix ID: RSM 3-10		
W/C	0.274	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.61	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	295.7	\$ -	\$ -
HRWR (gallons)	6.32	\$ 14.00	\$ 88.53
Portland Cement	1219.1	\$ 145.00	\$ 88.38
Silica Fume	261.2	\$ 840.00	\$ 109.72
Fly Ash	348.3	\$ 135.00	\$ 23.51
Fine Aggregate	1706.7	\$ 26.00	\$ 22.19
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 332.32

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	61.04	0.1221
Fine Aggregate	38.96	0.0779
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.035	cu ft	2.19
HRWR	0.03	0.006	cu ft	0.41
Portland Cement	0.23	0.046	cu ft	9.03
Silica Fume	0.07	0.014	cu ft	1.94
Fly Ash	0.10	0.021	cu ft	2.58
Fine Aggregate	0.39	0.078	cu ft	12.64
Steel Fibers	0.00	0.000	cu ft	0.00

177.3 ml

Figure 76. Mix 3-10 Proportions

Mix Specifications		
Mix ID: RSM 3-11		
W/C	0.24	Unitless
HRWR Dosage Rate	0.011	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	292.1	\$ -	\$ -
HRWR (gallons)	1.65	\$ 14.00	\$ 23.07
Portland Cement	1258.0	\$ 145.00	\$ 91.21
Silica Fume	269.6	\$ 840.00	\$ 113.22
Fly Ash	359.4	\$ 135.00	\$ 24.26
Fine Aggregate	1761.2	\$ 26.00	\$ 22.90
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 274.65

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	1.1364	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.79	0.1196
Fine Aggregate	40.21	0.0804
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.17	0.035	cu ft	2.16
HRWR	0.01	0.002	cu ft	0.11
Portland Cement	0.24	0.047	cu ft	9.32
Silica Fume	0.07	0.015	cu ft	2.00
Fly Ash	0.11	0.021	cu ft	2.66
Fine Aggregate	0.40	0.080	cu ft	13.05
Steel Fibers	0.00	0.000	cu ft	0.00

46.2 ml

Figure 77. Mix 3-11 Proportions

Mix Specifications		
Mix ID:		RSM 3-12
W/C	0.24	Unitless
HRWR Dosage Rate	0.079	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	230.5	\$ -	\$ -
HRWR (gallons)	11.25	\$ 14.00	\$ 157.49
Portland Cement	1241.1	\$ 145.00	\$ 89.98
Silica Fume	265.9	\$ 840.00	\$ 111.70
Fly Ash	354.6	\$ 135.00	\$ 23.93
Fine Aggregate	1737.5	\$ 26.00	\$ 22.59
Steel Fibers	0.0	\$ 1,600.00	\$ -
Total			\$ 405.69

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	7.8636	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.34	0.1207
Fine Aggregate	39.66	0.0793
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.14	0.027	cu ft	1.71
HRWR	0.06	0.011	cu ft	0.72
Portland Cement	0.23	0.047	cu ft	9.19
Silica Fume	0.07	0.014	cu ft	1.97
Fly Ash	0.11	0.021	cu ft	2.63
Fine Aggregate	0.40	0.079	cu ft	12.87
Steel Fibers	0.00	0.000	cu ft	0.00

315.4 ml

Figure 78. Mix 3-12 Proportions

Mix Specifications		
Mix ID: RSM 3-13		
W/C	0.24	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.33	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	260.3	\$ -	\$ -
HRWR (gallons)	6.46	\$ 14.00	\$ 90.46
Portland Cement	1245.7	\$ 145.00	\$ 90.31
Silica Fume	154.4	\$ 840.00	\$ 64.84
Fly Ash	468.5	\$ 135.00	\$ 31.62
Fine Aggregate	1744.0	\$ 26.00	\$ 22.67
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 299.91

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.19	0.1204
Fine Aggregate	39.81	0.0796
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.93
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.23	0.047	cu ft	9.23
Silica Fume	0.04	0.008	cu ft	1.14
Fly Ash	0.14	0.028	cu ft	3.47
Fine Aggregate	0.40	0.080	cu ft	12.92
Steel Fibers	0.00	0.000	cu ft	0.00

181.2 ml

Figure 79. Mix 3-13 Proportions

Mix Specifications		
Mix ID: RSM 3-14		
W/C	0.24	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	1.17	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	261.6	\$ -	\$ -
HRWR (gallons)	6.49	\$ 14.00	\$ 90.91
Portland Cement	1251.8	\$ 145.00	\$ 90.76
Silica Fume	337.5	\$ 840.00	\$ 141.74
Fly Ash	288.4	\$ 135.00	\$ 19.47
Fine Aggregate	1752.5	\$ 26.00	\$ 22.78
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 365.65

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

From RSM Model

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.99	0.1200
Fine Aggregate	40.01	0.0800
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.16	0.031	cu ft	1.94
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.24	0.047	cu ft	9.27
Silica Fume	0.09	0.018	cu ft	2.50
Fly Ash	0.09	0.017	cu ft	2.14
Fine Aggregate	0.40	0.080	cu ft	12.98
Steel Fibers	0.00	0.000	cu ft	0.00

182.1 ml

Figure 80. Mix 3-14 Proportions

Mix Specifications		
Mix ID: RSM 3-15 C		
W/C	0.24	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	261.1	\$ -	\$ -
HRWR (gallons)	6.48	\$ 14.00	\$ 90.74
Portland Cement	1249.5	\$ 145.00	\$ 90.59
Silica Fume	267.7	\$ 840.00	\$ 112.45
Fly Ash	357.0	\$ 135.00	\$ 24.10
Fine Aggregate	1749.3	\$ 26.00	\$ 22.74
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 340.61

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.07	0.1201
Fine Aggregate	39.93	0.0799
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.93
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.24	0.047	cu ft	9.26
Silica Fume	0.07	0.014	cu ft	1.98
Fly Ash	0.11	0.021	cu ft	2.64
Fine Aggregate	0.40	0.080	cu ft	12.96
Steel Fibers	0.00	0.000	cu ft	0.00

181.7 ml

Figure 81. Mix 3-15 C Proportions

Mix Specifications		
Mix ID: RSM 3-16 C		
W/C	0.24	Unitless
HRWR Dosage Rate	0.045	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.75	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	261.1	\$ -	\$ -
HRWR (gallons)	6.48	\$ 14.00	\$ 90.74
Portland Cement	1249.5	\$ 145.00	\$ 90.59
Silica Fume	267.7	\$ 840.00	\$ 112.45
Fly Ash	357.0	\$ 135.00	\$ 24.10
Fine Aggregate	1749.3	\$ 26.00	\$ 22.74
Steel Fibers	0.0	\$1,600.00	\$ -
Total			\$ 340.61

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.5	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.07	0.1201
Fine Aggregate	39.93	0.0799
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.93
HRWR	0.03	0.006	cu ft	0.42
Portland Cement	0.24	0.047	cu ft	9.26
Silica Fume	0.07	0.014	cu ft	1.98
Fly Ash	0.11	0.021	cu ft	2.64
Fine Aggregate	0.40	0.080	cu ft	12.96
Steel Fibers	0.00	0.000	cu ft	0.00

181.7 ml

Figure 82. Mix 3-16 C Proportions

APPENDIX D

OPTIMIZED MIX PROPORTIONS

Mix Specifications		
Mix ID:		3M1
W/C	0.236	Unitless
HRWR Dosage Rate	0.0415	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.378	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	259.7	\$ -	\$ -
HRWR (gallons)	5.98	\$ 14.00	\$ 83.75
Portland Cement	1250.5	\$ 145.00	\$ 90.66
Silica Fume	171.5	\$ 840.00	\$ 72.02
Fly Ash	453.8	\$ 135.00	\$ 30.63
Fine Aggregate	1750.8	\$ 26.00	\$ 22.76
Steel Fibers	0.0	\$ 1,600.00	\$ -
Total			\$ 299.83

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.15	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.03	0.1201
Fine Aggregate	39.97	0.0799
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.031	cu ft	1.92
HRWR	0.03	0.006	cu ft	0.38
Portland Cement	0.24	0.047	cu ft	9.26
Silica Fume	0.05	0.009	cu ft	1.27
Fly Ash	0.13	0.027	cu ft	3.36
Fine Aggregate	0.40	0.080	cu ft	12.97
Steel Fibers	0.00	0.000	cu ft	0.00

167.7 ml

Figure 83. Mix 3M1 Proportions

Mix Specifications		
Mix ID:		3M2
W/C	0.237	Unitless
HRWR Dosage Rate	0.0458	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.305	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.60	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	256.2	\$ -	\$ -
HRWR (gallons)	6.59	\$ 14.00	\$ 92.24
Portland Cement	1248.1	\$ 145.00	\$ 90.48
Silica Fume	145.9	\$ 840.00	\$ 61.29
Fly Ash	478.1	\$ 135.00	\$ 32.27
Fine Aggregate	1747.3	\$ 26.00	\$ 22.71
Steel Fibers	0.0	\$ 1,600.00	\$ -
Total			\$ 299.00

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.58	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	60.11	0.1202
Fine Aggregate	39.89	0.0798
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.15	0.030	cu ft	1.90
HRWR	0.03	0.007	cu ft	0.42
Portland Cement	0.24	0.047	cu ft	9.24
Silica Fume	0.04	0.008	cu ft	1.08
Fly Ash	0.14	0.028	cu ft	3.54
Fine Aggregate	0.40	0.080	cu ft	12.94
Steel Fibers	0.00	0.000	cu ft	0.00

184.8 ml

Figure 84. Mix 3M2 Proportions

Mix Specifications		
Mix ID:		3M3
W/C	0.274	Unitless
HRWR Dosage Rate	0.0432	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.425	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.61	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	297.4	\$ -	\$ -
HRWR (gallons)	6.06	\$ 14.00	\$ 84.79
Portland Cement	1216.3	\$ 145.00	\$ 88.18
Silica Fume	181.3	\$ 840.00	\$ 76.14
Fly Ash	426.9	\$ 135.00	\$ 28.81
Fine Aggregate	1702.8	\$ 26.00	\$ 22.14
Steel Fibers	0.0	\$ 1,600.00	\$ -
Total			\$ 300.07

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.32	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	61.13	0.1223
Fine Aggregate	38.87	0.0777
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.18	0.035	cu ft	2.20
HRWR	0.03	0.006	cu ft	0.39
Portland Cement	0.23	0.046	cu ft	9.01
Silica Fume	0.05	0.010	cu ft	1.34
Fly Ash	0.13	0.025	cu ft	3.16
Fine Aggregate	0.39	0.078	cu ft	12.61
Steel Fibers	0.00	0.000	cu ft	0.00

169.8 ml

Figure 85. Mix 3M3 Proportions

Mix Specifications		
Mix ID:		3M4
W/C	0.216	Unitless
HRWR Dosage Rate	0.0493	Fraction of Cement wt
SCM to Cement Ratio	0.5	Unitless
Silica Fume to Fly Ash Ratio	0.683	Unitless
Aggregate to Cement Ratio	1.40	Unitless
Fiber Content	0.00	Fraction of Volume
Paste Content	0.59	Fraction of Volume
Volume	0.20	cu. Ft

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	230.9	\$ -	\$ -
HRWR (gallons)	7.22	\$ 14.00	\$ 101.10
Portland Cement	1270.8	\$ 145.00	\$ 92.13
Silica Fume	257.9	\$ 840.00	\$ 108.34
Fly Ash	377.4	\$ 135.00	\$ 25.48
Fine Aggregate	1779.1	\$ 26.00	\$ 23.13
Steel Fibers	0.0	\$ 1,600.00	\$ -
Total			\$ 350.18

Aggregates	
Type	Specific Gravity
Fine Aggregate	2.6
Steel Fibers	7.8
Weighted Average	2.60

Cementitious Materials	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2
Silica Fume	2.2

High Range Water Reducer			
Type	Percent of Cement Wt	Specific Gravity	Fraction of Weight in Water
Chryso Premia 150	4.93	1.04	0.69

Mix Proportions		
Item	Percent	Volume (cu ft)
Water +HRWR + Cementitious	59.39	0.1188
Fine Aggregate	40.61	0.0812
Steel Fibers	0.00	0.0000
Total	100.00	0.2000

Mix Weights				
Item	Fraction of Volume	Volume		Mix Weight (lbs)
Water	0.14	0.027	cu ft	1.71
HRWR	0.04	0.007	cu ft	0.46
Portland Cement	0.24	0.048	cu ft	9.41
Silica Fume	0.07	0.014	cu ft	1.91
Fly Ash	0.11	0.022	cu ft	2.80
Fine Aggregate	0.41	0.081	cu ft	13.18
Steel Fibers	0.00	0.000	cu ft	0.00

202.5 ml

Figure 86. Mix 3M4 Proportions