# *DEVELOPMENT OF NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE*

FHWA/MT-17-010/8237-001

*Final Report*

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THE STATE OF MONTANA
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FEDERAL HIGHWAY ADMINISTRATION

*December 2017*

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RESEARCH PROGRAMS

MDT

# DEVELOPMENT OF NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE

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| 16. Abstract<br>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 20 times conventional concrete mixes.<br>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). An optimal mix that provided desired workability and strength was selected for further evaluation through a suite of mechanical and durability tests. The mixes developed as part of this research obtained compressive strengths of approximately 20 ksi with flows of 8-11 inches.<br>The mechanical properties tested in this research were compressive and tensile strength, elastic modulus, and shrinkage. Durability tests included alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze-thaw resistance, and scaling. | | | |
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# UNIT CONVERSIONS

| Measurement | Metric | English |
|---|---|---|
| Length | 1 cm | 0.394 in |
| | 1 m | 3.281 ft |
| | 1 km | 0.621 mile |
| Area | 1 $cm^2$ | 0.155 $in^2$ |
| | 1 $m^2$ | 1.196 $yd^2$ |
| Volume | 1 $m^3$ | 1.308 $yd^3$ |
| | 1 ml | 0.034 oz |
| Force | 1 N | 0.225 lbf |
| | 1 kN | 0.225 kip |
| Stress | 1 MPa | 145 psi |
| | 1 GPa | 145 ksi |
| Unit Weight | 1 $kg/m^3$ | 1.685 $lbs/yd^3$ |
| Velocity | 1 kph | 0.621 mph |

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# 1 INTRODUCTION

## 1.1 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 $2,000 per cubic yard, which is about 20 times the cost of conventional concrete.

## 1.2 Objectives

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.

## 1.3 Scope

These objectives were realized through the following tasks:

- A literature review was conducted to summarize material behaviors documented in past UHPC studies.
- Suitable UHPC mixes were developed 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.
- The resulting mixes obtained in the previous task were then scaled-up to more realistic batch sizes, and the effect of including steel fibers was investigated. The mixes were then modified accordingly to achieve a mix that consistently delivered the desired target parameters (e.g., 8-inch flow, 20 ksi 28-day compressive strength). The mechanical and durability performance of the mix was then characterized.

# 2 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.

## 2.1 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, 2010; 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; C. Goodspeed, S. Vanikar, & R. A. Cook, 1996; C. H. Goodspeed, S. Vanikar, & R. A. Cook, 1996; 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 expected to be 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 C1202 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).

## 2.2 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$^3$ for non-fiber-reinforced mixes (adding fiber reinforcement increases the material costs by \$470/yd$^3$). 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, Alkaysi, Naaman, & Hansen, 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. (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.

## 2.3 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 et al., 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 et al. (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, 2010; 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.

# 3 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.

## 3.1 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.

### 3.1.1 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 500μm, 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:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \qquad \text{(Equation 1)}$$

The parameter P is the percent of particles passing a sieve with diameter D. Dmin and Dmax 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≈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 (Dmax=1.18mm, Dmin=0.075mm, 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 |

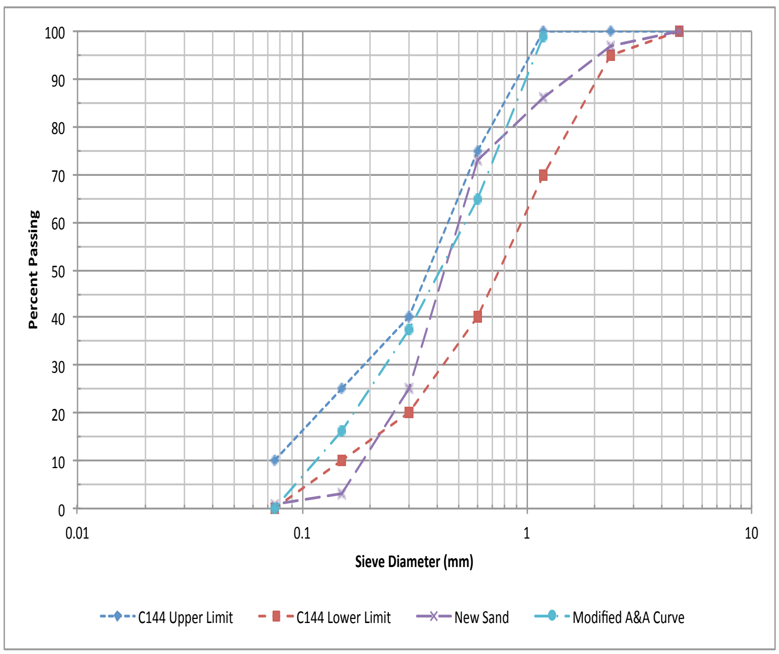



**Figure 1: Gradation Limits and Fine Aggregate Gradation Curve**

## 3.2 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**

| Item | Limit | Result |
|---|---|---|
| **Chemical Properties** | | |
| $SiO_2$ (%) | NA | 20.6 |
| $Al_2O_3$ (%) | 6.0 max | 4.0 |
| $Fe_2O_3$ (%) | 6.0 max | 2.8 |
| CaO (%) | NA | 64.2 |
| MgO (%) | 6.0 max | 2.5 |
| $SO_3$ (%) | 3.0 max | 3.1 |
| Loss on Ignition (%) | 3.0 max | 2.7 |
| Insoluble Residue (%) | 0.75 max | 0.4 |
| $CO_2$ (%) | NA | 1.7 |
| Limestone (%) | 5.0 max | 4.0 |
| $CaCO_3$ in Limestone (%) | 70 min | 98.0 |
| Inorganic Processing Addition (%) | 5.0 max | 1.2 |
| Potential Phase Compositions: | | |
| $C_3S$ (%) | NA | 58.0 |
| $C_2S$ (%) | NA | 15.0 |
| $C_3A$ (%) | 8.0 max | 6.0 |
| $C_4AF$ (%) | NA | 8.0 |
| $C_3S + 4.75C_3A$ (%) | NA | 86.5 |
| **Physical Properties** | | |
| Air Content (%) | 12.0 max | 29.75 |
| Blaine Fineness (m2/kg) | 260 min | 413 |
| Autoclave Expansion | 0.80 max | 0.02 |
| Compressive Strength (Mpa) (psi): | | |
| 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 | |
| Heat of Hydration (kJ/kg) (cal/g) | | |
| 7 days | NA | |

## 3.3 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**

| Item | Limit | Result |
|---|---|---|
| **Chemical Properties** | | |
| $SiO_2$ (%) | 85.0 min | 92.19 |
| $SO_3$ (%) | NA | 0.31 |
| $CL^-$ (%) | 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 ($kg/m^3$) | NA | 739.32 |
| Specific Surface Area ($m^2/g$) | 15.0 min | 22.42 |
| Accelerated Pozzolanic Activity - w/ Portland Cement (%) | 105 Min | 140.41 |

## 3.4 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 pozzolanicly 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**

| Item | Limit | Result |
|---|---|---|
| **Chemical Properties** | | |
| $SiO_2$ (%) | NA | 54.99 |
| $Al_2O_3$ (%) | NA | 16.77 |
| $Fe_2O_3$ (%) | NA | 6.00 |
| Sum of Constituents | 70.0 min | 77.76 |
| $SO_3$ (%) | 5.0 max | 0.5 |
| CaO (%) | NA | 11.4 |
| Moisture (%) | 3.0 max | 0.03 |
| Loss on Ignition (%) | 6.0 max | 0.06 |
| Avaliable Alkalis, as $Na_2O$ (%) | 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 |

## 3.5 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.

## 3.6 Steel Fibers

The steel fibers used in this research were 0.2 mm diameter by 13mm in length and were supplied by Nycon (Nycon-SF Type I "Needles"). The fibers are made of mono cold-drawn steel and have a specified tensile capacity of 400 ksi and a specified modulus of eleasticity of 29,000 ksi.

## 3.7 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**

| Material | Manufacturer | Cost (per ton) |
|---|---|---|
| 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 |
| Steel Fibers | Nycon | $1,600 |

# 4 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.

## 4.1 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. 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 |

## 4.2 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 2.

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 2: Hobart A200 Mixer**

## 4.3 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 3. 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 ¼ inch.

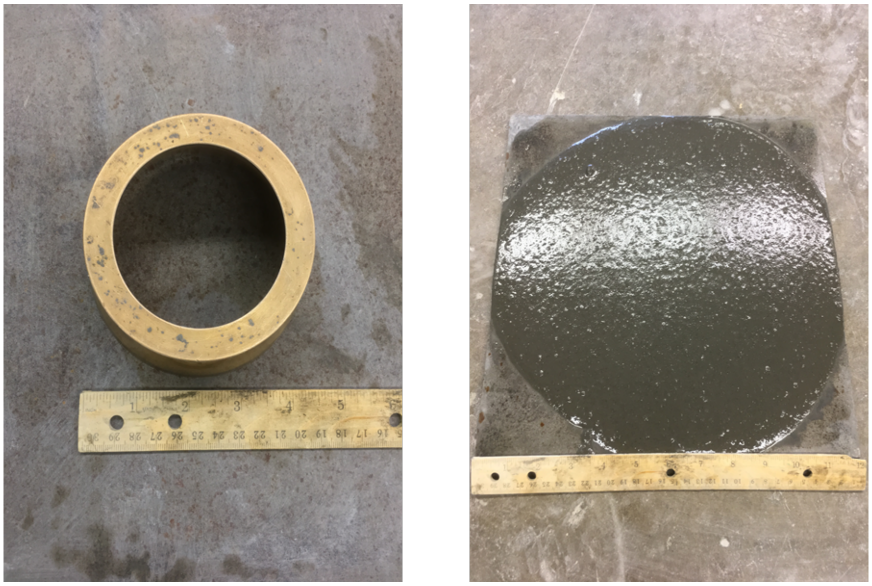


**Figure 3: Spread Cone Mold and spread measurement**

## 4.4 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 4, 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.

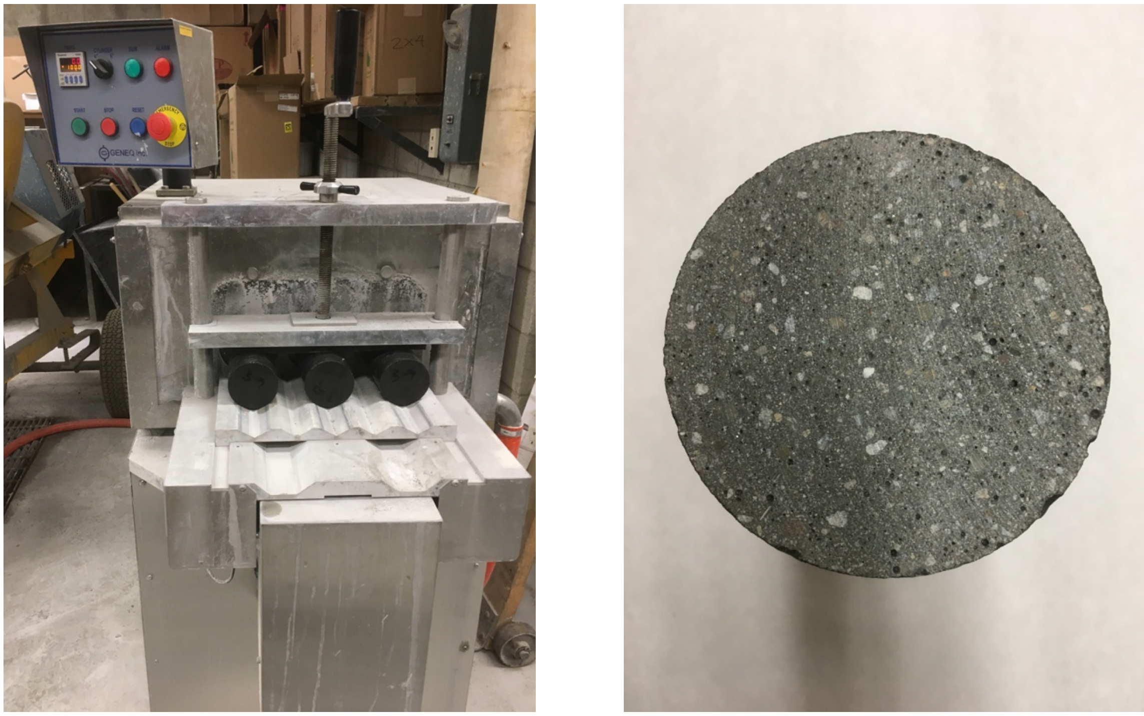


**Figure 4: Cylinder end grinder and prepared test specimen**

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 5 below shows a sample before and after failure.

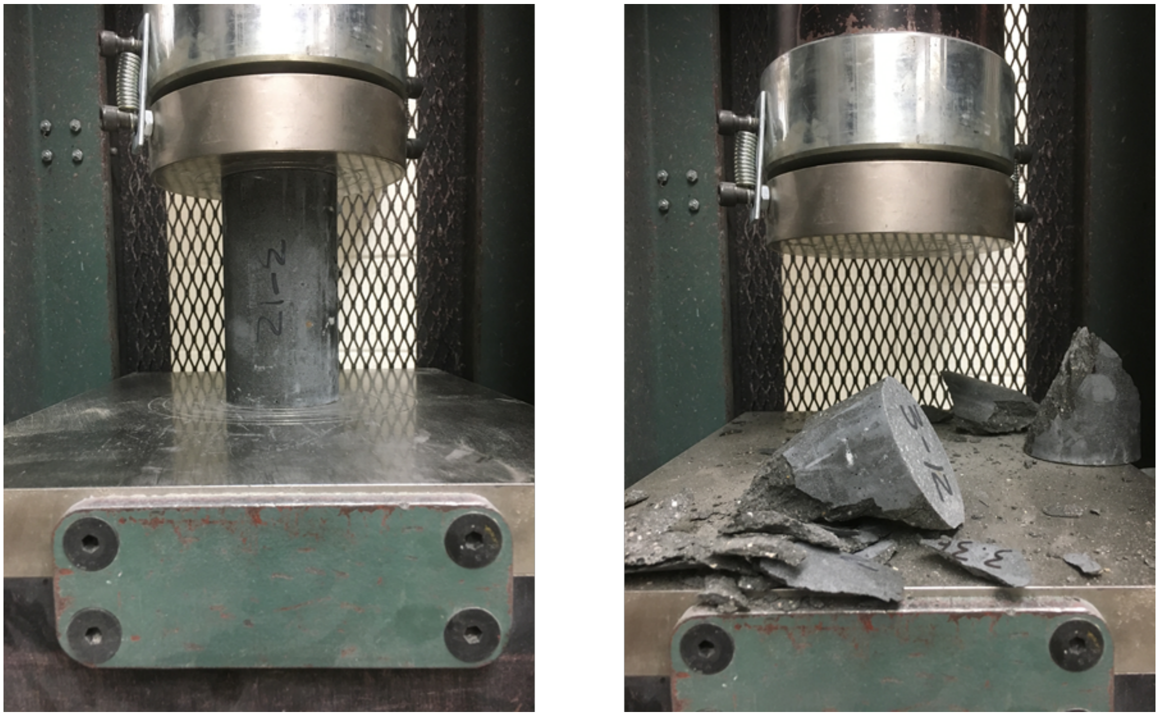


**Figure 5: UHPC specimen before and after testing**

# 5 EXPERIMENTAL DESIGN

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. (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.

## 5.1 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**

| Response | Specification |
|---|---|
| Flow | 11 to 13 inches |
| 28-Day Compressive Strength | 20 ksi |
| Cost | Maximum of \$500 per $yd^3$ |

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 |

## 5.2 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.

### 5.2.1 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.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2^2 + \beta_3 x_2 + \beta_4 x_2^2 + \cdots \beta_8 x_4^2 + \beta_9 x_1 x_2 + \beta_{10} x_1 x_3 + \cdots \beta_{14} x_3 x_4 \qquad \text{(Equation 2)}$$

Where y is the particular response of interest, $x_1 \ldots x_4$ are the independent variables, and $\beta_0 \ldots \beta_{14}$ 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$^3$ | Unit Wt. (lb/ft$^3$) |
| 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$^2$ | 96.10 | 0.877 | -1408.41 | 0.050 |
| HRWR/c | 206.44 | 0.000 | 2116.88 | 0.000 |
| HRWR/c$^2$ | -1232.45 | 0.341 | -8237.58 | 0.000 |
| SF/FA | -18.59 | 0.562 | 22.49 | 0.458 |
| SF/FA$^2$ | -9.83 | 0.572 | -27.12 | 0.156 |
| Sand/c | 3.01 | 0.009 | 26.07 | 0.003 |
| Sand/c$^2$ | 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

### 5.2.2 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 6 shows the flow plotted as a function of HRWR/c ratio and w/c ratio, while Figure 7 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.

Shown below in Figure 8 is the flow plotted as a function of Sand/c ratio and SF/FA ratio. Figure 9 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.

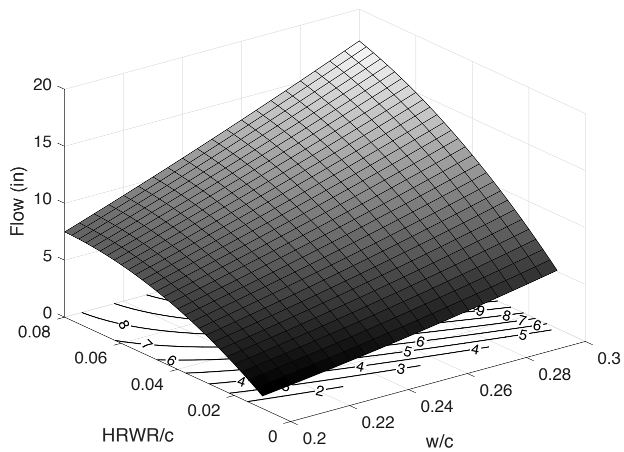



**Figure 6: Flow vs. HRWR/c Ratio and w/c Ratio**

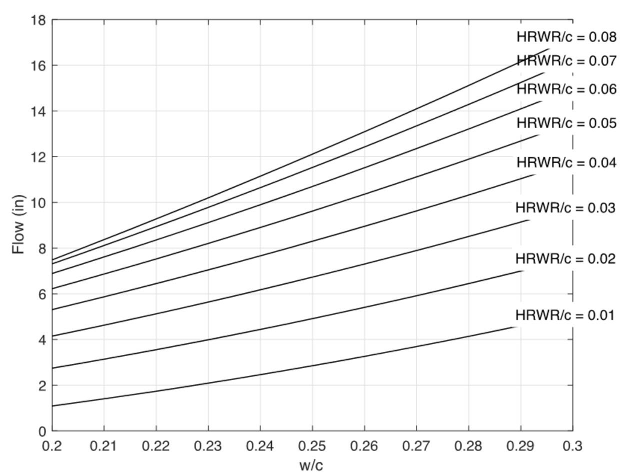



**Figure 7: Effect of HRWR/c Ratio and w/c Ratio on Flow**

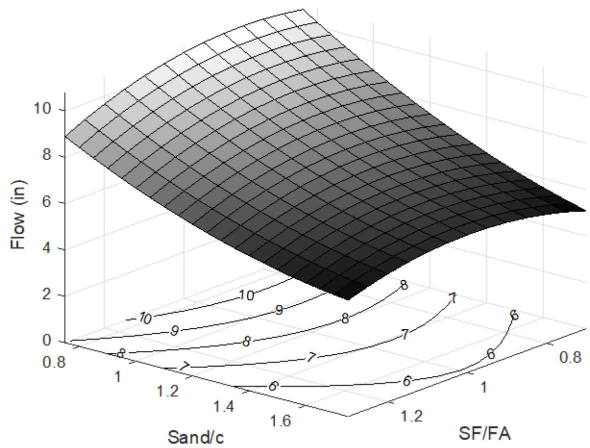



**Figure 8: Flow vs. Sand/c Ratio and SF/FA Ratio**

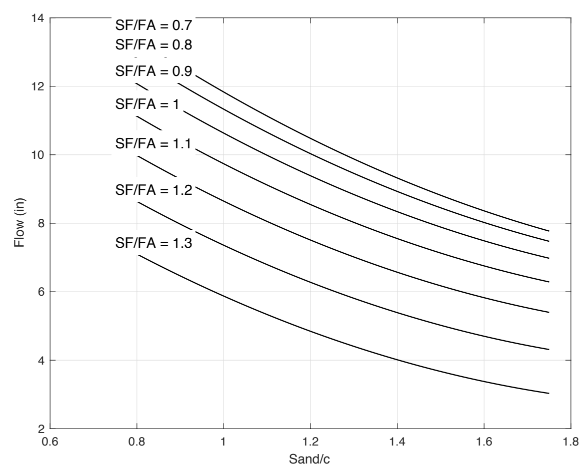



**Figure 9: Effect of SF/FA Ratio and Sand/c Ratio on Flow**

Figure 10 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 11. 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.

Shown in Figure 12 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 13. 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.

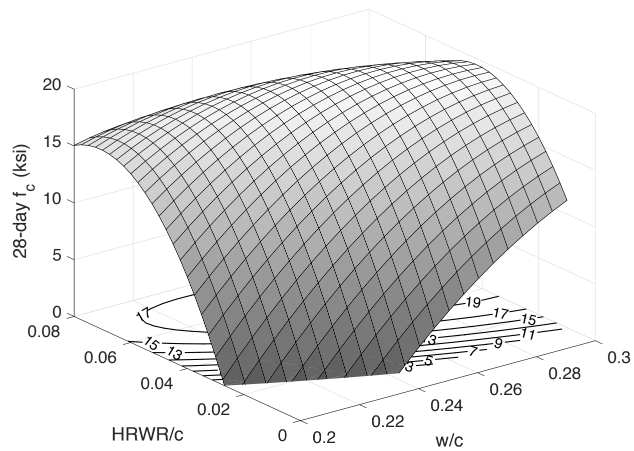



**Figure 10: 28-day Compressive Strength vs. HRWR/c Ratio and w/c Ratio**

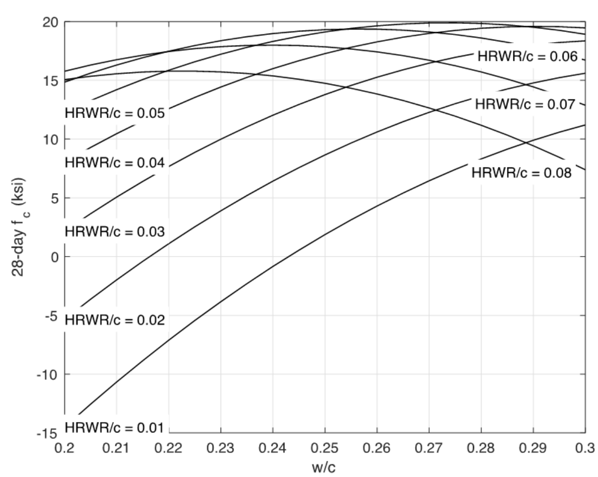



**Figure 11: Effect of HRWR/c Ratio and w/c Ratio on 28-day Compressive Strength**

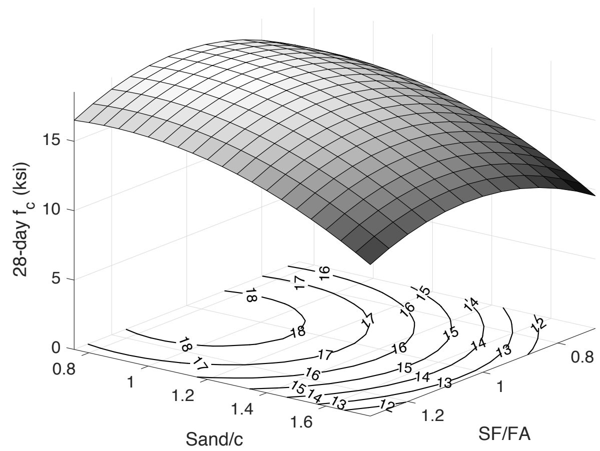



**Figure 12: 28-day Compressive Strength vs. Sand/c Ratio and SF/FA Ratio**

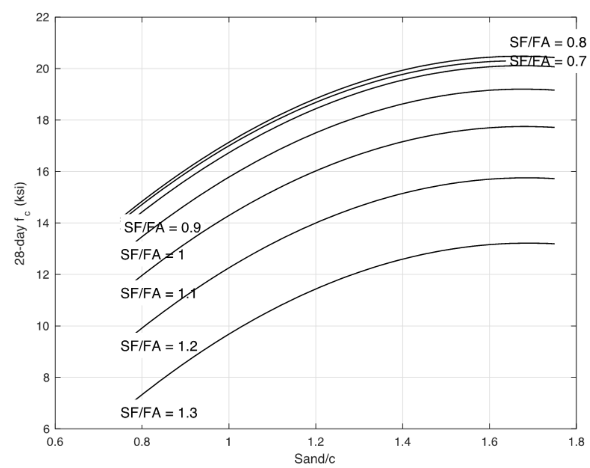



**Figure 13: Effect of SF/FA Ratio and Sand/c Ratio on 28-day Compressive strength**

### 5.2.3 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.

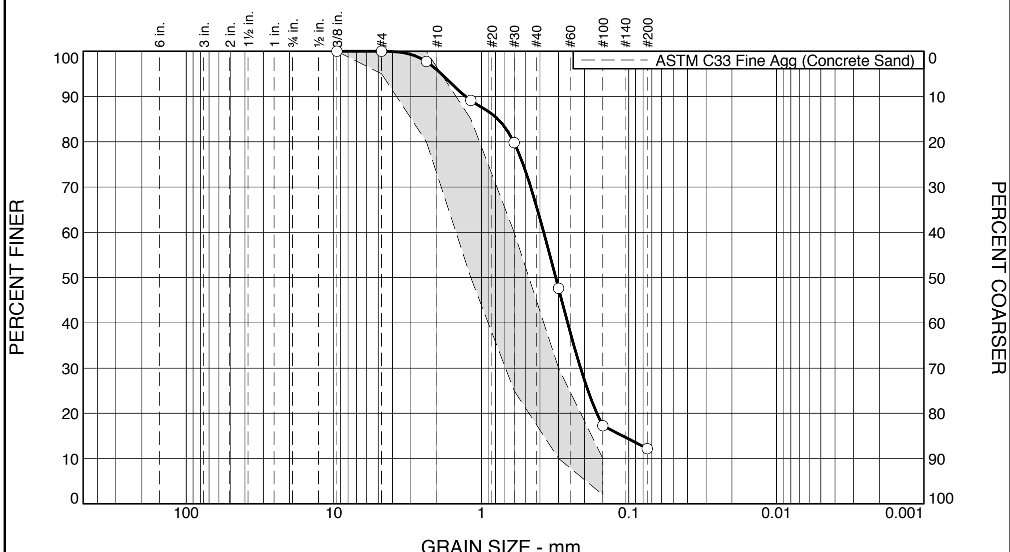
The 4-variable sand is shown in Figure 14, while the newly obtained sand is shown in Figure 15. The physical difference between these two sands can be observed in these figures, with the 4-variable sand appearing to be significantly finer than the new sand.

**Figure 14: 4-Variable Sand**

**Figure 15: 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 16 and Figure 17 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.

# Particle Size Distribution Report




| % +3" | % Gravel | | % Sand | | | % Fines | |
|---|---|---|---|---|---|---|---|
| | Coarse | Fine | Coarse | Medium | Fine | Silt | Clay |
| 0 | 0 | 0 | 4 | 30 | 54 | 12 | |

| Test Results (ASTM C136 & ASTM C117) | | | |
|---|---|---|---|
| Opening Size | Percent Finer | Spec.* (Percent) | Pass? (X=Fail) |
| 3/8" | 100 | 100 | |
| #4 | 100 | 95 - 100 | |
| #8 | 98 | 80 - 100 | |
| #16 | 89 | 50 - 85 | X |
| #30 | 80 | 25 - 60 | X |
| #50 | 48 | 10 - 30 | X |
| #100 | 17 | 2 - 10 | X |
| #200 | 12 | | |

* ASTM C33 Fine Agg (Concrete Sand)

**Material Description**

Quickcrete Bag

**Atterberg Limits (ASTM D 4318)**

**PL=** **LL=** **PI=**

**Classification**

**USCS (D 2487)=** **AASHTO (M 145)=**

**Coefficients**

$D_{90}$= 1.2794 $D_{85}$= 0.7723 $D_{60}$= 0.3777
$D_{50}$= 0.3134 $D_{30}$= 0.2124 $D_{15}$= 0.1100
$D_{10}$= $C_u$= $C_c$=

**Remarks**

F.M.=1.68

**Date Received:** **Date Tested:**

**Tested By:** CP

**Checked By:** CP

**Title:**

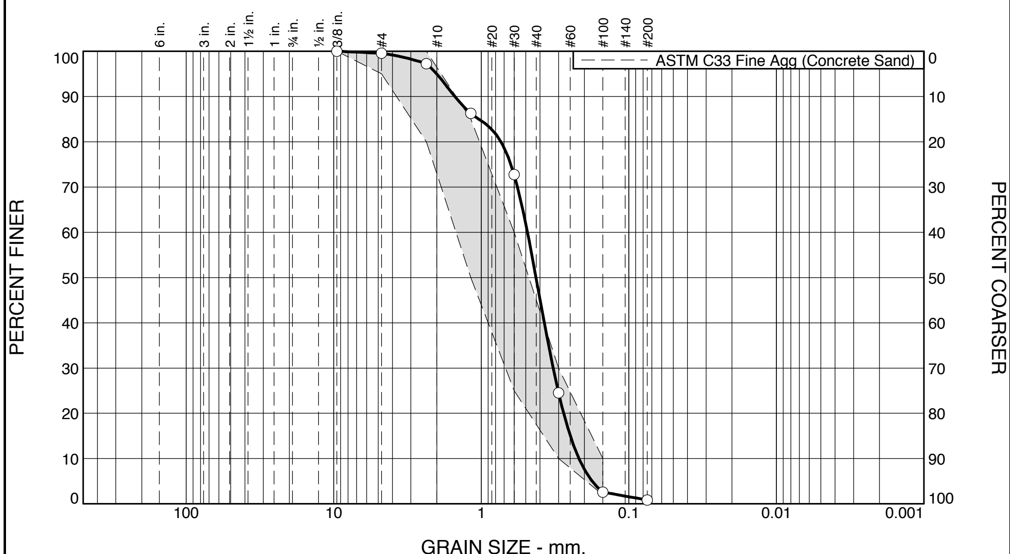
**Sample Number:** 8955 **Date Sampled:**

DOWL

**Client:**
**Project:**
**Project No:** **LAB #** 8955

**Figure 16: 4-Variable Sand Sieve Analysis**

## Particle Size Distribution Report




| % +3" | % Gravel | | % Sand | | | % Fines | |
|---|---|---|---|---|---|---|---|
| | Coarse | Fine | Coarse | Medium | Fine | Silt | Clay |
| 0 | 0 | 0 | 5 | 45 | 49 | 1 | |

**Test Results (ASTM C136 & ASTM C117)**

| Opening Size | Percent Finer | Spec.* (Percent) | Pass? (X=Fail) |
|---|---|---|---|
| 3/8" | 100 | 100 | |
| #4 | 100 | 95 - 100 | |
| #8 | 97 | 80 - 100 | |
| #16 | 86 | 50 - 85 | X |
| #30 | 73 | 25 - 60 | X |
| #50 | 25 | 10 - 30 | |
| #100 | 3 | 2 - 10 | |
| #200 | 0.9 | | |

* ASTM C33 Fine Agg (Concrete Sand)

**Material Description**

6"x12" cyl mold

**Atterberg Limits (ASTM D 4318)**

**PL=** **LL=** **PI=**

**Classification**

**USCS (D 2487)=** SP **AASHTO (M 145)=**

**Coefficients**

$D_{90}$= 1.5101 $D_{85}$= 1.0441 $D_{60}$= 0.4872
$D_{50}$= 0.4259 $D_{30}$= 0.3263 $D_{15}$= 0.2494
$D_{10}$= 0.2178 $C_u$= 2.24 $C_c$= 1.00

**Remarks**

F.M.=2.17

**Date Received:** **Date Tested:**
**Tested By:** CP
**Checked By:** CP
**Title:**

**Sample Number:** 8954 **Date Sampled:**

DOWL

**Client:**
**Project:**
**Project No:** **LAB #** 8954

**Figure 17: 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.

## 5.3 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.

### 5.3.1 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**

| Independent Variable | Axial Low | Axial High | Factorial Low | Center | Factorial High |
|---|---|---|---|---|---|
| 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$^3$ |
| 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 |

**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$^2$ | -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$^2$ | -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$^2$ | -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*Sand/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.

### 5.3.2 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 18 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.

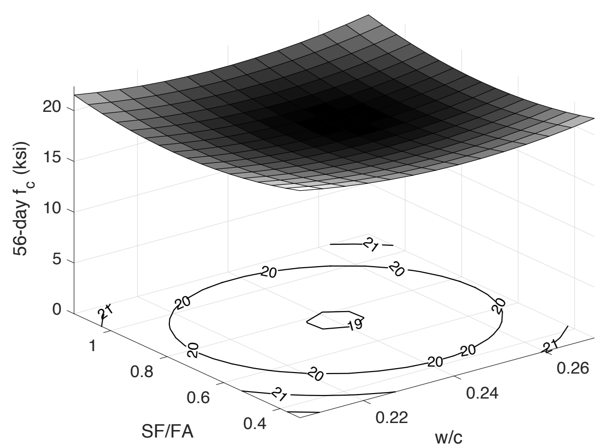



**Figure 18: 56-day Compressive Strength vs. SF/FA Ratio and w/c Ratio**

Figure 19 shows 56-day compressive strength plotted as a function of HRWR/c ratio and SF/FA ratio. Like the trend observed in Figure 18, 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.

56-day compressive strength is plotted as a function of HRWR/c ratio and w/c ratio in Figure 20. 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).

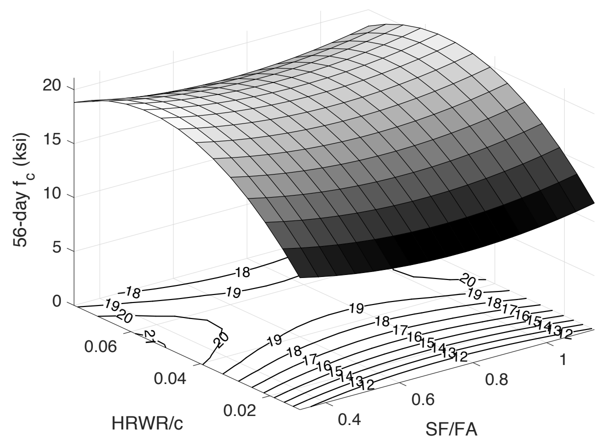



**Figure 19: 56-day Compressive Strength vs. HRWR/c Ratio and SF/FA Ratio**

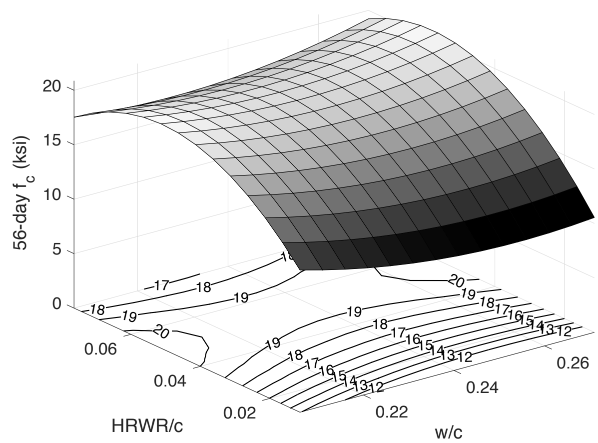



**Figure 20: 56-day Compressive Strength vs. HRWR/c Ratio and w/c Ratio**

Figure 21 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).

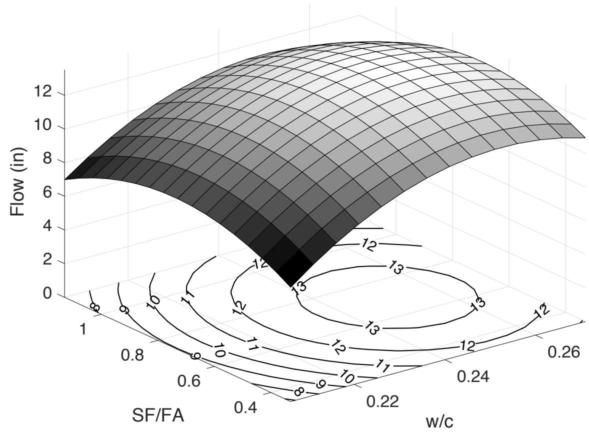



**Figure 21: Flow vs. SF/FA Ratio and w/c Ratio**

Flow is plotted as a function of HRWR/c ratio and SF/FA ratio in Figure 22. 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 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.

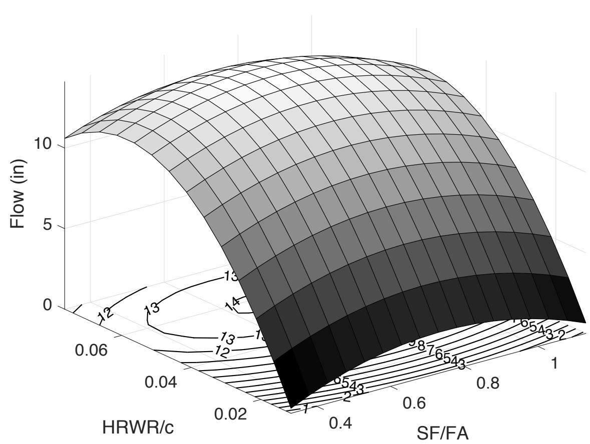



**Figure 22: Flow vs. HRWR/c Ratio and SF/FA Ratio**

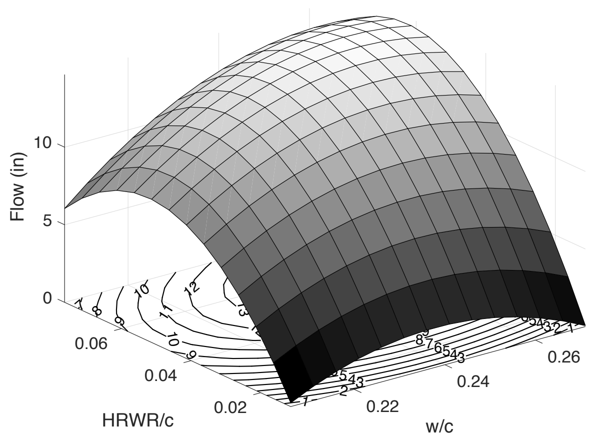



**Figure 23: Flow vs. HRWR/c Ratio and w/c Ratio**

The 7-, 28-, and 56-day compressive strength surfaces (bottom, middle, and top respectively) are plotted vs. the various concrete mix parameters in Figure 24, Figure 25, and Figure 26 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 24, 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.

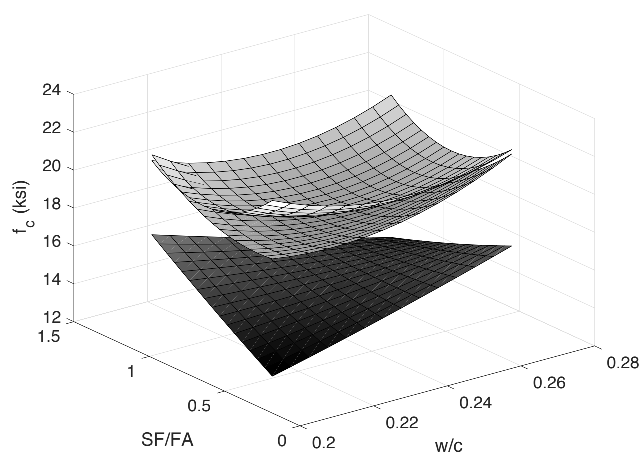



**Figure 24: Compressive Strength vs. SF/FA Ratio and w/c Ratio**

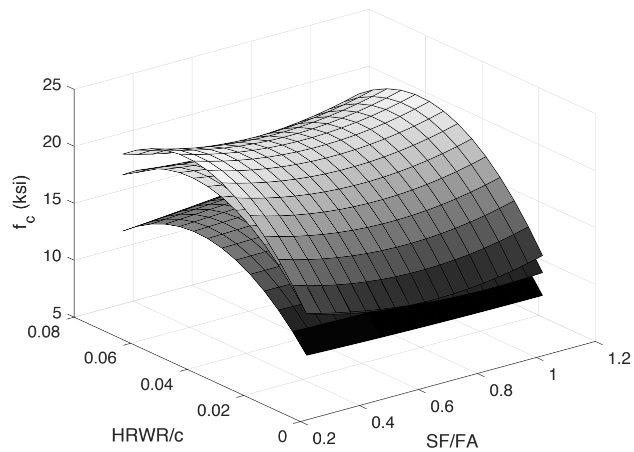



**Figure 25: Compressive Strength vs. HRWR/c Ratio and SF/FA Ratio**

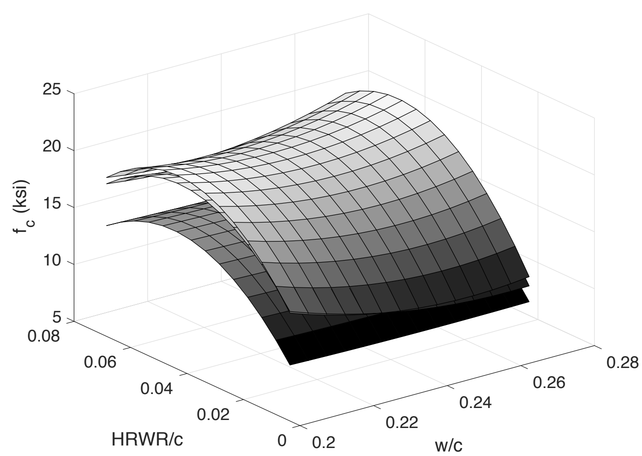



**Figure 26: Compressive Strength vs. HRWR/c Ratio and w/c Ratio**

Figure 27 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.

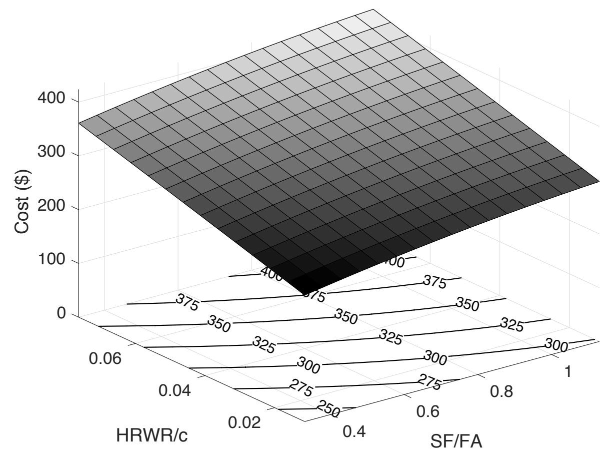



**Figure 27: Cost vs. HRWR/c Ratio and SF/FA Ratio**

### 5.3.3 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.

# 6 OPTIMIZATION, MODIFICATION, AND SELECTION OF MIX

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 8-11 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. 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.

## 6.1 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 used the same Sand/c 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).

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.

**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 | Predicted (95% CI) | Measured | Predicted (95% CI) | Measured | 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) | 15.1 |
| 56-day *f'c* (ksi) | 20.0 (17.3 to 22.7) | 16.9 | 21.0 (17.5 to 24.5) | 18.2 | 21.0 (15.9 to 26.0) | 20.4 | 20.0 (17.6 to 22.3) | 18.6 |

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 Figure 28 through Figure 31. 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.

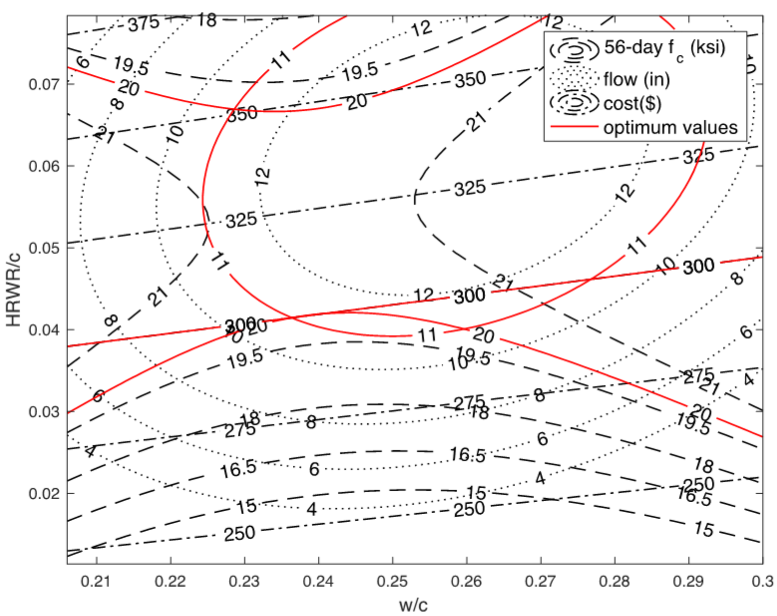



**Figure 28: 3M1 Optimization Contour Lines**

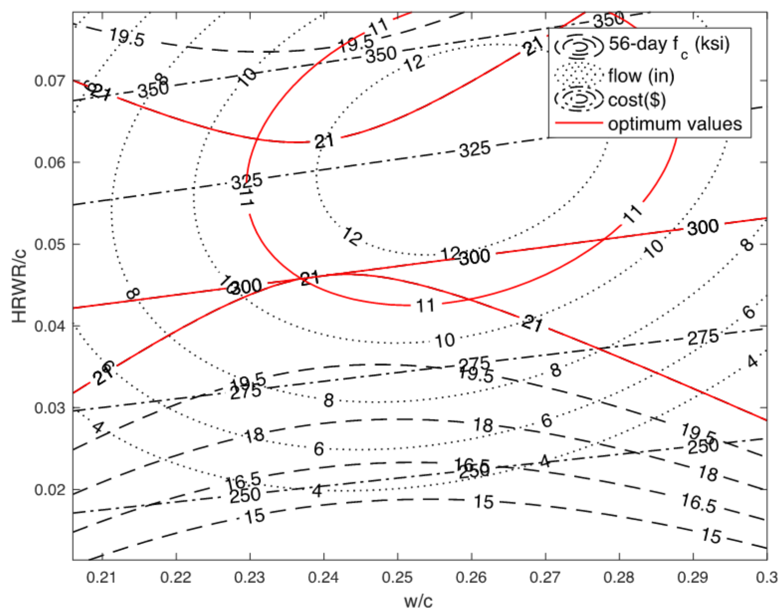



**Figure 29: 3M2 Optimization Contour Lines**

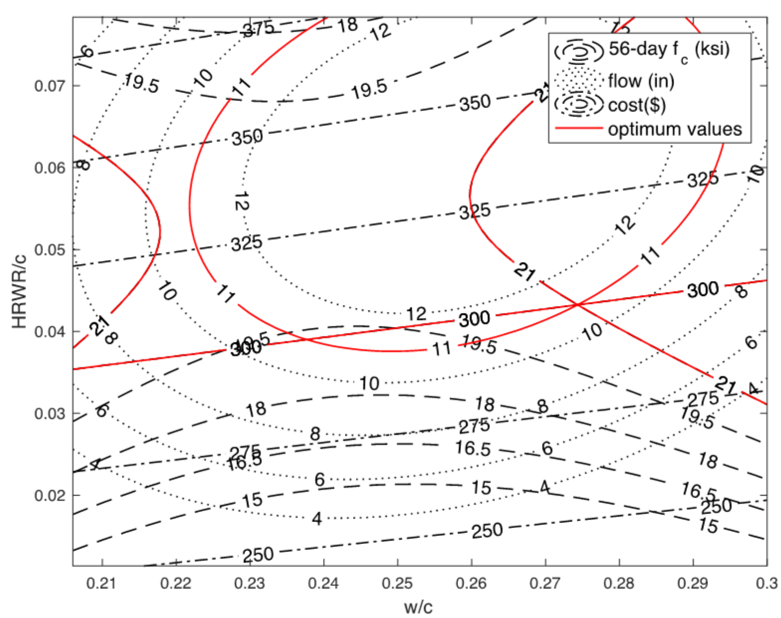



**Figure 30: 3M3 Optimization Contour Lines**

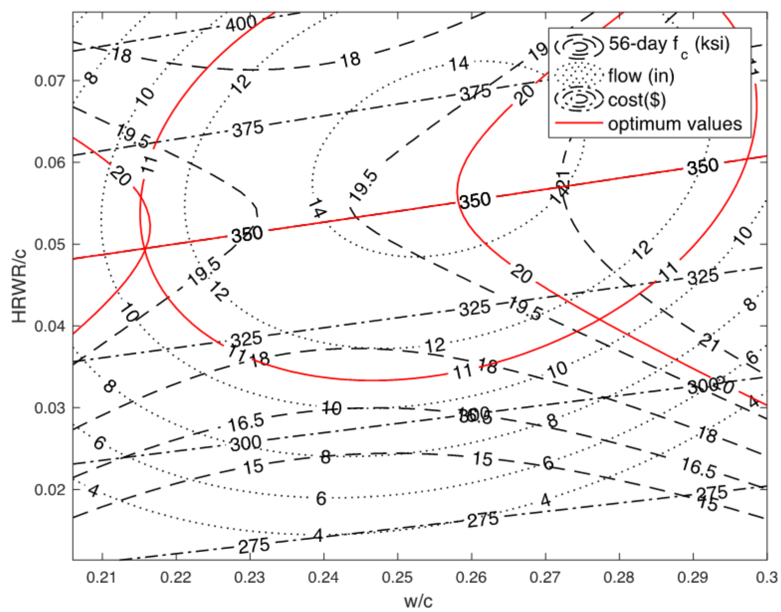



**Figure 31: 3M4 Optimization Contour Lines**

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. Included in Table 16 are the measured response obtained from these mixes. As can be observed in this table, 3M1 had a measured flow within 1.0 inch of the predicted value, and had measured 7-, 28-, and 56-day compressive strengths within 10, 14, and 15 percent of the predicted strengths, respectively. 3M2 had a measured flow within 0.25 inches of the predicted value, while the 7-, 28-, and 56-day strengths were within 4, 7, and 13 percent of the respective predicted values. 3M3 had a measured flow within 1.5 inches of the predicted flow, and measured 7-, 28-, and 56-day compressive strengths within 12, 12, and 3 percent of their predicted values. 3M4 had a measured flow within 0.5 inches of the predicted value, and a 7-, 28-, and 56-day compressive strength within 26, 21, and 7 percent of the predicted values.

Overall, the response surface models developed in this study reasonably predicted the responses and served as an efficient tool for developing mix designs. All measured responses fell within the 95% confidence interval, with the exception of the 56-day compressive strength of 3M1, and the 7-day and 28-day compressive strength of 3M4, which are slightly below the lower bounds. However, it is worth noting that all of the measured compressive strengths were lower than the predicted values. 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.

## 6.2 Scaled-Up Trial Mixes, Resultant Modifications, and Selection of Mix

The mixes discussed above were evaluated further by carrying out scaled-up 1.5-$ft^3$ batches using conventional concrete/mortar mixing equipment. It should be restated that all of the mixes conducted thus far in the research were 0.2 $ft^3$, and were mixed using a Hobart bench-top mixer (Figure 2). Several 1.5-$ft^3$ mixes were attempted using a 7-$ft^3$ fixed-vane rotating drum mixer, and it was determined that this type of mixer was not appropriate for the UHPC mixes developed in this research; the mixing action provided by this mixer did not adequately distribute the water and water reducer, which resulted in a very stiff, non-flowing mixes. The 1.5-$ft^3$ mixes were then attempted in a standard fixed-drum rotating-vane mortar mixer, and it was determined that this type of mixer provided adequate mixing action/energy to properly mix the UHPC mixes developed in this research. However, it was observed that the hardened concrete properties of these scaled-up mixes varied from what was observed for the 0.2-$ft^3$ batches. Of particular importance, the compressive strengths and flows of these scaled-up mixes were less than what was observed for the small-scale mixes.

To address the issues discussed above, several modified mixes were carried out at this larger scale, and it was determined that the center point mix used in the 3-variable CCD (mixes 3-15C and 3-16C) performed the best with respect to desired responses at this scale. Because of this, this mix was chosen for further evaluation with the mechanical and durability tests (discussed in the following chapters). For convenience, the mix proportions for this mix are repeated in Table 17. It should also be noted that the effect of steel fibers on the performance of this mix was investigated, and it was determined that the inclusion of fibers (2 percent by volume) did not significantly affect the flow or ultimate compressive strength. That being said, the steel fibers increased the tensile capacity of the concrete, and reduced the variability observed in the compressive strengths. The projected cost of this mix (sans freight costs) was estimated at \$350/$yd^3$ without fibers, and \$560/ $yd^3$ with steel fibers.

**Table 17: Selected-UHPC Mix Parameters**

| w/c Ratio | Sand/c Ratio | SF/FA Ratio | HRWR/c Ratio |
|---|---|---|---|
| 0.240 | 1.40 | 0.75 | 0.045 |

In addition to the observed variability with batch size, a significant amount of variability was observed between repetitions of identical batches. A study was then carried out to determine the cause of this variability between batches, and based on this study it was determined that much of this variability could be reduced by including steel fibers, and modifying the curing procedure and the cylinder preparation technique. Specifically, newly cast cylinders were capped with plastic wrap rather than conventional plastic cylinder mold caps, which prevented the loss of moisture at the surface of these cylinders. Also, based on findings from the FHWA (Graybeal, 2006a), the concrete cylinders were left in their molds for 48 hours before being stripped and placed in the cure room (rather than 24 hours). In regards to hardened concrete cylinder preparation, the top half inch of compressive cylinders were cut off with a tile saw prior to grinding, which removed the portion of concrete where entrapped air was prevalent.

# 7 MECHANICAL PROPERTIES OF UHPC MIX

The concrete mixture developed in the previous chapter was evaluated with a suite of mechanical and durability tests to assess its potential for use in construction projects in Montana. This chapter reports on the results of the mechanical tests, while the following chapter reports the results of the durability tests. A summary of the mechanical properties tested in this research is provided in Table 18. It should be noted that multiple batches of the UHPC mix was required to complete all of these tests, and although some variation was observed between mixes, this variation was not substantial.

**Table 18: Mechanical Properties**

| Material Property | ASTM Test Method |
|---|---|
| Compressive Strength | C39 |
| Elastic Modulus | C469 |
| Modulus of Rupture | C78 |
| Splitting Tensile Strength | C496 |
| Shrinkage | C512 |

## 7.1 Unconfined Compressive Strength

An often cited and important property of hardened concrete is its unconfined compressive strength, which can also be indicative of many other material properties. Table 19 and Figure 32 provide the average compressive strength profile as a function of time for the UHPC concrete over 56 days. These strengths were determined in accordance with ASTM C39, and were calculated as the averages of two 3-by-6-inch test cylinders. As can be seen in the table and figure, as, expected, the concrete continued to gain strength over time, reaching a strength of just over 20 ksi at 56 days.

**Table 19: Unconfined Compressive Strength**

| Age (days) | *f'c* (ksi) |
|---|---|
| 7 | 16.4 |
| 28 | 19.2 |
| 56 | 20.1 |

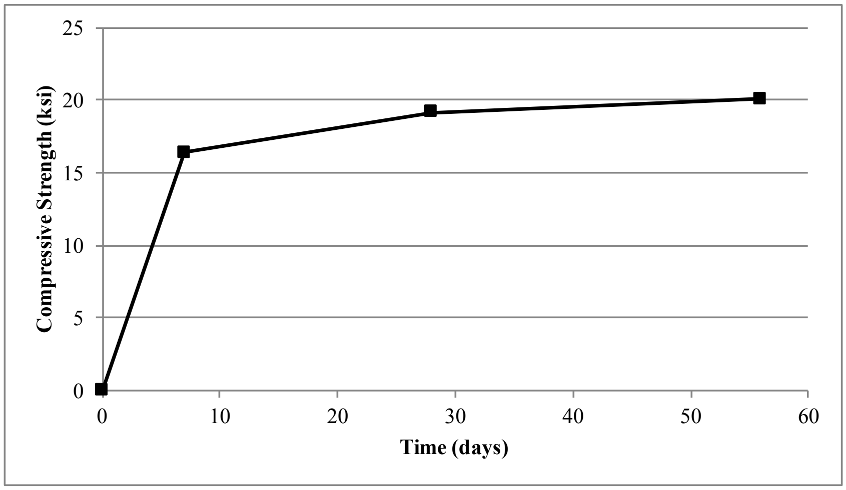



**Figure 32: Unconfined Compressive Strength vs. Time**

## 7.2 Elastic Modulus

The elastic modulus of the concrete was determined as the average of two tests on 4-by-8-inch cylinders, tested in accordance to ASTM C469. The results for each concrete are provided in Table 20 and Figure 33. Also included in the table, for comparison, are the predicted values of the modulus according to ACI 318: $E_c = {w_c}^{1.5} 33\sqrt{f'_c}$. In this equation, $E_c$ is the elastic modulus in psi, $w_c$ is the unit weight of the concrete in pcf (153 pcf for UHPC in this study), and $f'_c$ is the compressive strength of the concrete in psi.

Generally speaking, the elastic modulus of the concrete increased with time, as one would expect with increasing compressive strength, reaching a value of approximately 6,800 ksi at 56 days. With respect to the ACI predicted moduli, the tested moduli were significantly less than what is predicted by this methodology, with a ratio of measured to predicted moduli between 0.73 and 0.77. This result is consistent with what can be observed in the data collected by the FHWA (Graybeal, 2006a) study on the characterization of UHPC material properties, and may be associated with the high paste content and lack of coarse aggregates in the UHPC mixtures.

**Table 20: Elastic Modulus**

| Age (days) | $f'c$ (ksi) | $E_{Meas}$ (ksi) | $E_{Pred}$ (ksi) | $\frac{E_{Meas}}{E_{Pred}}$ |
|---|---|---|---|---|
| 7 | 16.4 | 5977 | 7993 | 0.75 |
| 28 | 19.2 | 6289 | 8643 | 0.73 |
| 56 | 20.1 | 6787 | 8847 | 0.77 |

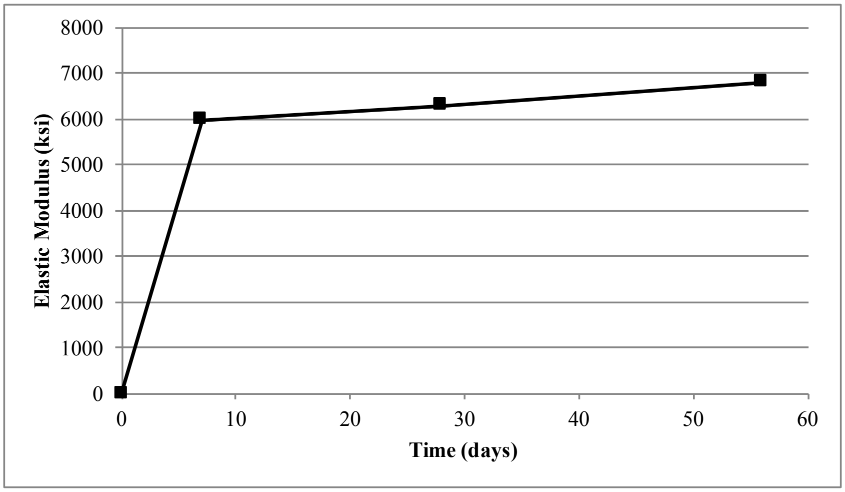



**Figure 33: Elastic Modulus**

## 7.3 Flexural Tensile Strength

The flexural tensile strength of the concrete at 28 days was calculated as the average of two 20-by-6-by-6 inch prisms tested according to ASTM C78. The results of these tests are provided in Table 21. The steel fibers included in the UHPC mix allow the flexural specimens to continue to carry load beyond the formation of an initial crack; therefore, the measured ultimate load from these tests do not provide a good measure for the cracking capacity of the concrete. The overall force-deformation response from the flexural tests can be used to determine the stress at the onset of cracking. Specifically, initial cracking was determined from the force-deformation response by finding the first point at which there is a sudden reduction in applied load and a distinct reduction in stiffness. This point was clearly defined in the two specimens tested in this research. Included Table 21 are the stresses calculated from the observed load at initial cracking and ultimate capacity, along with the tensile strengths predicted by the ACI equation for modulus of rupture: $f_r = 7.5\sqrt{f'_c}$ ($f_r$ and $f'_c$ in psi). It should be noted that the tensile stress calculated at ultimate load is for comparative purposes, as the equation used to calculate this stress from applied load assumes no cracking and linear-elastic behavior, which is not the case at ultimate load (Graybeal, 2006a).

As can be observed in the table, the UHPC concrete has significant tensile strength, with an average stress at initial cracking of nearly 2 ksi, approximately 90 percent greater than what would be expected of a conventional non-fiber reinforced concrete with similar compressive strength. The stress calculated at ultimate load is significantly higher than the load at initial cracking (approximately 70 percent). Again, these findings are consistent with previous research conducted by the FHWA (Graybeal, 2006a).

**Table 21: Flexural Tensile Strength**

| Stress at Initial Crack (ksi) | Stress at Ultimate (ksi) | Predicted (ksi) | Meas/Predicted Initial | Meas/Predicted Ultimate |
|---|---|---|---|---|
| 1.98 | 3.39 | 1.05 | 1.89 | 3.23 |

## 7.4 Splitting Tensile Strength

The splitting tensile strength of the UHPC mix was tested by applying a diametral compressive force along the length of 6-by-12 inch concrete cylinders according to ASTM C496. As discussed above for flexural tensile strength, the steel fibers included in this mix provided for increased strength beyond the formation of an initial crack, and therefore the ultimate load observed in these tests are not a good measure for the cracking strength of the concrete. That being said, the test setup used for these tests did not allow for the determination of the onset of initial cracks, as was done for the flexural tests. Therefore, only the average stresses calculated from the ultimate loads are provided in Table 22. Additionally, the mechanics equations used to calculate these stresses again assume uncracked linear-elastic behavior, which is not the case at ultimate load. Because of these factors, the results here are provided for comparative purposes only. Also, for comparison, the predicted strengths calculated according to ACI 318 as $f_{ct} = 6.7\sqrt{f'_c}$ ($f_{ct}$ and $f'_c$ in psi) are included in this table.

Referring to Figure 34, as expected, the concrete gained strength between 7 and 28 days, but experienced a slight decrease in strength between 28 and 56 days. It should be noted that the 28-day stress at ultimate load from the split cylinder tests is close to that observed from the flexural tests discussed above (3.30 ksi vs 3.39 ksi). In regards to the applicability of the ACI estimate for tensile capacity based on compressive strength, the observed tensile strength is significantly greater than what is predicted the ACI methodology, as expected since this methodology is meant for non-fiber-reinforced conventional concrete.

**Table 22: Splitting Tensile Strength**

| Age (days) | Stress at Ultimate (ksi) | Predicted at Initial Crack (ksi) | Meas/Predicted |
|---|---|---|---|
| 7 | 2.52 | 0.96 | 2.62 |
| 28 | 3.30 | 1.04 | 3.18 |
| 56 | 2.25 | 1.06 | 3.06 |

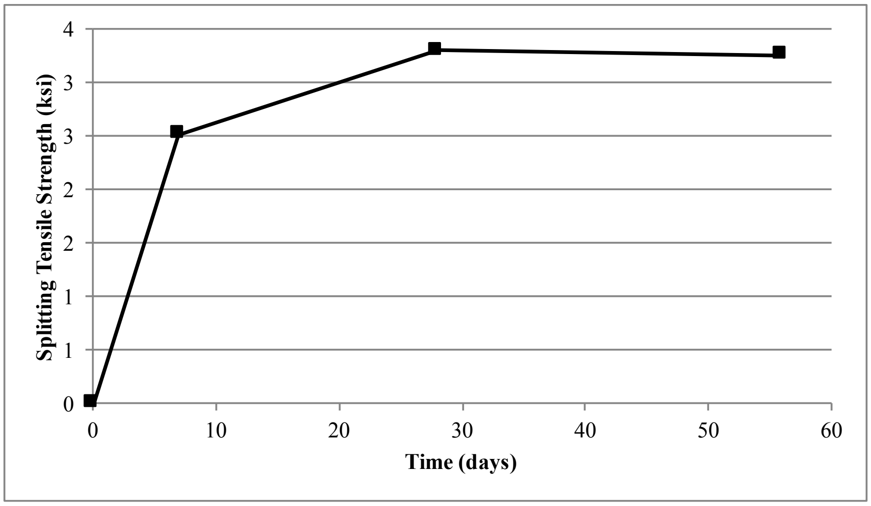



**Figure 34: Splitting Tensile Strength vs. Time**

## 7.5 Shrinkage

Shrinkage strains were measured from two 6-by-12 inch cylinders in substantial accordance with the procedures outlined in ASTM C512. Although this test methodology is not intended for strictly measuring shrinkage, it provides a simple methodology of measuring shrinkage strain in concrete specimens. It should be noted, that variations in humidity would affect these results, and this was not controlled in this experiment. That being said, these results provide a benchmark for expected shrinkage under humidity conditions typically found in Montana. Each cylinder was equipped with a vibrating wire strain gauges to monitor deflections (Geokon Model 4000). After moist curing for 28 days, the cylinders were placed in the laboratory at room temperature, where they remained for the duration of the test.

The average measured shrinkage strains over 123 days are provided in Figure 35. As can be seen in this figure, the concrete continues to shrink over time, with the rate of shrinkage decreasing with time.

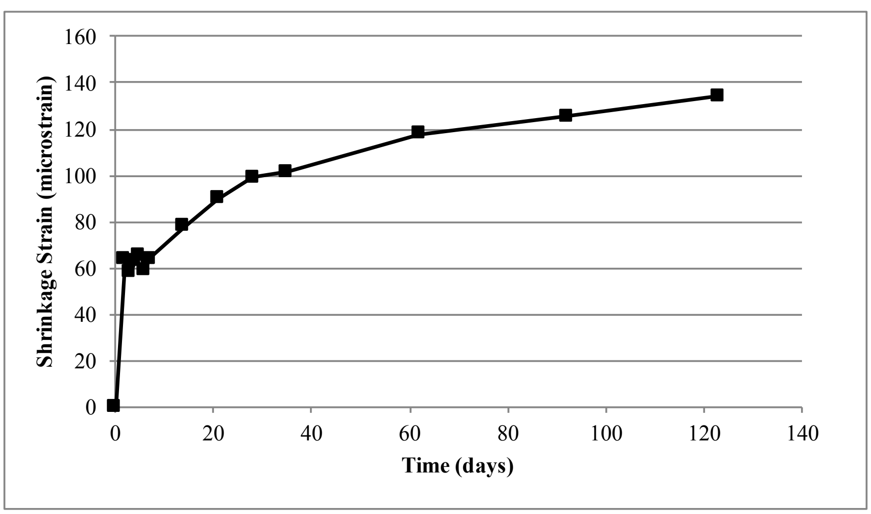



**Figure 35: Average Shrinkage Strain vs. Time**

# 8 DURABILITY OF UHPC MIX

In this chapter, the durability of the UHPC mix developed in this study is evaluated. The tests used to evaluate the durability are summarized in Table 23.

**Table 23: Durability Properties**

| Durability Property | ASTM Test Method |
|---|---|
| Abrasion | C944 |
| Absorption | C642 |
| Alkali Silica Reactivity | C1567 |
| Chloride Permeability | C1202 |
| Freeze-Thaw | C666 |
| Scaling | C672 |

## 8.1 Abrasion

The abrasion properties of the UHPC mix design was determined according to ASTM C944. Two specimens were abraded using a 22-pound load applied to a 3¼-inch rotating cutter. The cutter was rotated at approximately 200 rpm for a duration of 2 minutes. The resulting change in mass for the two specimens is provided in Table 24. As can be observed in this table, both specimens experienced very little mass loss with the 22-pound load (11.3 and 10.9 grams). It should also be noted that both specimens had wear depths less than 1.0 mm. For reference, concretes with wear depths of less than 1.0 mm meet FHWA standards for Grade 2 high performance structural concrete (Goodspeed et al., 2013). Both specimens warranted a further investigation using a doubled load (44 pounds), and again, there was very little mass loss and wear depth for either sample.

**Table 24: Abrasion tests results**

| | Mass Loss | |
|---|---|---|
| Specimen # | 22 Pound (g) | 44 Pound (g) |
| 1 | 11.3 | 23.4 |
| 2 | 10.9 | 31.5 |

## 8.2 Absorption

Absorption is one of several methods used to gauge the permeability of concrete. Permeability can serve as an indicator of performance. For example, concrete with low permeability typically has an increased resistance to freeze-thaw cycles and to infiltration of deleterious substances. For this research, absorption was determined with two 3-by-6 inch cylinders in accordance with ASTM C642, which estimates the total void volume of the test samples.

As expected the UHPC concrete was found to have very little pore space. Specifically, the two UHPC specimens were found to have void volumes of 1.36 and 1.304 percent. Relative to conventional Portland cement concrete pavements, a total void volume less than or equal to 12 percent will typically result in a durable concrete with respect to permeability (Fick, 2008).

## 8.3 Alkali Silica Reactivity

Alkali-silica reactivity of the UHPC concrete was tested according to ASTM C1567. This method monitors the expansion of mortar bars that are submerged in an alkaline solution at 176°F for 14 days. According to this specification, for conventional concretes, expansion of less than 0.10 percent after 14 days of exposure is indicative of innocuous behavior, while expansion of more than 0.20 percent is indicative of potentially deleterious expansions. It should be noted that the mix design parameters (e.g., w/cm ratio and paste content) and gradations prescribed by ASTM C1567 were not explicitly followed in this research, as these parameters were not appropriate for UHPC. For this research, no modifications were made to the UHPC mix design, and steel fibers were included. Because the mix design varies from what is specified in ASTM C1567, the specified thresholds in this test and this test in general may not be appropriate for evaluating the ASR potential of this mix. Further, unintended curing may take place during the testing process, and would subsequently affect the results (Graybeal & Tanesi, 2007).

Despite the above-mentioned issues with this testing methodology, ASR is not expected to be an issue with UHPC due to its low permeability, and high silica fume and fly ash contents (Graybeal & Tanesi, 2007). The average expansions of four mortar bars are plotted versus time in Figure 36. As can be observed, and as expected, the mortar bars expanded very little during this testing.

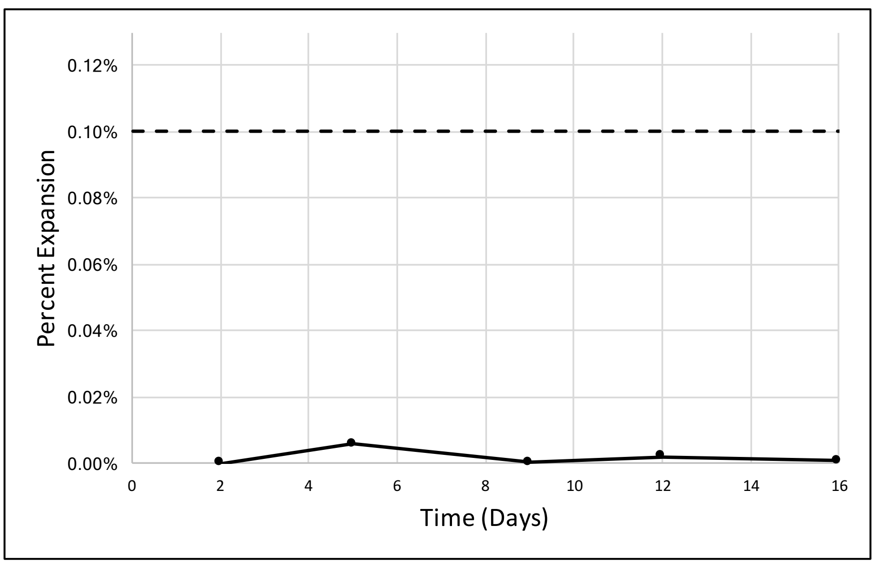



**Figure 36: Average ASR Expansion vs Time**

## 8.4 Chloride Permeability

ASTM C1202/AASHTO T277 was used to determine the chloride permeability resistance of the UHPC concrete. This test methodology measures the coulombs passed through a vacuum saturated 4-inch diameter by 2-inch thick cylinder exposed to a current for 6 hours. It should be noted that the concrete mix used in this test included steel fibers; however, because these fibers are not interconnected throughout the concrete matrix they are not expected to affect the results of this test. Two specimens were tested for this research, and the results are reported in Table 25. As can be observed in this table, and as expected, this concrete is not susceptible to chloride ion penetration, with an average of 70 coulombs passed and a rating of Negligible. For reference, a concrete determined to have a low susceptibility to chloride ion penetration would be in the range of 1,000-2,000 coulombs.

**Table 25: Chloride permeability results**

| Mix | Age at Test (days) | Avg. Adj. Charge Passed (coulombs) | Chloride Ion Penetrability |
|---|---|---|---|
| Specimen 1 | 56 | 75 | Negligible |
| Specimen 2 | 56 | 56 | Negligible |

## 8.5 Freeze-Thaw Resistance

A primary mechanism of physical deterioration for unprotected concrete is prolonged exposure to cycles of freezing and thawing in the presence of moisture. This damage, which can occur at both a microscopic and macroscopic level, accumulates over time, eventually contributing to the failure of the concrete. The freezing-and-thawing resistance of the UHPC was quantified according to ASTM C666. This test method consists of subjecting concrete specimens to multiple freezing-and-thawing cycles while fully saturated. Mass loss and change in dynamic modulus are monitored as a function of accumulated freezing-and-thawing cycles. As may be obvious, the degree of damage sustained by the concrete due to microcracking and macrocracking under freezing-and-thawing action is reflected by its attendant loss of mass and stiffness, where material stiffness can be nondestructively measured in terms of dynamic modulus. The relative dynamic moduli were calculated from fundamental transverse frequency measurements (ASTM C215). The durability factor, $DF$, is used as one of the indicators of performance. The durability factor is defined as: $DF = PN/M$, where $P$ is the relative dynamic modulus, and $N$ and $M$, in this case, are the total number of cycles at which the exposure is to be terminated (300).

Three 3-by-4-by-16 inch rectangular prisms were cast from the UHPC mix, and exposed to several freeze-thaw cycles per day for 300 cycles. The results from this test are reported in Table 26, while the relative dynamic moduli for the three specimens are plotted in Figure 37 as a function of cycles.

**Table 26: Freeze-thaw durability results**

| Specimen # | # of Cycles | Mass Change (%) | Durability Factor |
|---|---|---|---|
| 1 | 300 | -0.089 | 103.2 |
| 2 | 300 | -0.096 | 103.5 |
| 3 | 300 | -0.066 | 103.4 |

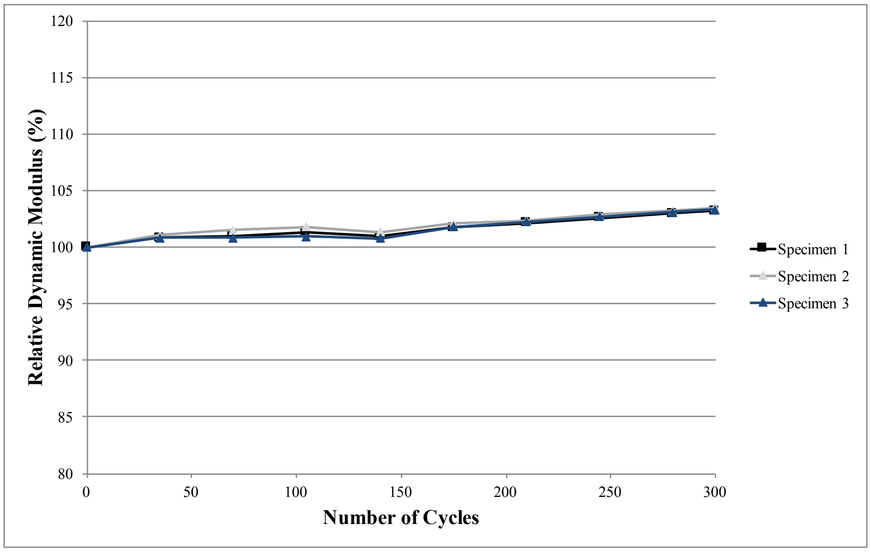



**Figure 37: Relative Dynamic Modulus vs. Cycles**

All three specimens performed exceptionally well under prolonged exposure to freeze-thaw cycles, with all three specimens having nearly no mass loss, and durability factors greater than 103. For reference, a value of 100 corresponds to no loss of stiffness, with decreasing values corresponding to increasing deterioration; a relative dynamic modulus of 80% or greater after 300 cycles is often assumed to indicate good freezing-and-thawing resistance. A durability factor greater than 100 (as is the case here) would indicate that the concrete not only did not experience any deterioration, the concrete actually gained stiffness during exposure. This gained stiffness is most likely due to continued hydration of the concrete that would take place during thaw cycles. The good freeze-thaw resistance of this concrete is most likely due to its low permeability and high strength.

## 8.6 Scaling

The resistance to scaling resulting from deicing chemicals was determined from one 7.5-by-12 inch rectangular prism following the methods outlined in ASTM C672. The specimen was immersed in a 0.04 g/ml solution of CaCl2 for 25 freeze-thaw cycles and a visual evaluation of the scaling was conducted every 5 cycles. At each evaluation stage, a numerical rating is assigned to the specimen. This rating is prescribed by ASTM; it ranges from 0, or "no scaling", up to 5, which corresponds to "severe scaling" (where coarse aggregate is visible over the entire surface). After 50 cycles, there was no visible deterioration of the specimen (Figure 38), resulting in a 0 rating at every stage. As was the case with freeze-thaw resistance, this concrete's resistance to scaling is most likely associated with its low permeability and high compressive and tensile strengths.

0 Cycles

50 Cycles

**Figure 38: Scaling Surface Conditions**

# 9 SUMMARY AND CONCLUSIONS

The primary objective of this research was to develop an economical, non-proprietary UHPC mix 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. A 4-variable central composite design (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. The effect of batch size and mixing/curing procedure was then investigated with these optimized mixes. Based on this study, a suitable protocol was established, and a modified mix design was selected for further evaluation. The mechanical properties and durability of this selected UHPC mix was then evaluated through a suite of ASTM tests.

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 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 to meet the desired performance

criteria: \$300-\$350 cost (without fibers), 8-11 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.

- Batch size and mixing method were observed to have a significant effect on resultant plastic and hardened concrete properties. It was determined that a conventional fixed-vane rotating drum concrete mixer was not adequate for mixing these UHPC mixes (at least not at the batch sizes used in this research); however, a conventional fixed-drum rotating-fin mortar mixer was found to provide adequate mixing action/energy. In addition to the observed variability with batch size, a significant amount of variability was observed between repetitions of identical batches. It was determined that much of this variability could be reduced by including steel fibers, and modifying the curing procedure and the cylinder preparation technique.
- The mechanical and durability tests performed on the selected UHPC mix demonstrated the exceptional mechanical properties and durability of this material.
- Overall this research demonstrated that self-consolidating, non-proprietary UHPC mixes can be made economically (less than \$1,000/yd$^3$) with materials readily available in the state of Montana.

While this research demonstrated the feasibility and benefits of using non-proprietary UHPC, further research is required before this material can be used in real-world applications, and more specifically before it can be used in field-cast joints between adjacent precast deck panels. In the research discussed herein, the concrete batches were 0.2- to 1.5-cubic feet in size, and were mixed using equipment available in the MSU concrete lab (i.e., a Hobart industrial cake mixer, and a conventional horizontal mortar mixer). This research and previous research on UHPC has shown that batch size, mixing equipment, mixing method, and mixing energy can have a significant effect on the performance of the resulting UHPC mix. Therefore, further research should be conducted on the proposed UHPC mix using the equipment that will be used in the field (most likely a high-shear pan mixer), under various mixing conditions (e.g., various temperatures, various aggregate moisture contents), and in larger batch sizes.

Further, previous research on UHPC field cast joints has shown that UHPC can reduce development lengths of the reinforcing in the inter-element connection zone, and thus reduce spacing between decks. However, this research was conducted using only proprietary UHPC concrete mixes. Further research should be conducted on field cast joints using the newly developed non-proprietary mix to ensure that this mix behaves as expected in this application (e.g., increased bond strength, decreased deck spacing).

# REFERENCES


Aaleti, S., & Sritharan, S. (2014). Design of Ultrahigh-Performance Concrete Waffle Deck for Accelerated Bridge Construction. *Transportation Research Record*(2406), 12-22. doi:10.3141/2406-02.

Aaleti, S. R., Sritharan, S., Bierwagen, D., & Wipf, T. J. (2011). Structural Behavior of Waffle Bridge Deck Panels and Connections of Precast Ultra-High-Performance Concrete Experimental Evaluation. *Transportation Research Record*(2251), 82-92. doi:10.3141/2251-09.

Alqadi, A. N. S., Bin Mustapha, K. N., Naganathan, S., & Al-Kadi, Q. N. S. (2012). Uses of central composite design and surface response to evaluate the influence of constituent materials on fresh and hardened properties of self-compacting concrete. *Ksce Journal of Civil Engineering, 16*(3), 407-416. doi:10.1007/s12205-012-1308-z.

Berry, M., Kappes, B., & Kappes, L. (2015). Optimization of Concrete Mixtures Containing Reclaimed Asphalt Pavement. *Aci Materials Journal, 112*(6), 723-733.

Brouwers, H. J. H., & Radix, H. J. (2005). *Self-compacting concrete: The role of the particle size distribution* (Vol. 42). Bagneux: R I L E M Publications.

Cihan, M. T., Guner, A., & Yuzer, N. (2013). Response surfaces for compressive strength of concrete. *Construction and Building Materials, 40*, 763-774. doi:10.1016/j.conbuildmat.2012.11.048.

El-Tawil, S., Alkaysi, M., Naaman, A., & Hansen, W. L., Z. (2016). *Development, Characterization and Applications of a Non Proprietary Ultra High Performance Concrete for Highway Bridges*. Retrieved from http://www.michigan.gov/mdot/0,4616,7-151-9622_11045_24249_24251-386988--,00.html.

FHWA. (2013). Development of Non-Proprietary Ultra-High Perfomance Concrete for Use in the Highway Bridge Sector. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/13100/index.cfm.

Fick, G. J. (2008). Testing Guide for Implementing Concrete Paving Quality Control Procedures. Retrieved from http://publications.iowa.gov/id/eprint/13618.

Folliard, K. J., Du, L., & Trejo, D. (2003). Effects of curing conditions on strength development of controlled low-strength material. *Aci Materials Journal, 100*(Compendex), 79-86.

Ghezal, A., & Khayat, K. H. (2002). Optimizing self-consolidating concrete with limestone filler by using statistical factorial design methods. *Aci Materials Journal, 99*(3), 264-272.

Goodspeed, C., Vanikar, S., & Cook, R. (2013). High-Performance Concrete (HPC) Defined for Highway Structures. Retrieved from http://www.fhwa.dot.gov/bridge/hpcdef.htm.

Goodspeed, C., Vanikar, S., & Cook, R. A. (1996). High-performance concrete defined for highway structures. *Concrete International, 18*(2).

Goodspeed, C. H., Vanikar, S., & Cook, R. A. (1996). High-performance concrete defined for highway structures. *Concrete International, 18*(2).

Graybeal, B. (2006a). Material property characterization of ultra-high performance concrete. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/06103/06103.pdf.

Graybeal, B. (2006b). Structural Behavior of Ultra High Performance Concrete Prestressed I-Girders. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/06115/06115.pdf.

Graybeal, B. (2010). Field-cast UHPC connections for modular bridge deck elements. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/bridge/11022/11022.pdf.

Graybeal, B. (2011). Ultra-high performance concrete. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/11038/11038.pdf.

Graybeal, B. (2012). *Ultra-High Performance Concrete Composite Connections for Precast Concrete Bridge Decks*: US Department of Transportation, Federal Highway Administration.

Graybeal, B., & Tanesi, J. (2007). Durability of an ultrahigh-performance concrete. *Journal of Materials in Civil Engineering, 19*(10), 848-854. doi:10.1061/(asce)0899-1561(2007)19:10(848).

Honarvar, E., Sritharan, S., Rouse, J. M., & Aaleti, S. (2016). Bridge Decks with Precast UHPC Waffle Panels: A Field Evaluation and Design Optimization. *Journal of Bridge Engineering, 21*(1). doi:10.1061/(asce)be.1943-5592.0000775.

Khayat, K. H., Ghezal, A., & Hadriche, M. S. (2000). Utility of Statistical Models in Proportioning Self-Consolidating Concrete. *Materials and Structures, 33*(229), 338-344. doi:10.1007/bf02479705.

Kockal, N. U., & Ozturan, T. (2011). Optimization of properties of fly ash aggregates for high-strength lightweight concrete production. *Materials & Design, 32*(6), 3586-3593. doi:10.1016/j.matdes.2011.02.028.

Lee, G. C., Huang, C., Song, J., & O'Connor, J. S. (2014). *Seismic Performance Evaluation of Precast Girders with Field-Cast Ultra High Performance Concrete (UHPC) Connections*. Retrieved from http://hdl.handle.net/10477/29491.

Lepech, M. D., & Li, V. C. (2009). Application of ECC for bridge deck link slabs. *Materials and Structures, 42*(9), 1185-1195. doi:10.1617/s11527-009-9544-5.

Li, V. C. (2004). Strategies for High Performance Fiber Reinforced Cementitious Composites Development. *Proceedings of the International Workshop on Advances in Fiber Reinforced Concrete, Proceedings of the International Workshop on Advances in Fiber Reinforced Concrete*(Bergamo, Italy, Sept. 2004), 93-98.

Long, W.-J., Lemieux, G., Hwang, S.-D., & Khayat, K. H. (2012). Statistical Models to Predict Fresh and Hardened Properties of Self-Consolidating Concrete. *Materials and Structures, 45*(7), 1035-1052. doi:10.1617/s11527-011-9815-9.

Lovato, P. S., Possan, E., Coitinho Dal Molin, D. C., Masuero, A. B., & Ribeiro, J. L. D. (2012). Modeling of mechanical properties and durability of recycled aggregate concretes. *Construction and Building Materials, 26*(1), 437-447. doi:10.1016/j.conbuildmat.2011.06.043.

Mohammed, B. S., Fang, O. C., Hossain, K. M. A., & Lachemi, M. (2012). Mix proportioning of concrete containing paper mill residuals using response surface methodology. *Construction and Building Materials, 35*, 63-68. doi:10.1016/j.conbuildmat.2012.02.050.

Myers, R. H., & Montgomery, D. C. (2002). *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. New York: Wiley.

Nambiar, E. K. K., & Ramamurthy, K. (2006). Models relating mixture composition to the density and strength of foam concrete using response surface methodology. *Cement & Concrete Composites, 28*(9), 752-760. doi:10.1016/j.cemconcomp.2006.06.001.

Ng, K. W., Garder, J., & Sritharan, S. (2015). Investigation of ultra high performance concrete piles for integral abutment bridges. *Engineering Structures, 105*, 220-230. doi:10.1016/j.engstruct.2015.10.009.

Piotrowski, S., & Schmidt, M. (2012). *Life Cycle Cost Analysis of a UHPC-Bridge on Example of two Bridge Refurbishment Designs*. Paper presented at the Proceedings of Hipermat 2012 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials.

Ranade, R., Li, V. C., Stults, M. D., Heard, W. F., & Rushing, T. S. (2013). Composite Properties of High-Strength, High-Ductility Concrete. *Aci Materials Journal, 110*(4), 413-422.

Rouse, J., Wipf, T., Phares, B., Fanous, F., & Berg, O. (2011). Design, Construction, and Field Testing of an Ultra-High Performance Concrete Pi-Girder Bridge.

Simon, M. J. (2003). *Concrete Mixture Optimization Using Statistical Methods: Final Report*. Retrieved from https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/03060/03060.pdf.

Sonebi, M., & Bassuoni, M. T. (2013). Investigating the effect of mixture design parameters on pervious concrete by statistical modelling. *Construction and Building Materials, 38*, 147-154. doi:10.1016/j.conbuildmat.2012.07.044.

Wang, S. X., & Li, V. C. (2007). Engineered cementitious composites with high-volume fly ash. *Aci Materials Journal, 104*(3), 233-241.

Wille, K., & Boisvert-Cotulio, C. (2015). Material efficiency in the design of ultra-high performance concrete. *Construction and Building Materials, 86*, 33-43. doi:10.1016/j.conbuildmat.2015.03.087.

Wille, K., Naaman, A. E., El-Tawil, S., & Parra-Montesinos, G. J. (2012). Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing. *Materials and Structures, 45*(3), 309-324. doi:10.1617/s11527-011-9767-0.

Wille, K., Naaman, A. E., & Parra-Montesinos, G. J. (2011). Ultra-High Performance Concrete with Compressive Strength Exceeding 150 MPa (22 ksi): A Simpler Way. *Aci Materials Journal, 108*(1), 46-54.

Wipf, T., Sritharan, S., Abu-Hawash, A., Phares, B., & Bierwagen, D. (2011). Iowa's ultra-high performance concrete implementation.

Yuan, J., & Graybeal, B. (2014). *Bond Behavior of Reinforcing Steel in Ultra-High Performance Concrete* (FHWA-HRT-14-090). Retrieved from https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/14090/14090.pdf.

Yuan, J., & Graybeal, B. (2015). Bond of Reinforcement in Ultra-High-Performance Concrete. *Aci Structural Journal, 112*(6), 851-860.

Zdeb, T. (2013). Ultra-high performance concrete - properties and technology. *Bulletin of the Polish Academy of Sciences-Technical Sciences, 61*(1), 183-193. doi:DOI 10.2478/bpasts-2013-0017.

Zohrevand, P., & Mirmiran, A. (2013). Seismic Response of Ultra-High Performance Concrete-Filled FRP Tube Columns. *Journal of Earthquake Engineering, 17*(1), 155-170. doi:10.1080/13632469.2012.713560.

# 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 | 127.5 | ml |
| 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 | | |

**Figure 39: 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 | 127.7 | ml |
| 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 | | |

**Figure 40: 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 | 109.6 | ml |
| 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 | | |

**Figure 41: 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 | 109.7 ml |
| 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 | |

**Figure 42: 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 | 287.6 | ml |
| 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 | | |

**Figure 43: 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 | 288.0 | ml |
| 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 | | |

**Figure 44: 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 | 247.4 | ml |
| 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 | | |

**Figure 45: 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 | 247.7 | ml |
| 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 | | |

**Figure 46: 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 | 105.7 ml |
| 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 | |

**Figure 47: 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 | 122.5 | ml |
| 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 | | |

**Figure 48: 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 | 105.7 | ml |
| 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 | | |

**Figure 49: 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 | 105.9 ml |
| 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 | |

**Figure 50: 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 | 275.9 ml |
| 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 | |

**Figure 51: 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 | 276.3 | ml |
| 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 | | |

**Figure 52: 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 | 238.7 ml |
| 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 | |

**Figure 53: 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 | 239.0 ml |
| 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 | |

**Figure 54: 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 | 196.2 ml |
| 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 | |

**Figure 55: 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 | 181.6 | ml |
| 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 | | |

**Figure 56: 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 | 42.2 | ml |
| 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 | | |

**Figure 57: 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 | 332.9 ml |
| 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 | |

**Figure 58: 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 | 221.4 ml |
| 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 | |

**Figure 59: 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 | 164.3 | ml |
| 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 | | |

**Figure 60: 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 | 188.3 ml |
| 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 | |

**Figure 61: 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 | 188.8 ml |
| 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 | |

**Figure 62: 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 | 188.6 ml |
| 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 | |

**Figure 63: 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 | 188.6 ml |
| 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 | |

**Figure 64: 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 | 188.6 ml |
| 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 | |

**Figure 65: 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 | 182.8 | ml |
| 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 | | |

**Figure 66: Mix S1 Proportions**

| 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 | 182.8 ml |
| 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 | |

**Figure 67: 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 | 141.9 ml |
| 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 | |

**Figure 68: 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 | 141.9 | ml |
| 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 | | |

**Figure 69: 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 | 181.6 | ml |
| 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 | | |

**Figure 70: 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 | 164.4 | ml |
| 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 | | |

**Figure 71: 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 | 141.9 | ml |
| 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 | | |

**Figure 72: 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 | 82.3 | ml |
| 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 | | |

**Figure 73: 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 | 82.5 | ml |
| 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 | | |

**Figure 74: 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 | 244.8 ml |
| 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 | |

**Figure 75: 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 | 245.5 ml |
| 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 | |

**Figure 76: 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 | 79.9 | ml |
| 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 | | |

**Figure 77: 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 | 80.1 ml |
| 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 | |

**Figure 78: 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 | 237.7 ml |
| 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 | |

**Figure 79: 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 | 238.3 | ml |
| 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 | | |

**Figure 80: 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 | 186.4 | ml |
| 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 | | |

**Figure 81: 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 | 177.3 ml |
| 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 | |

**Figure 82: 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 | 46.2 ml |
| 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 | |

**Figure 83: 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 | 315.4 | ml |
| 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 | | |

**Figure 84: 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 | 181.2 ml |
| 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 | |

**Figure 85: 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 |

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| 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 | 182.1 ml |
| 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 | |

**Figure 86: 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 | 181.7 | ml |
| 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 | | |

**Figure 87: Mix 3-15C 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 | 181.7 ml |
| 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 | |

**Figure 88: Mix 3-16 C Proportions**

# APPENDIX D: OPTIMIZATION 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 | 167.7 ml |
| 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 | |

**Figure 89: 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 | 184.8 ml |
| 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 | |

**Figure 90: 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 | 169.8 ml |
| 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 | |

**Figure 91: 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 | 202.5 ml |
| 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 | |

**Figure 92: Mix 3M4 Proportions**

| Mix Specifications | | |
|---|---|---|
| Mix ID: | 3M4 | |
| W/C | 0.240 | Unitless |
| HRWR Dosage Rate | 0.045 | Fraction of Cement wt |
| SCM to Cement Ratio | 0.5 | Unitless |
| Silica Fume to Fly Ash Ratio | 0.750 | Unitless |
| Aggregate to Cement Ratio | 1.40 | Unitless |
| Fiber Content | 0.02 | Fraction of Volume |
| Paste Content | 0.62 | Fraction of Volume |
| Volume | | cu. Ft |

| Cubic Yard Calculations | | | |
|---|---|---|---|
| | Mix Wt. (lbs) | Cost/ton | Cost/ cu. Yd |
| Water | 271.5 | $ - | $ - |
| HRWR (gallons) | 6.74 | $ 14.00 | $ 94.37 |
| Portland Cement | 1299.5 | $ 145.00 | $ 94.21 |
| Silica Fume | 278.5 | $ 840.00 | $ 116.95 |
| Fly Ash | 371.3 | $ 135.00 | $ 25.06 |
| Fine Aggregate | 1556.4 | $ 26.00 | $ 20.23 |
| Steel Fibers | 262.8 | $ 1,600.00 | $ 210.26 |
| | | Total | $ 561.09 |

| Aggregates | |
|---|---|
| Type | Specific Gravity |
| Fine Aggregate | |
| Steel Fibers | |
| Weighted Average | 3.35 |

| Cementitious Materials | |
|---|---|
| Type | Specific Gravity |
| Portland Type I-II | |
| Fly Ash | |
| Silica Fume | |

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

| Mix Proportions | | |
|---|---|---|
| Item | Percent | Volume (cu ft) |
| Water +HRWR + Cementitious | 62.47 | 0.1249 |
| Fine Aggregate | 35.53 | 0.0711 |
| Steel Fibers | 2.00 | 0.0040 |
| Total | 100.00 | 0.2000 |

| Mix Weights | | | | | |
|---|---|---|---|---|---|
| Item | Fraction of Volume | Volume | | Mix Weight (lbs) | |
| Water | 0.16 | 0.032 | cu ft | 2.01 | |
| HRWR | 0.03 | 0.007 | cu ft | 0.43 | 189.0 ml |
| Portland Cement | 0.24 | 0.049 | cu ft | 9.63 | |
| Silica Fume | 0.08 | 0.015 | cu ft | 2.06 | |
| Fly Ash | 0.11 | 0.022 | cu ft | 2.75 | |
| Fine Aggregate | 0.36 | 0.071 | cu ft | 11.53 | |
| Steel Fibers | 0.02 | 0.004 | cu ft | 1.95 | |

**Figure 93: Selected Mix with Steel Fibers**