FEASIBILITY OF NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) FOR USE IN HIGHWAY RIDGES IN MONTANA: *PHASE II FIELD APPLICATION*

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March 2021

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Final Report

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16. Abstract The overall objective of this research was to further develop and characterize an economical non-proprietary ultra high performance concrete (UHPC) made with materials readily available in Montana. Specifically, this research focused on (1) investigating the potential variability in performance related to differences in constituent materials, (2) investigating issues related to the field batching/mixing of these UHPC mixes, and (3) testing rebar bond strength and studying how this will affect requisite development lengths. Based on this research, it was determined that, while variations in the source of the constituent materials had some effects on performance, the effects were fairly minor, with all recorded flows and 28-day compressive strengths exceeding 6 inches and 16 ksi, respectively. Further, in regard to the effects of mixing/batching conditions, only temperature was observed to have a significant effect on performance, with flows and set times decreasing with increasing temperature. Regarding the pullout tests, all of the specimens that met the minimum embedment depth requirements specified by the FHWA yielded prior to concrete bond failure, indicating the suitability of these recommendations for the Montana UHPC developed in this research.			
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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. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) resulted in non-proprietary UHPC mixes made with materials readily available in Montana [1]. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The MDT Bridge Bureau is interested in using UHPC in field-cast joints between precast concrete deck panels. The use of UHPC in this application will reduce development lengths, and subsequently reduce the requisite spacing between the decks and improve the overall performance of the bridge. A second phase of research, discussed herein, builds on the non-proprietary UHPC research already completed, and focuses on ensuring the successful application of this material in these field-cast joints. Specifically, this research investigates several items related to the field batching of these mixes, and the potential variability in performance related to differences in constituent materials. Further, rebar bond strength and the subsequent effect this has on development length is investigated.

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 (Phase I) and to test these mixes for successful application in field-cast joints (Phase II). This objective was achieved by (1) investigating the potential variability in concrete performance related to differences in constituent materials, (2) investigating issues related to the field batching/mixing of these UHPC mixes, and (3) testing rebar bond strength and studying how this will affect requisite development lengths.

1.3 Scope

These objectives were realized through the following tasks:

- A comprehensive literature review was conducted to evaluate the state-of-the-practice and recent advances in UHPC. In particular this review focused on nonproprietary UHPC and the use of UHPC in field cast joints.
- The effects that variations in the materials (e.g., fly ash source, water reducer, steel fiber source, type and source of sand) and material properties (e.g., aggregate moisture content and gradation) have on the performance of the UHPC were investigated.
- The effects of various mixing conditions (e.g., batch sizes, various temperatures, and aggregate moisture contents) were investigated.
- The bond behavior of deformed reinforcing steel in the newly developed non-proprietary UHPC was characterized, and its effect on bar development lengths was investigated to confirm its performance in the proposed application. Specifically, the bond behavior was investigated by conducting direct tension pullout tests. In these tests, the effect of embedment length, concrete cover, bar spacing, and bar size were investigated.

2 LITERATURE REVIEW

It should be noted that an extensive literature review focused on UHPC and the development of non-proprietary UHPC mixes was conducted during the Phase I investigation [1]. The literature review conducted in this research focused on non-proprietary UHPC research conducted since the completion of the Phase I effort, and on the application of UHPC in the desired application (closure pours between precast deck panels).

2.1 Non-Proprietary UHPC Research

Researchers at the University of Arkansas recently developed a non-proprietary UHPC with locally sourced materials in order to reduce cost [2]. This research studied the effect of sand gradation, binder type and content, and curing regimes on the UHPC's compressive strength. The mixes developed in this research had compressive strengths in the range of 16.5 ksi to 22.5 ksi, with the maximum strengths occurring at 90-days. The researchers found that: (1) finer sands result in higher compressive strengths, but the inclusion of silica fume into the mix caused the addition or exclusion of fine sands to have minimal effects on the compressive strength, (2) using more than 10% silica fume had little effect on compressive strength, (3) compressive strengths increased as binder content increased regardless of binder type, (4) fly ash contents of more than 20% decreased concrete strengths at earlier ages but increased their strengths at later ages, (5) using steel fibers at 3% by volume increased compressive strengths, and (6) a curing environment of 140°F for 2 days followed by 194 °F for 3 days lead to the highest compressive strengths.

The University of Oklahoma [3] also researched the development of nonproprietary UHPC mix designs using materials available in their state. Additionally, a goal of this research was to develop a mixing, placing, and curing procedure feasible for field use. With the help of heat curing and steel fibers included at 2% by volume, a cost-effective non-proprietary UHPC mix design with compressive strengths above 20 ksi at 3 days, a first-cracking tensile strength of 2.0 ksi, and high flow was achieved. The researchers determined that using heat curing to reach high early strengths is one of UHPC's key advantages. This project also concluded that varying sources of the UHPC materials makes the reproduction of non-proprietary mixes unrealistic, since similar SCM combinations can produce drastic changes in strength and flow.

El-Tawil et al. at the University of Michigan [4] recently expanded on previous research on UHPC and investigated the commercial production of non-proprietary UHPC. Their previous research demonstrated the need for further research on field batching of UHPC mixes [5]. Specifically, this previous research demonstrated that: (1) high carbon content of the chosen silica fume caused a large spike in water demand as the mix was scaled up, (2) low HRWR dosage could not compensate for the increasing water demands, (3) densified silica fume did not sufficiently disperse during dry mixing, and (4) insufficient mixer capacity could not induce turnover in the larger wet mix. The follow-up research was focused on overcoming the difficulties in field application observed in the earlier research and establishing the expectant long- and short-term performance of this material. This research included investigating the effects of using multiple vendors for material sourcing as well as replacing portions of cement with slag cement. Additionally, the effects of variations in steel/polyethylene fibers was investigated. This research included a wide range of performance metrics, including workability, hydration heat, autogenous shrinkage, rapid chloride penetration, freeze-thaw performance, air void distribution, and compression and direct tension capacity.

This research demonstrated that it is possible to make a generic UHPC mix using constituents from a variety of sources, but found the HRWR dosage rate to be particularly important. Specifically, they observed that a HRWR dosage rate that is too low will prevent the mix from properly mixing, and a dosage rate that is too high could lead to fiber separation and possible loss of strength. They recommend that field trial batches be used to find the appropriate HRWR dosage rate for a particular mix. A HRWR dosage between 1.5% and 3% by weight of cement was recommended. The various mixes using a variety of local suppliers all fulfilled the minimum field-cast UHPC requirements by reaching 28-day compressive strengths of 21.7 ksi and 28-day tensile strengths of 1.2 ksi. They also recommended using silica fumes with 2% or less of carbon content instead of increasing HRWR dosage to account for the high water absorption that comes with higher carbon contents. Further, they concluded that the partial replacement of cement with slag cement can improve the workability and self-consolidating characteristic of the UHPC, while reducing air voids. It was recommended that 50% of cement by weight be replaced by GGBS because of these improved workability and durability qualities. It was found that a higher aspect ratio of steel fiber benefited the redistribution of stresses after the first tensile cracking and improved energy absorption characteristics. Steel fiber aspect ratios had little effect on compressive strength, as did reducing the amount of fibers from 2% to 1.5% by volume. During a field test, the researchers found mixing during warm temperatures can poorly affect the HRWR effectiveness and decrease workability, so some mix water can be replaced with cubed ice to help alleviate this issue.

A research project at University of Colorado also investigated cost-effective UHPC by using locally sourced materials [6]. Various concrete constituents were studied, emphasizing different silica compounds and fiber reinforcement. Digital microscopy was used to characterize the distribution of granular particles in the UHPC mixes to understand the micro-void-filling characteristics of the concrete. From this, it was determined that silica sand and fine silica sands result in better strengths than silica powder, and the use of pyrogenic silica and precipitated silica is not recommended. The use of steel fibers was recommended over polypropylene fibers, with fiber inclusion resulting in a 60% increase in flexure strength and a more gradual failure mode compared to mixes with no fibers. The use of HRWR between 511 and 604 oz/cubic yards was not found to have an effect on the compressive strength. Heat curing was found to increase the concrete strength, but conventional moisture curing was used for field practicality. The developed mix design, with a w/c ratio of 0.22, resulted in a UHPC mix with an average compressive strength of 21.5 ksi and an 8-inch slump. This research also developed new modulus of rupture equations because of the large discrepancy from the code's existing equations to test results.

Finally, the University of Nebraska [7] recently conducted research on proportioning nonproprietary UHPC using materials readily available in Nebraska. The impacts of varying UHPC constituents and mixture proportions were also evaluated, and included variations in aggregates, fibers, HRWRs, water/binder ratio, cements, and SCMs. The impact of mixers on fresh and hardened UHPC was also investigated. A particle packing model was used for initial constituent proportioning, but it was determined that experimental procedures were required to evaluate the impact of each ingredient because of the complexity and extreme sensitivity of UHPC mix designs. It was concluded from the material variation study that (1) different types of cement did not have a large effect on the performance of the UHPC, (2) silica fume inclusion up to approximately 11% by volume increased compressive strength, (3) slag is more reliable than fly ash because of the high variability of fly ash, (4) quartz powder had a negative effect on workability and negligible effect on strength, and (5) the FHWA's UHPC standards are feasibly reached with the appropriate mix design and materials. It was also found that different mixers do not sufficiently influence the UHPC's mechanical properties provided they supply enough energy to disperse all the fine particles. Higher mixing energies were found to correlate to higher flowability in the mixes.

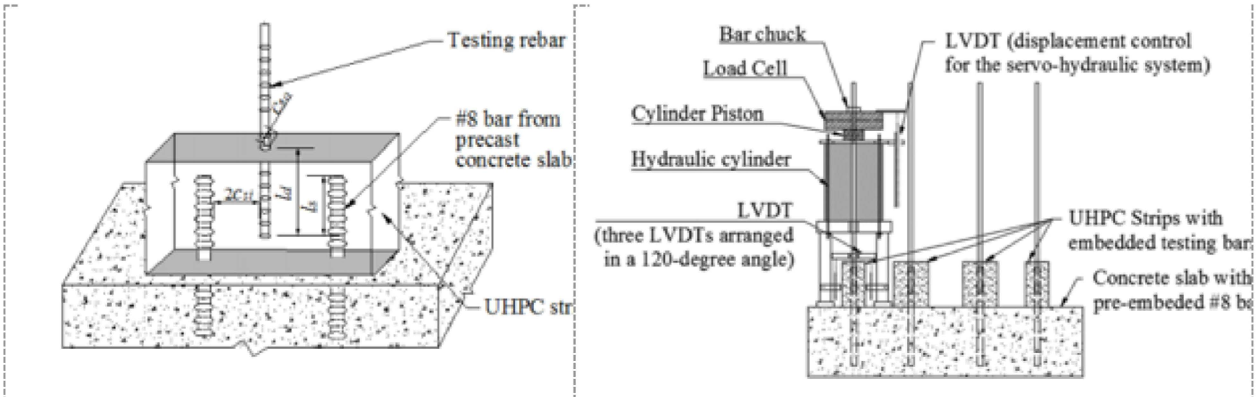
2.2 Research Related to Proposed Application – Closure Pours

Previous research on UHPC field-cast joints has shown that UHPC can reduce development lengths of the reinforcing bars in the inter-element connection zone, and thus reduce the spacing and congestion between decks [8-11].

The FHWA investigated bond behavior of reinforcing steel embedded in a proprietary UHPC through a series of bar pullout tests [8, 9]. In these tests, reinforcing bars were embedded into UHPC curbs, which were in turn bonded to a normal strength concrete slab with reinforcing steel. In these tests, the reinforcing steel was loaded in tension until the concrete bond failed or significant yielding of the reinforcing was observed. A typical test specimen and testing configuration are shown in Figure 1. As part of their investigation, they varied side cover (c_{so}), clear cover between bars ($2c_{si}$), bar size, embedment length (l_d), epoxy coating, and yield strength. Based on this research, minimum recommended embedment depths were developed for deformed mild steel tensile reinforcement embedded in ultra-high performance fiber reinforced concrete. These recommendations specify that the embedded reinforcing steel will reach either the bar yield strength or 75 ksi before bond failure if the following conditions are met:

- Bar sizes ranging from No. 4 to No. 8,
- Uncoated or epoxy coated bars,
- Minimum embedment length of $8d_b$,
- Minimum side cover of $3d_b$,
- Bar clear spacing of $2d_b$, and
- Minimum UHPC compressive strength of 13.5 ksi.

This recommended minimum embedment length of $8d_b$ is substantially lower than minimum embedment lengths specified for structural applications in ACI 318-11.



(a) Typical Test Specimen | (b) Test Setup

Figure 1: Test Configuration used in FHWA Pullout Tests [8, 9]

Similar bond strength tests were conducted at the University of Washington using a nonproprietary UHPC mix developed for the Washington State Department of Transportation [10]. This researcher concentrated on the effects of splice and embedment lengths, and side cover on a specific reinforcement configuration. Two different pullout curb setups were used. The first was a pure pullout test similar to what was used in the FHWA study wherein a reinforcement was embedded in a UHPC curb (Figure 2). In this research Grade 60, epoxy-coated No. 5 bars were embedded in the UHPC curb at varying lengths and spaced with a clear spacing adequate to remove any effect of pullout specimens interacting with one another. Side clear cover was varied between each curb. The second test setup investigated the effect of non-contact splice length on bond strength (Figure 3). In this setup, Grade 60 epoxy-coated No. 5 bars with a clear cover of $3d_b$ were embedded in the UHPC curb. Again, side clear cover was varied between each curb. Based on this research, it was determined that an increase in side cover did not have a significant effect on bond strength within the side cover dimensions examined ($1.6d_b$ to $2.5d_b$). The desired failure mechanism of rebar fracture was shown to be achieved at a splice length of $8d_b$, or an embedment length of nearly $9.6d_b$ [10].

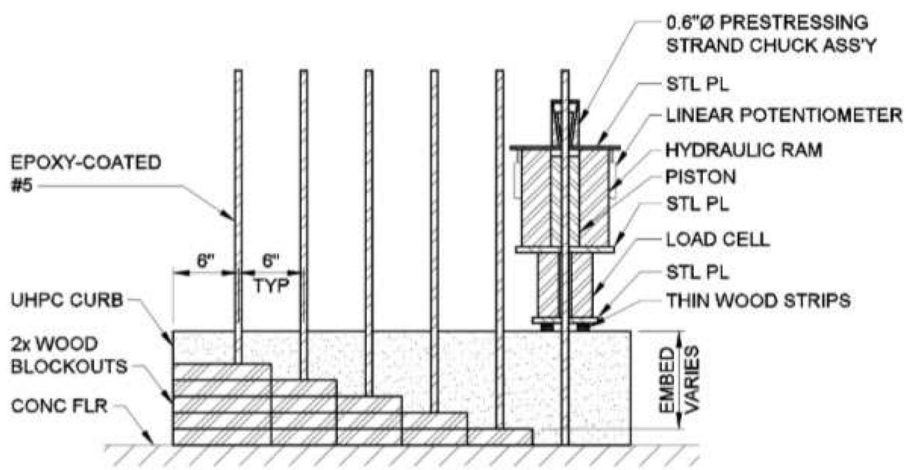


Figure 2: UW Bar Pullout Test Configuration [10]

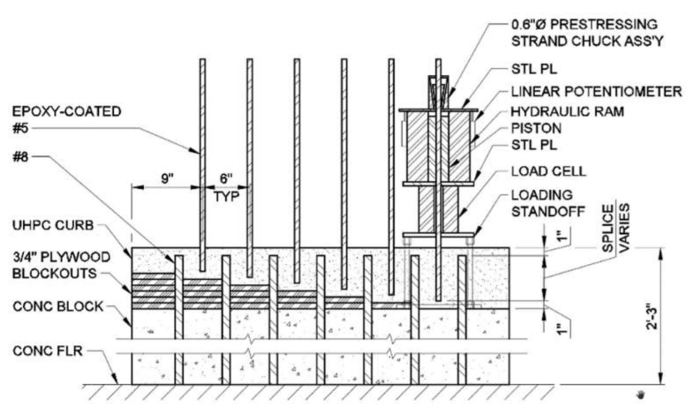


Figure 3: Non-contact Lap Splice Connection Test Configuration [10]

Alkaysi and El-Tawil at the University of Michigan conducted a thorough study on the bond strength of non-proprietary UHPC, investigating the effect of volumetric fiber fraction, bar size, epoxy coating, embedment length, and casting orientation [5, 11]. Pullout specimens were comprised of a rebar embedded a specific depth within a UHPC prism, possessing adequate side cover (see Figure 4). The UHPC prism was fixed and a tensile load was applied to the embedded reinforcement. Resulting load and bar slip were observed. Results showed that bond strength was minimally affected by casting orientation, indicating that preferential fiber alignment was minimal in these specimens. It is critical to note, however, that pullout specimen size was limited to nearly six inches in plan view and that distance traveled by steel fibers during casting would be minimal. Also, they observed a nonlinear stress distribution along the length of reinforcement, which is consistent with bond strength studies on HPC but contradicts previous findings on UHPFRC. Reinforcement yielding was observed to occur at a minimum embedment length of $6d_b$ for No. 4 bars, regardless of coating. A minimum embedment length was not established for No. 5 and No. 6 bars, as these tested bars experienced pullout for all embedment lengths investigated.

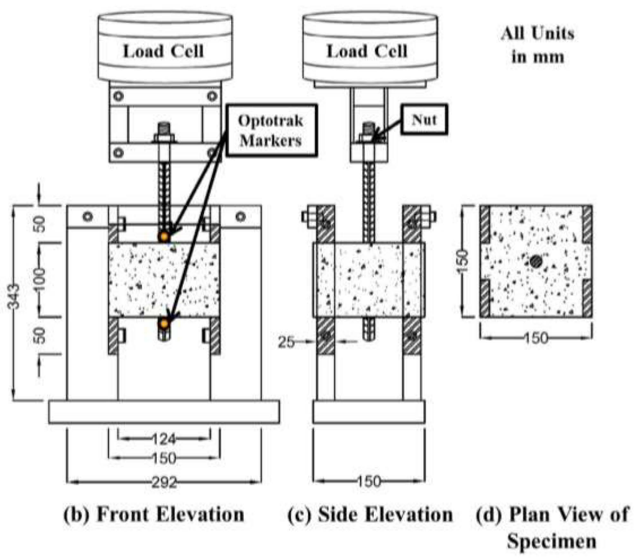


Figure 4. Test configuration of pullout specimen [11]

A comprehensive study on bond length was performed at the University of Michigan [5] on the UHPC blend that was developed during their research. It was determined that this UHPC blend requires significantly reduced bond length than is required for normal concrete; however, the authors suggest additional research be conducted as their results differ slightly from those reported by the FHWA [9]. Bond strength models for this UHPC were proposed and used to cast a field joint between two pre-cast bridge deck sections. This joint was tested, and it was determined that a 6-inch joint length could be sufficient for load transfer between the two elements.

Several research programs also focused on testing the structural performance of UHPC field-cast connections between precast bridge elements. Specifically, the research conducted by El-Tawil et al. [5] 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. Further, the FHWA [12, 13] tested a series of field-cast transverse and longitudinal connections under static and cyclic loading, and found that the use of UHPC in these connections can mitigate some of their potential issues, and may actually enhance performance relative to monolithically cast decks. The decreased reinforcement development length and increased bond strength between UHPC and precast specimens were shown to facilitate simpler and more effective/durable connection details.

3 METHODS

This chapter discusses the methods used to prepare and evaluate the UHPC mixes in this research.

3.1 Mixing Procedure

The small laboratory mixtures were produced in an industrial benchtop Hobart A200 mixer in 0.20-ft^3 batches (Figure 5). The A200 is a ½-horsepower mixer with a 20-quart capacity bowl. The larger-scale mixes were produced in an IMER Mortarman 360 high-shear horizontal mortar mixer (Figure 6). The IMER Mortarman was powered by an 11-hp gas engine, and has a drum capacity of 12 ft^3. However, it should be noted that this mixer cannot yield 12 ft^3 of UHPC due to the nature of the mixing procedure and the state of the materials prior to the UHPC becoming fluid.

The mix procedure used in this research is summarized below. Note that this procedure is similar to that proposed by Wille, Naaman [14] and FHWA [15].

- Combine fine aggregate and silica fume. Mix for 5 minutes on low speed.
- Add cement and fly ash to mixer. Mix for 5 minutes on low speed.
- Combine water and HRWR in separate container. Mix thoroughly.
- Add water & HRWR to mixing bowl. Mix on low speed until mix becomes fluid (typically around 3-6 minutes).
- Add steel fibers and mix for approximately 3 minutes after becoming fluid.

It should be noted, that mixing this UHPC rapidly for more than 10 minutes after it first becomes fluid was shown to have detrimental effects on concrete strength. It is suspected that this effect may be due to an increase in entrapped air within the mix.

Figure 5: Hobart A200 Mixer

Figure 6: IMER Mortarman 360 mixer

3.2 Flow Testing Procedure

Workability was measured via a spread cone mold in accordance with ASTM C1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete [16]. Prior to removing any UHPC from the batching container, a wetted spread cone was placed on a flow table and a single scoop of UHPC was used to fill the spread cone. The spread cone was then lifted from the base, and the remaining material in the cone was scraped off onto the base plate. A maximum and minimum diameter was recorded after two minutes, and the batch spread was recorded as the average of these two diameters. The spread cone and a typical UHPC spread are shown in Figure 7.

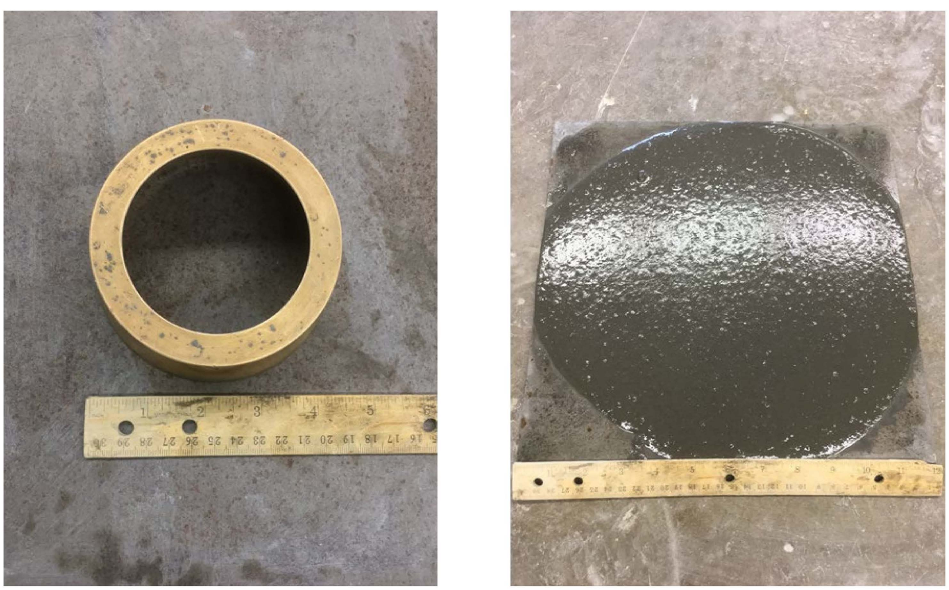


Figure 7: Spread Cone Mold & Measurement of Flows

3.3 Specimen Casting, Preparation, and Curing

For each batch, 3-by-6-in test cylinders were prepared in substantial accordance to ASTM C1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete [16]. The UHPC was placed into reusable plastic cylinder molds in a single lift, and were consolidated by tapping on the sides with a mallet. Rather than using the plastic caps that accompanied cylinder molds, a single layer of plastic wrap was placed over the cylinders and tightly secured to prevent any surface drying at the specimen surfaces.

After approximately 48 hours, cylinders were removed from the molds, and a diamond-blade tile saw was used to remove the uneven top surface of the cylinder. The cylinders were then ground using an automatic cylinder end grinder (Figure 8), and placed in a temperature-controlled cure room at 100% humidity until the respective test date.

Figure 8: Cylinder end grinder and prepared specimen

3.4 Compression Testing

The compressive strength of the concrete was determined in substantial accordance to ASTM C 1856 (Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete) by testing at least three 3-by-6-in cylinders loaded to failure in a Testmark CM Series hydraulic compression load frame with a 400,000-pound capacity. The cylinders were loaded at a target rate of 975-1075 lbs/second (138-152 psi/s). 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. A typical compression test is shown in Figure 9 below.

Figure 9: Compression cylinder in load frame

3.5 Flexural Testing

The flexural tensile strength of the concrete was calculated as the average of two 20-by-6-by-6 inch prisms tested according to ASTM C78 -- Standard Test Method for Flexural Strength of Concrete [17]. A typical flexural specimen in the load frame is shown in Figure 10. It should be noted that 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 initial cracking capacity of the concrete. In this research, the initial cracking was determined from the recorded force-deformation response of each specimen by finding the first point at which there is a sudden reduction in applied load and a distinct reduction in stiffness. It should be noted that this point was clearly defined for the specimens in this research.

Figure 10: Flexural test specimen in load frame

4 MATERIALS

This chapter discusses the constituent materials used in this research, which were portland cement, silica fume, fly ash, aggregates, HRWR, and steel fibers. All of these materials are readily available in Montana.

4.1 Portland Cement

The two following cement sources were used in this research to investigate the effects of varying cement source: Trident and Ash Grove. The Trident cement was a Type I/II/IV cement from the GCC cement plant in Trident, MT, and was used in original mix development [1]. The Ash Grove cement was a Type I/II cement from the Ash Grove cement plant in Clancy, MT. Chemical and physical properties of the cement are included in Table 1, along with the applicable C150 limits.

Table 1: Chemical and Physical Properties of Portland Cements

Chemical Properties	**C150 Limit**	**Trident**	**Ash Grove**
SiO_2 (%)	NA	20.8	20.8
Al_2O_3 (%)	6.0 max	4.0	3.9
Fe_2O_3 (%)	6.0 max	3.2	3.3
CaO (%)	NA	64.7	63.9
MgO (%)	6.0 max	2.2	3.7
SO_3 (%)	3.0 max	2.8	2.1
Loss on Ignition (%)	3.0 max	2.7	2.1
Insoluble Residue (%)	0.75 max	0.3	0.9
CO_2 (%)	NA	1.6	1.6
Limestone (%)	5.0 max	3.6	4.2
$CaCO_3$ in Limestone (%)	70 min	98.0	86.8
Inorganic Processing Addition (%)	5.0 max	0.5	-
Potential Phase Compositions:			
C_3S (%)	NA	57.0	59.0
C_2S (%)	NA	16.0	13.0
C_3A (%)	8.0 max	5.0	4.0
C_4AF (%)	NA	10.0	10.0
$C_3S + 4.75C_3A$ (%)	NA	-	78.0
Physical Properties			
Air Content (%)	12.0 max	7	8
Blaine Fineness (m2/kg)	260 min	418	414.2
Autoclave Expansion	0.80 max	0.006	
Compressive Strength (psi):			
3 days	1740	4240	3224
7 days	2760	5320	5239
Initial Vicat (minutes)	45 - 375	142	152
Mortar Bar Expansion (%) (C 1038)	NA	-0.008	-

4.2 Silica Fume

The silica fume used in this research was MasterLife SF 100 from BASF. The Chemical and physical properties of the silica fume are compared with the applicable ASTM C1240 limits in Table 2.

Table 2: Chemical and Physical Properties of Silica Fume, ASTM C1240

Chemical Properties		
Item	Limit	Result
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

4.3 Fly Ash

The following three Class F fly ash sources were used in this research: Coal Creek, Genesee, and Sheerness. The Coal Creek ash was the sole fly ash studied in the original mix development and was from the Coal Creek power plant in Underwood, North Dakota. The Genesee fly ash was from the Genesee Generating Station near Warburg, Alberta, and was supplied by the GCC cement plant near Trident, MT. It should be noted that the Genesee ash was used in this phase of research for almost all mixes, because this ash was the most readily available in the state at the time of this research. The Sheerness fly ash was supplied by the Ash Grove cement plant and obtained from the Sheerness Generating Station in Hanna, Alberta. The chemical and physical properties of the fly ashes are provided in Table 3, along with the ASTM C618 limits.

Table 3: Chemical and Physical Properties of Fly Ash Studied, ASTM C618

		Source		
Chemical Properties	**C168 Limit**	**Coal Creek**	**Genesee**	**Sheerness**
SiO_2 (%)	NA	55.0	59.9	52.3
Al_2O_3 (%)	NA	16.8	21.4	22.6
Fe_2O_3 (%)	NA	6.0	4.2	6.4
Sum of Constituents	70.0 min	77.8	85.5	81.2
SO_3 (%)	5.0 max	0.50	0.19	0.46
CaO (%)	NA	11.4	6.7	11.2
Moisture (%)	3.0 max	0.03	0.03	0.07
Loss on Ignition (%)	6.0 max	0.1	0.8	0.5
Available Alkalis, as Na_2O (%)	NA	0.9	-	-
Physical Properties				
Fineness (% retained on #325)	34% max	29.8	29.2	26.6
Strength Activity Index (% of control)				
7 days	75% min	78.0	89.6	83.3
28 days	75% min	93.0	84.3	88.2
Water Requirement (% control)	105 % max	95.0	95.3	95.8
Autoclave Soundness (%)	0.8% max	-	0.07	0.06
True Particle Density (g/cm^2)	NA	2.42	-	2.25

4.4 Aggregates

During the initial phase of research [1], 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. To investigate the effects of varying sand source, the phase of research discussed herein investigated several other sand sources from across Montana. While the original research focused on only using a fine aggregate source that met the specifications for masonry sand (ASTM C144 - Standard Specifications for Aggregate for Masonry Mortar), this research also looked at using conventional concrete fine aggregates (ASTM C33 - Standard Specification for Concrete Aggregates). Conventional concrete fine aggregates were investigated because, in comparison to masonry sands, concrete sands are less expensive and more widely available from gravel pits across the state.

A variety of local fine aggregate sources were identified using the MDT Gravel Pit Index and obtained for use in this study. Specifically, five masonry sands, four concrete sands, and two silica sands were examined during the aggregate variability study. The aggregate sources, locations, and key physical properties are provided in Table 4, the aggregate types are grouped by masonry sand or concrete sand and separated by a line in the table. The gradation curves for each aggregate are provided in Figure 11 and Figure 12. Included in the gradation curves are the respective upper and lower ASTM limits for the particular aggregate type.

Table 4: Fine Aggregate Sources and Properties

Fine Aggregate Source	Supplier	Location	FM	Absorption	OD S.G.	SSD S.G.
QUIKRETE-Masonry	QUIKRETE	Billings, MT	1.86	1.87%	2.56	2.60
Diamond Mountain-Masonry	BBB&T	Frenchtown, MT	2.69	3.99%	2.45	2.60
Pioneer-Masonry	Pioneer Concrete & Fuel	Butte, MT	2.36	1.90%	2.55	2.60
S&N-Masonry	S&N Concrete & Materials	Anaconda, MT	2.51	2.46%	2.50	2.56
Helena-Masonry	Helena Sand & Gravel	Helena, MT	2.12	2.24%	2.48	2.54
Capital-Masonry	Capital Concrete	East Helena, MT	2.23	2.41%	2.54	2.60
BBB&T-Concrete	BBB&T	Bozeman, MT	2.76	1.97%	2.61	2.66
Pioneer-Concrete	Pioneer Concrete & Fuel	Butte, MT	2.77	2.09%	2.50	2.55
S&N-Concrete	S&N Concrete & Materials	Anaconda, MT	3.08	2.68%	2.48	2.55
Helena-Concrete	Helena Sand & Gravel	Helena, MT	3.31	1.67%	2.49	2.54

*Note: The line in the above table separate the masonry sands (upper) from the concrete sands (lower)

4.5 High Range Water Reducer (HRWR)

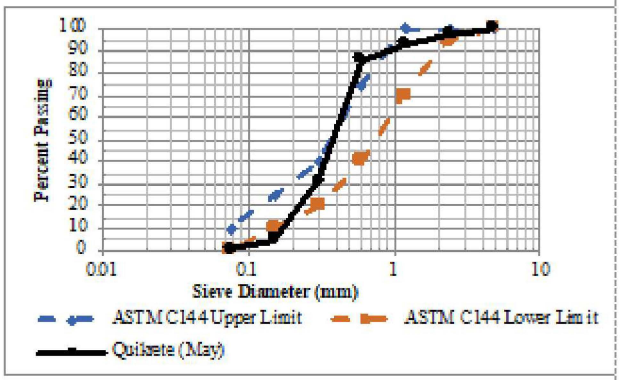
This research used the same water reducer that was used in the original phase of research: CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. This HRWR was used because it was shown to provide the best workability and least amount of entrapped air.

4.6 Steel Fibers

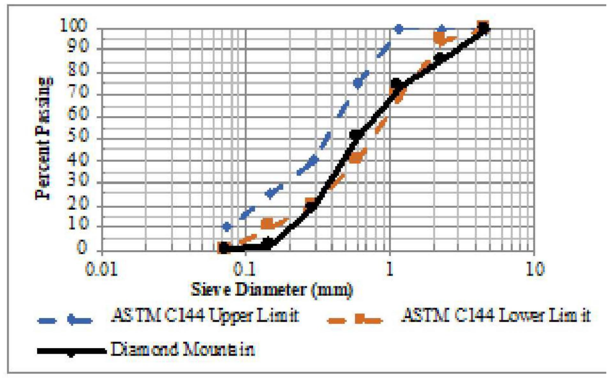
Steel fibers from two suppliers were investigated in this research: Nycon and Bekaert (see Table 5). The fibers from both suppliers had identical dimensions with diameters of 0.2 mm and lengths of 13 mm. However, the Bekaert fibers had a tensile strength 40% higher than the Nycon fibers. It should be noted that at the time of reporting, both of these fibers are not produced domestically, and therefore are not currently permitted on federally funded projects. A new supplier has been identified for domestically-produced drawn fiber of these dimensions and strength that are currently available on the market. However, these fibers have not been tested in the MT UHPC mix discussed herein. These fibers will be tested in the next phase of research.

Table 5: Properties of Steel Fibers

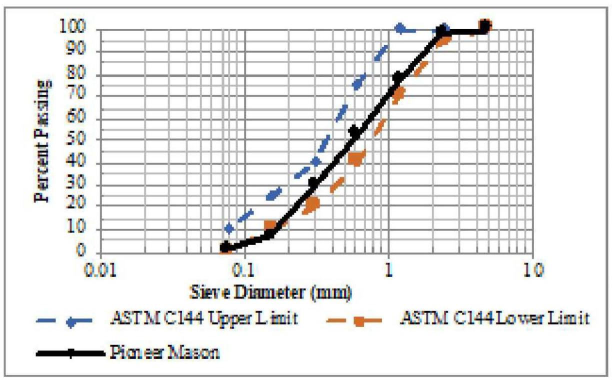
Properties	Nycon-SF Type I	Bekaert Dramix OL 13/0.20
Length (mm)	13	13
Diameter (mm)	0.2	0.2
Aspect Ratio	65	65
Tensile Strength (ksi)	285	399
Elastic Modulus (ksi)	29000	29000
Coating	Copper	Copper



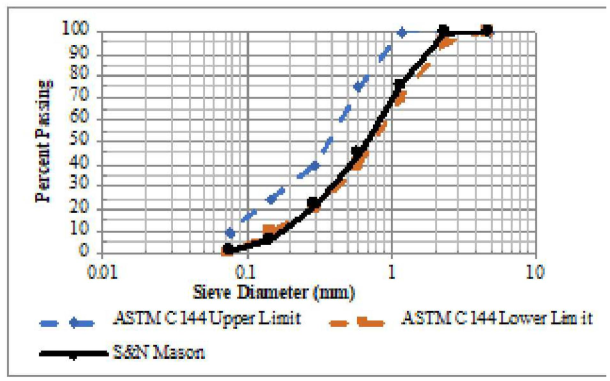
(a) QUIKRETE-Masonry



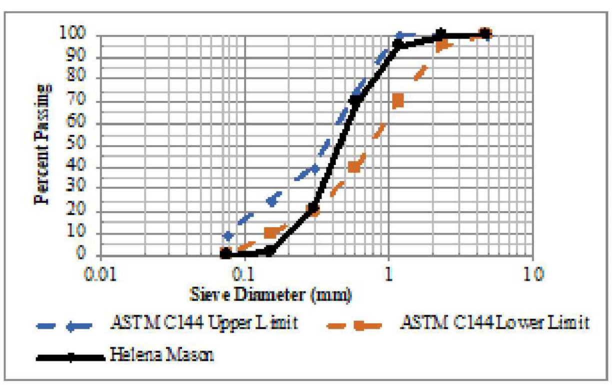
(b) Diamond Mountain-Masonry



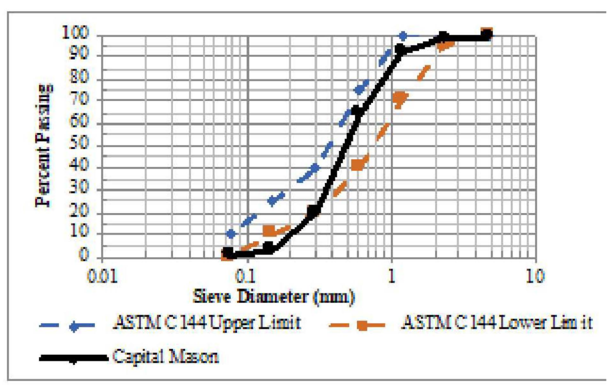
(c) Pioneer-Masonry



(d) S&N-Masonry

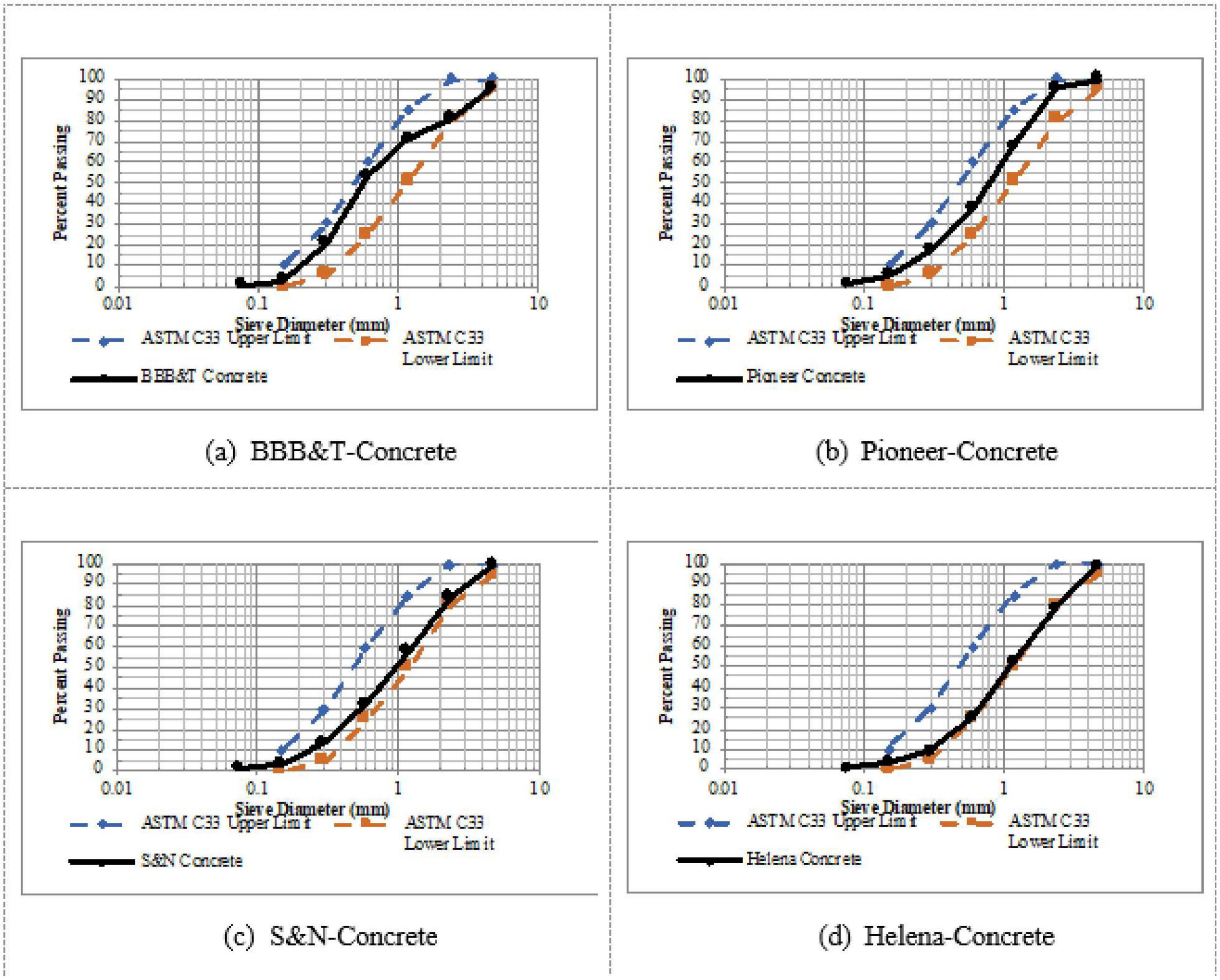


(e) Helena-Masonry



(f) Capital-Masonry

Figure 11: Particle Size Distribution of Mason Sands



(a) BBB&T-Concrete (b) Pioneer-Concrete

(c) S&N-Concrete (d) Helena-Concrete

Figure 12: Particle Size Distribution of Concrete Sands

5 SENSITIVITY OF UHPC TO MATERIAL VARIABILITY

This chapter documents the sensitivity of the MT UHPC mix to constituent material variability. Specifically, this chapter investigates the effects of cement source, fly ash source, fine aggregate source, aggregate moisture content, and steel fibers on UHPC performance.

5.1 Base Mix Design and Proportions

The mix design recommended from the Phase I research effort [1] was used in this phase of research, with slight modifications. This mix was proportioned using the absolute volume method using prescribed values for water to cement ratio (w/c), high range water reducer to cement ratio (HRWR/c), supplemental cementitious materials to cement ratio (SCM/c - includes silica fume and fly ash), silica fume to fly ash ratio (SF/FA), and sand to cement ratio (Sand/c). The w/c ratio in Table 6 includes a portion of the HRWR, as the majority of this admixture is water with only a small portion being chemical constituents. The base mixes in this research – unless noted otherwise – were 0.2 ft^3 and used cement from the Trident cement plant, fly ash from the Genesee Generating Station, QUIKRETE masonry sand, and Nycon steel fibers. The prescribed ratios for the mix designs are provided in Table 6, and the mix weights are provided for different volumes in Table 7.

Table 6: Mix Parameters for Base Mix

w/c Ratio	HRWR/c Ratio	Sand/c Ratio	SF/FA Ratio	SCM/c Ratio	Fiber Content	Paste Content
0.25	0.05	1.40	0.75	0.50	2%	62%

Table 7: Mix Proportions for Base Mix

Batch Size (cu ft)	Water (lbs)	HRWR (lbs)	Cement (lbs)	SF (lbs)	Fly Ash (lbs)	Fines (lbs)	Steel Fibers (lbs)
0.2	2.11	0.45	9.63	2.06	2.75	11.53	1.95
2.5	26.40	5.69	120.32	25.78	34.38	144.11	24.34
27	285.10	61.40	1299.46	278.46	371.27	1556.41	262.83

It should be noted that the base mix design was not modified/optimized for the various materials used in this research. That is, to isolate the effect of simply varying the material, the only variable between mixes was the material of interest. Increased strengths and improved flows could be expected if the mixes were modified/optimized for each of the materials.

5.2 Effect of Cement Source

Two cement sources (i.e., Trident and Ash Grove) were used to prepare UHPC using the methods discussed above. Flow, and 7- and 28-day compressive strength results for these mixes are provided in Table 8. As can be observed in this table, the mix using the Trident cement had slightly higher compressive strengths than the mix using the Ash Grove cement (10 percent higher at 7 days and 4 percent higher at 28). The measured flow for the Trident cement was 8.5 inches, while the Ash Grove cement had a flow of only 5.9 inches. It should also be noted that the Ash Grove mix had a delayed turnover time that occurred at around 11 minutes of mixing rather than the typical 5 minutes required for the Trident mix. Related to this, the Ash Grove mix also required an additional two minutes of mixing beyond the initial turnover. These results indicate that the Ash Grove cement may have had a slightly higher water demand, and better flows and strengths could possibly be obtained if the mix design was modified to include more water or HRWR.

Table 8: Flow and Compressive Strengths for Different Cement Sources

		Compressive strength, f'c (ksi)	
Cement Source	**Flow (in.)**	**7-day**	**28-day**
Trident (May 2018)	8.50	14.7	17.5
Ash Grove	5.88	13.3	16.8

5.3 Effect of Fly Ash Source

Three different Class F fly ash sources were tested in this research (Genesee, Coal Creek, and Sheerness). The resulting flows and compressive strengths are provided in Table 9. As can be observed, the different fly ash sources had a slight effect on flow, with the Genesee mix recording around 9 inches of flow, the Coal Creek mix recording around a 10-inch flow, and the Sheerness mix having a flow of just under 11 inches. Despite the differences in flow, the fly ash sources did not have a significant effect on compressive strength, with all 7-day strengths within 0.6 ksi of each other, and 28-day strengths within 0.1 ksi.

Table 9: Flow and Compressive Strengths for Various Fly Ashes

		Compressive strength, f'c (ksi)	
Fly Ash Source	**Flow (in.)**	**7-day**	**28-day**
Genesee	9.13	14.6	18.2
Coal Creek	10.13	15.2	18.2
Sheerness	10.88	14.9	18.1

5.4 Effect of Fine Aggregate Source and Properties

This research investigated ways in which fine aggregates could affect the performance of the UHPC mix evaluated in this research. Specifically, the research investigated the effects of fine aggregate source and aggregate moisture content, as discussed in the following sections.

5.4.1 Source and Type

As discussed in the materials section, 6 masonry sands and 4 concrete sands were evaluated in this research. UHPC mixes were prepared using these aggregates and the mix design specified above, and were tested to evaluate the effect of the aggregate sources. The flow and average compressive strengths from these mixes are provided in Table 10 and the compressive strengths are plotted in Figure 13. Included in Table 10 are the average compressive strengths for the masonry sands and the average strengths for the concrete sands. As can be observed in the data, all aggregate sources produced concrete flows between 8 and 9.4 inches, with 7- and 28-day compressive strengths of at least 13 and 16 ksi, respectively. The average flows and compressive strengths obtained from the concrete aggregates were nearly identical to those obtained from the masonry aggregates, indicating that both types of aggregates might be suitable for UHPC mixes.

It should be noted that the aggregates were all oven dried, and then used in the mixes without making modifications to the mix proportions to account for the different absorption capacities of the aggregates. Further, no modifications were made to account for the differences in fineness moduli, which could also affect UHPC performance. To evaluate the effects that these properties could have on the performance of the UHPC mixes, the flows and compressive strengths were plotted vs absorption capacity (Figure 14) and fineness modulus (Figure 15) for each of the aggregate sources. Included in these figures are the least-squared best fit lines, and their respective R^2 values. As can be observed in Figure 14, the absorption capacity appears to have a somewhat significant effect on flow ($R^2 = 35\%$) and slight effect on compressive strengths ($R^2 = 15\%$ and $R^2 = 9\%$). In regard to the effect of fineness modulus, no significant trend can be observed. It should be noted that the trend observed in flow is counterintuitive. That is, one would expect the flow to decrease with increasing absorption capacity, as the oven-dried aggregates with higher absorption capacities would absorb more mix water, leaving less to contribute to flow. It was observed that the trends above are controlled by the outlying aggregate with a nearly 4% absorption capacity (Diamond Mountain-Masonry). If this aggregate source is removed, the trends mentioned above are nonexistent. This aggregate source should be investigated further before use in UHPC.

Table 10: Flow and Compressive Strength for Various Fine Aggregate Sources

					Compressive Strength (ksi)	
Fine Aggregate Source	**Abbreviation**	**FM**	**Absorption**	**Flow (in)**	**7-day**	**28-day**
QUIKRETE	**QK**	3.32	1.87%	8.0	14.7	17.5
Diamond Mountain-Masonry	**DM-M**	4.68	3.99%	9.4	13.8	16.6
Pioneer-Masonry	**P-M**	4.35	1.90%	8.8	15.8	18.6
S&N-Masonry	**SN-M**	4.50	2.46%	8.8	15.5	18.8
Helena-Masonry	**H-M**	4.12	2.24%	8.4	14.2	16.9
Capital-Masonry	**C-M**	4.22	2.41%	9.0	14.3	17.3
Masonry Average				8.7	14.7	17.6
BBB&T-Concrete	**BBBT-C**	4.75	1.97%	8.9	14.7	18.7
Pioneer-Concrete	**P-C**	4.75	2.09%	8.8	13.4	15.9
S&N-Concrete	**SN-C**	5.07	2.68%	8.3	14.0	17.2
Helena-Concrete	**H-C**	5.30	1.67%	8.5	14.7	17.3
Concrete Average				8.6	14.2	17.3

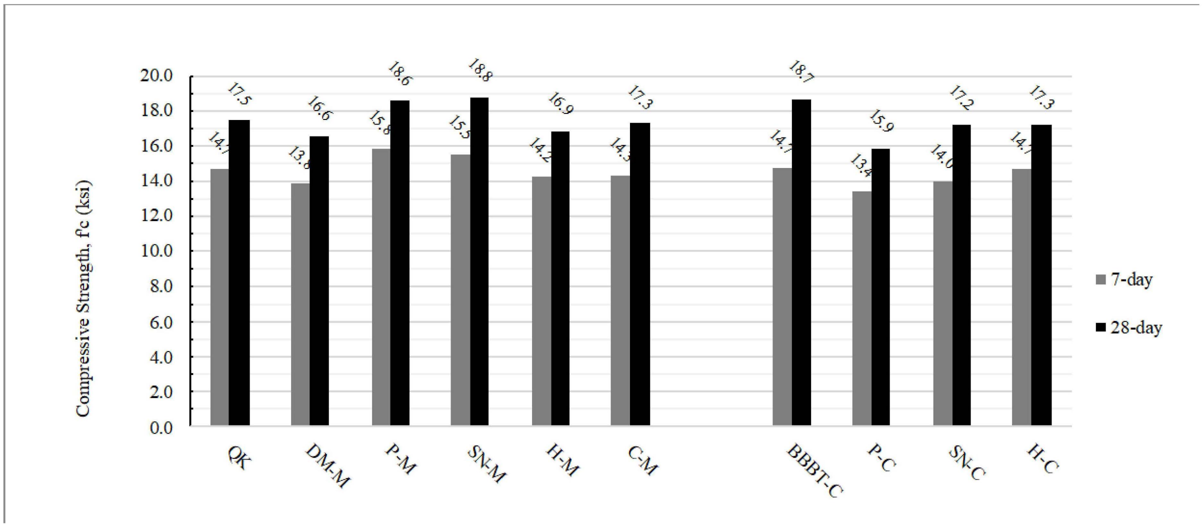


Figure 13: Compressive Strengths for Various Fine Aggregate Sources

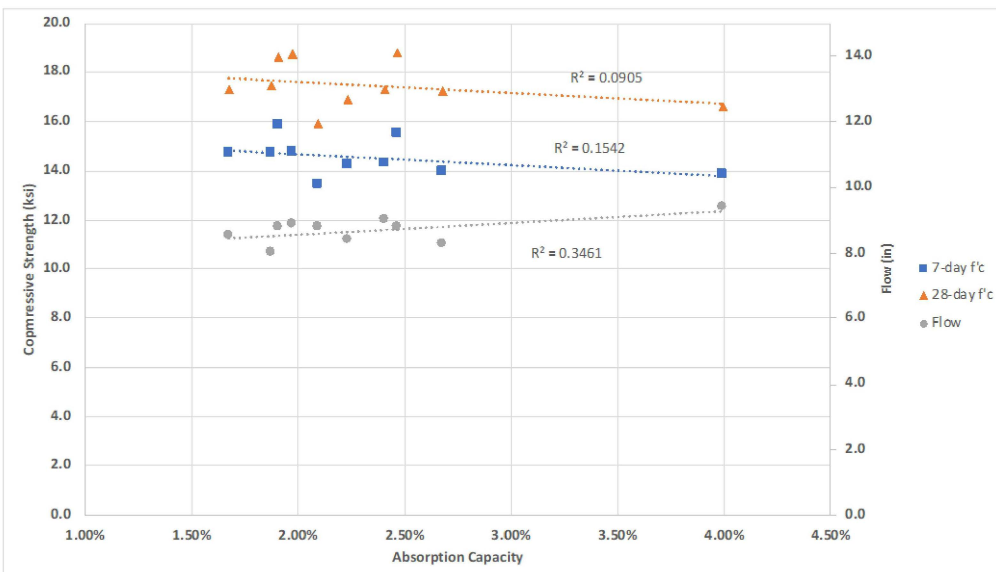


Figure 14: UHPC Properties vs Absorption Capacity

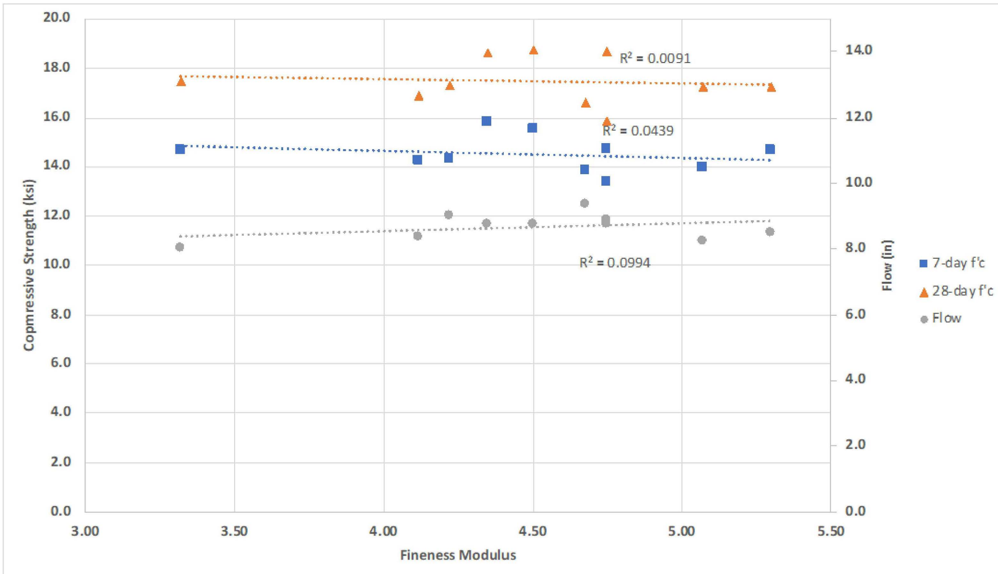


Figure 15: UHPC Properties vs Fineness Modulus

5.4.2 Moisture Content

To evaluate the effects of varying moisture content, UHPC mixes were prepared with the BBB&T concrete sand with varying levels of moisture: oven dried, 50% of SSD, 100% of SSD, 150% of SSD, and 300% of SSD. To start, no moisture content corrections were applied. The resulting flows and compressive strengths are provided in Table 11, while the compressive strengths are plotted vs percentage of SSD in Figure 16. As can be observed in the table and figures, as expected the flow generally increased with increasing moisture content, while the 7- and 28-day compressive strengths generally decreased.

To evaluate the efficacy of using the moisture content correction method in UHPC mixtures, modified UHPC mixes were prepared for each of the aggregate moisture contents by withholding water from the mixture to account for the moisture present within the aggregate. The resulting effects can be seen in Table 11, Figure 16, and Figure 17.

Theoretically, correcting for moisture content, and targeting the baseline mix in which the aggregates were oven dried, should result in flows and compressive strengths that match the baseline mix. However, this was only loosely observed in this study. While flows and compressive strengths did not come particularly close to matching the baseline mix, they were generally closer than the uncorrected mix data. This indicates that moisture content correcting aggregates might not be as effective in UHPC mixes, and may need to be investigated further. This also indicates the need for trial batches using all constituent materials prior to use in actual construction projects.

Table 11: Flow and Compressive Strengths for Various Moisture Contents

Moisture Target	Flow (in.)	Compressive Strength, f'c (ksi)	
		7-day	28-day
Oven Dried	7	13.61	17.73
50% of SSD	8	13.14	16.62
100% of SSD	7.5	13.35	16.83
150% of SSD	10.5	11.28	13.14
300% of SSD	11.5	11.71	16.31
50% of SSD - MCC	8	13.25	17.75
100% of SSD - MCC	10	13.44	16.37
150% of SSD - MCC	10.5	12.33	16.36
300% of SSD - MCC	11.5	13.50	16.20

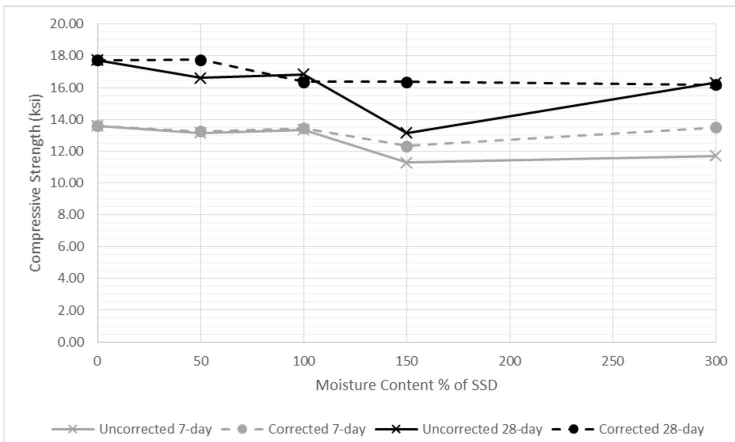


Figure 16: Effect of Moisture Content Correction on Compressive Strength

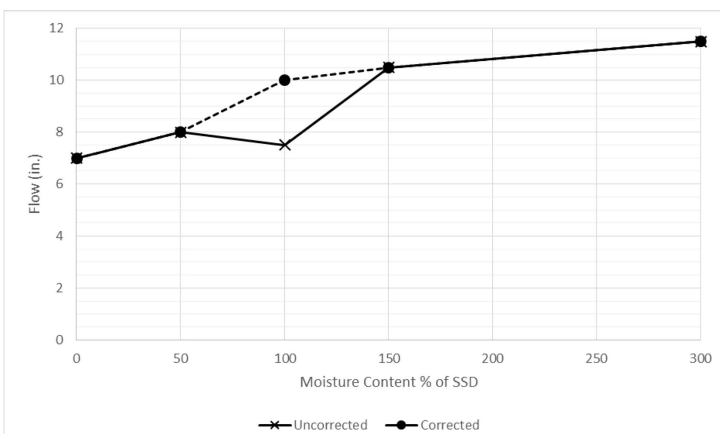


Figure 17: Effect of Moisture Content Correction on Flow

5.5 Steel Fibers

Two different steel fibers, with nearly identical properties, were investigated in this research. As can be observed in Table 12, the steel fibers did not have a significant effect on flow or compressive strength, as expected. The results also show there was not a significant effect on either flexure capacity (initial cracking capacity or total capacity) of the UHPC specimens with different fibers. It should be noted that neither of these fibers can currently be used in FHWA projects because they are not produced domestically. That being said, the findings from this research demonstrate that the performance of the newly developed UHPC mix is not sensitive to slight variations between steel fibers. It should also be noted that this shortage of domestically-produced steel fibers of this nature is affecting most UHPC research/applications nationally. Work is currently being done to find alternative domestically-produced fibers for use in UHPC, and Bekaert is being lobbied to reinstate their domestic production of these steel fibers.

Table 12: Effect of Steel Fibers on Compressive Strength

		Compressive Strength, f'c (ksi)		Flexure Strength (ksi)	
Cement Source	**Flow (in.)**	**7-day**	**28-day**	**Initial Cracking Capacity**	**Total Capacity**
NYCON	8.5	14.7	17.5	1.98	3.39
Bekaert	10.0	13.9	17.3	1.65	2.96

5.6 Summary

The effects of varying sources of cement, fly ash, fine aggregates, and steel fibers were investigated, along with the effect of varying moisture content. While these variations had some effects on UHPC performance, the effects were fairly minor. It is important to point out that all mixes in this study had a flow of at least 6 inches, and respective 7- and 28-day compressive strengths of at least 13 and 16 ksi. It should also be noted, that the mix designs were not modified to account for the variations in material sources and properties (with the exception of the moisture content correction study), and one would expect better performance if the mix designs were optimized for the specific materials.

6 SENSITIVITY OF UHPC TO MIXING VARIABILITY AND FIELD CONDITIONS

This chapter discusses the sensitivity of the MT UHPC to various mixing/field conditions.

6.1 Base Mix Design

The mix design recommended from the Phase I research effort [1] (and used in the previous chapter) was used in this phase of research, with slight modifications. The base mix in this phase of research used cement from the Trident cement plant, fly ash from the Genesee Generating Station, concrete sand from Bozeman Brick and Tile, and Bekaert steel fibers. The mix proportions for a 2.5 cu. ft mix are provided in Table 13. It should be noted that this mix design is identical to that used in the material sensitivity study discussed previously, with one exception – the amount of water. A majority of the mixes in this phase of research were at least 2.5 cu. ft and were mixed with the IMER Mortarman 360 mortar mixer, in contrast to the mixes in the material sensitivity study which were 0.2 cu. ft and were mixed using the industrial cake mixer. Early on, during initial trial batches using the larger batches, it was determined that the larger mixes required more water and HRWR, and therefore the mixes used in this phase of research included 10% more water and 10% more HRWR than the mixes used in the material sensitivity study. This increase in water was required to obtain the correct mix consistency and flow, and did not have a detrimental effect on strength. Note that the 10% increase of water and HRWR was constant for all mixes above 2.5 cu. ft.

Table 13: Mix Proportions for 2.5 cu. ft. Mix

Item	Item Type	Amount (lbs)
Water	-	27.66
HRWR	CHRYSO Fluid Premia 150	5.96
Portland Cement	Type I/II Trident	120.32
Silica Fume	BASF MasterLife SF 100	25.78
Fly Ash	Trident Genesee	34.38
Fine Aggregate	O.D. BBB&T Concrete Sand	144.11
Steel Fibers	Bekaert Dramix OL 13/0.20	24.34

6.2 Strength Gain vs Time

The strength gain of the UHPC mix developed in this research was measured over a 6-month period. The batch size used in this study was 2.5 cu. ft, and two identical mixes were tested. The measured compressive strength (average of 3 cylinders) for each mix is presented for the first 7 days in Figure 18, and over a 6-month period in Figure 19. As can be observed, both mixes had high early strengths, exceeding 10 ksi in the first 24 hours, and exceeding 14 ksi in the first week. The mixes continued to gain strength over time (with a few fluctuations), ultimately reaching compressive strengths of 20.4 and 19.1 ksi at 182 days, only a 6.6% difference for our 'identical' mixes.

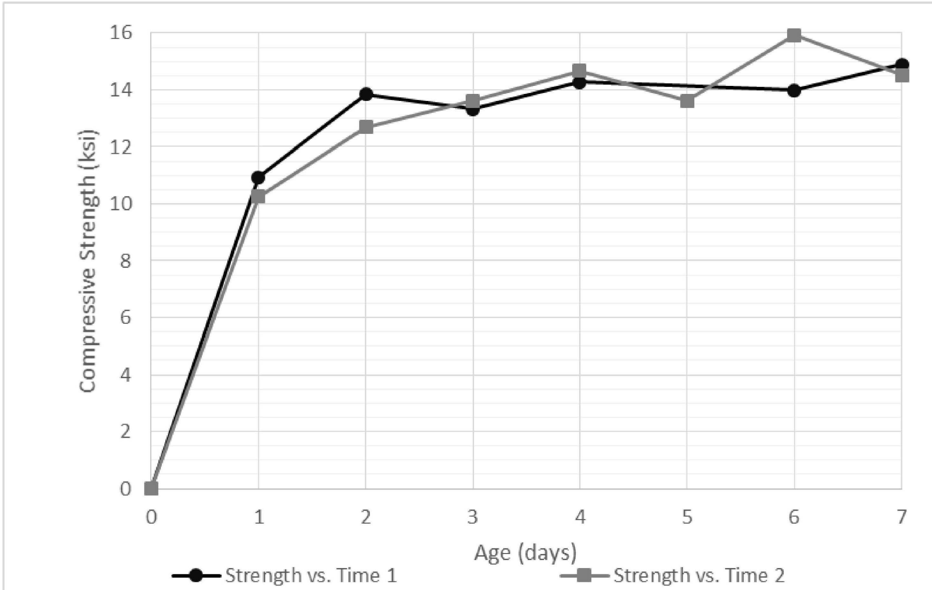


Figure 18: Strength Gain vs Time – 7 Days

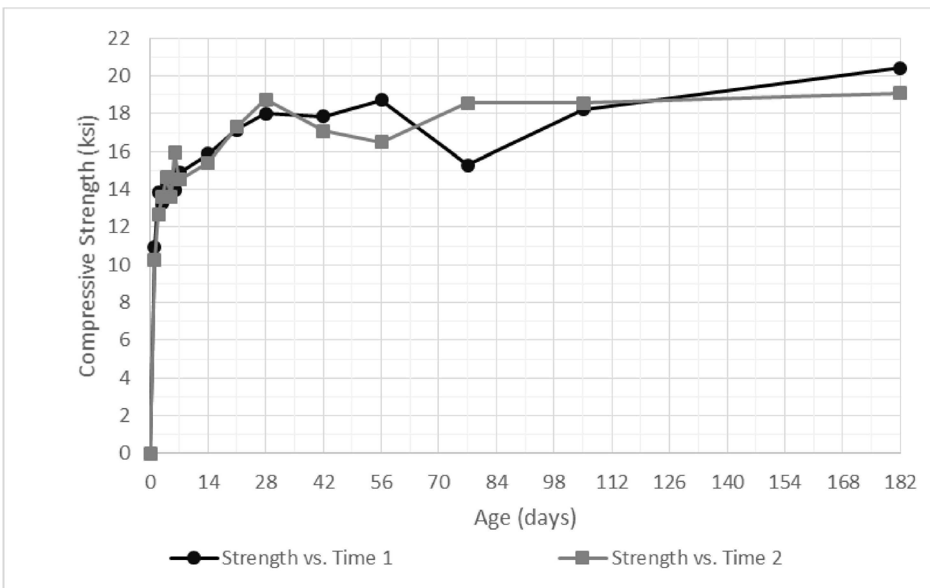


Figure 19: Strength Gain vs Time – 6 Months

6.3 Batch Size

The effect of batch size on UHPC performance was studied in this research by increasing the batch size from 2.5 to 4 cu. ft across four batches, and recording the flow and compressive strength at 7, 28, and 56 days. The results from this study are presented in Table 14 and Figure 20. As can be observed, the batch size did not have a significant effect on the performance of the UHPC mix, with no clear trends in flow or compressive strength. The measured flows were all between 7.5 and 9.5 inches with a coefficient of variation of 8.6%. The measured compressive strengths had coefficients of variation of less than 6% on each day, with a coefficient of variation of only 3.2% at 56 days. It should be noted that batch sizes above

4 ft^3 are most likely possible with this mixer, but the constituent materials were near the top of the mixer prior to the mix turning over and becoming fluid. If larger batches are to be used, trial batches should be conducted and possible modifications to the mixing procedure should be explored prior to its use in field applications.

Table 14: Effect of Mix Size on Compressive Strength

Mix Size (cu. ft.)	Flow (in.)	Compressive Strength, f'c (ksi)		
		7-day	**28-day**	**56-day**
2.5	9	14.90	18.01	18.71
3	9.5	17.29	18.81	18.01
3.5	7.5	16.25	15.97	19.57
4	8.5	15.38	17.73	18.24
Average:	8.63	15.95	17.63	18.63
C.O.V.:	8.6%	5.7%	5.9%	3.2%

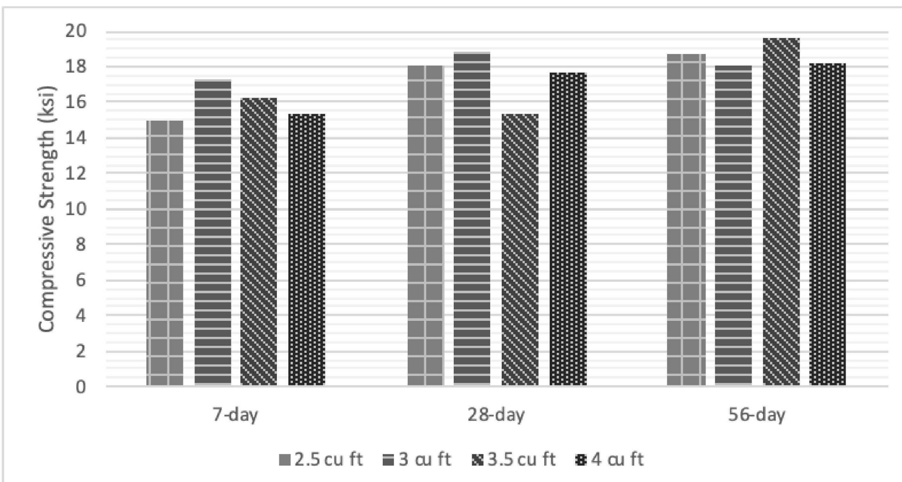


Figure 20: Effect of Mix Size on Compressive Strength

6.4 Temperature Effects

The effect of temperature on the performance of the UHPC mix was studied by varying the temperature of the dry UHPC constituents and by mixing the concrete at various temperatures. A total of 3 mixes were prepared and tested: a cold mix, a room-temperature mix, and a hot mix. The dry materials used in the cold mix were prepared by placing the materials in the structures cold lab at 32°F for 72 hours until the material came to thermal equilibrium. The batching and mixing were then performed outside when the temperature was 45°F. This mix was performed early in the morning prior to the site being exposed to the sun, and the mixer was exposed to these conditions 2 hours prior to mixing. Similarly, for the hot mix, the dry constituents were prepared by placing them in the concrete lab oven at 90°F for 72 hours, and the mixing and batching took place outside in the sun when the temperature was 75°F. It should also be noted that the mixer was outside and exposed to this environment for 2 hours prior to mixing. The temperature of the constituents used in the room-temperature mix were not altered from their lab condition (60°F), and the batching and mixing took place at the lab temperature (70°F).

The effects of temperature on the performance of the UHPC mix are provided in Table 15 and Figure 21. As can be observed, temperature had a noticeable effect on several performance measures. Specifically, flows decreased as temperature increased. That is, the cold mix had a flow of 10 inches, whereas the hot mix only had a flow of 6.25 inches. Similarly, the 7-day strengths decreased slightly with increasing temperatures. However, that same trend is not observable in the 28- and 56-day strength data. That being said, the hot mix had the lowest strength on all testing days, and although the set time was not directly measured, it was observed that the hot mix set significantly faster than the two lower temperature mixes. These results indicate that care should be given in mixing and placing UHPC at higher temperatures.

Table 15: Effect of Mix Temperature on Compressive Strength

Mix	**Outside Temperature (°F)**	**Dry Material Temperature (°F)**	**Flow (in.)**	**Compressive Strength, f'c (ksi)**		
				7-day	**28-day**	**56-day**
Cold Mix	45	32	10	16.15	17.89	17.98
Room Temperature	70	60	9	14.9	18.01	18.71
Hot Mix	75	90	6.25	14.78	16.62	17.03
		Average:	8.42	15.27	17.51	17.91
		C.O.V.:	18.8%	4.1%	3.6%	3.8%

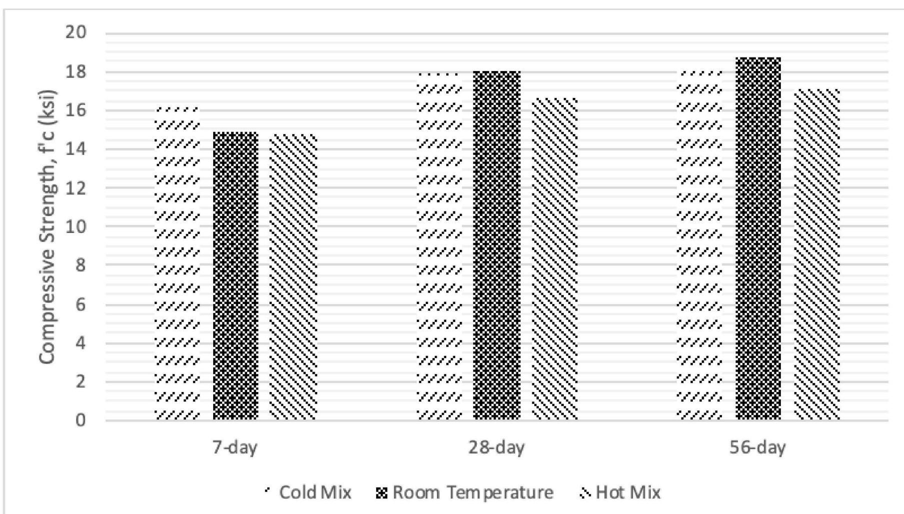


Figure 21: Effect of Mix Temperature on Compressive Strength

6.5 Summary

In this task, parameters that may affect field batching and mixing of UHPC were studied. Specifically, the rate at which UHPC gains strength over time was investigated, along with the effects that batch size and temperature might have on UHPC performance. It was observed that the UHPC mixes obtained high early strengths, exceeding 10 ksi in the first 24 hours. The mixes continued to gain strength over the duration of testing, ultimately reaching strengths of around 20 ksi at 182 days. Batch size was not observed to have a significant effect on flow or compressive strength; however, it was observed that the larger scale mixes used in this phase of research required 10% more water and HRWR in order to obtain the same performance observed for the smaller batches used in the material sensitivity study. Temperature was observed to have an effect on several parameters. Specifically, flow was observed to decrease with increasing temperature and the compressive strengths for the hot mix were consistently the lowest. These results indicate that care should be given while batching and mixing UHPC mixes at higher temperatures.

It should also be noted, that despite the wide range of mixing conditions studied in this phase of research, all mixes had flows of at least 6 inches, and respective 7- and 28- day compressive strengths of at least 13 and 16 ksi.

7 BOND STRENGTH AND PULLOUT TESTING

Direct pullout tests were performed to evaluate the bond strength of the nonproprietary Montana UHPC developed in this research. All UHPC mixes in this study used the UHPC mix design provided in Table 13, with a batch size of 3.5 cu. ft. In this chapter, the setup and instrumentation are discussed first, followed by a description of the specimen construction process. The test matrix and results are then presented, and the chapter concludes with a brief summary of results.

7.1 Test Setup and Instrumentation

In this research, reinforcing steel embedded into UHPC curbs were tested in direct tension to determine the bond capacity of the UHPC developed in this research, and to ultimately determine adequate development lengths. The test setup for this investigation was based on the setup used by the FHWA in a similar study [9]. The specimens in the research discussed herein consisted of UHPC curbs reinforced to and cast on top of conventional concrete slabs. Various sizes of reinforcing steel were embedded into the UHPC curbs, and the key dimensions were varied between specimens. The embedded rebar was tested in tension until failure. An idealized test specimen and the key dimensions are shown in Figure 22.

The slabs were made of conventional concrete and were 8 ft x 4 ft x 11.5 inches deep, and were cast with conventional No. 8 Grade 60 reinforcement embedded the full depth of the slab and extending 8 inches above the surface of the slab, which ultimately would result in an embedment length of 8 inches into the UHPC curb. The UHPC curbs were 10 inches tall, ran transversely across the slabs, and varied in width depending on the testing matrix. The reinforcement embedded in the UHPC curbs were all conventional Grade 60 rebar and varied in size from No. 4 to No. 7. Along with varying bar size, this research also studied the effects of varying embedment length (l_d), bar clear spacing (c_{si}), and concrete side cover (c_{so}).

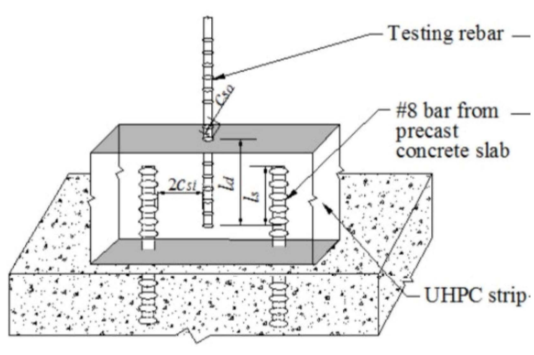


Figure 22. Test Specimen and Key Dimensions [9]

The pullout tests were performed after allowing the UHPC curbs to cure for 28 days after placement. An idealized view of the test setup is shown in Figure 23, while the actual setup is shown in Figure 24. This setup consisted of a hollow-core hydraulic actuator bearing on a steel plate that spanned across the curb and transferred the load to the slab. The actuator transferred the load to the rebar through a plate bearing on a rebar chuck attached to the top of the rebar. The load was monitored with a pressure transducer attached to the hydraulic pump. The displacement of the embedded rebar was monitored with three string potentiometers attached to the top of the rebar. The total deflection of the rebar was calculated as the average from these three readings.

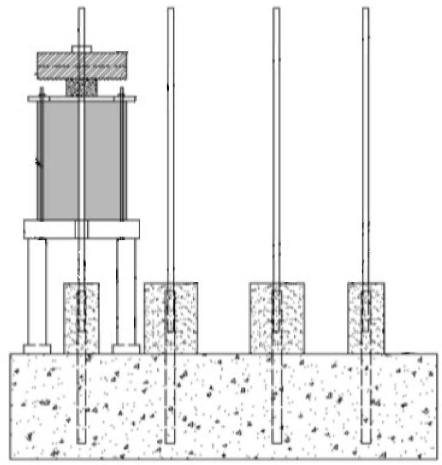


Figure 23: Idealized Test Setup and Instrumentation

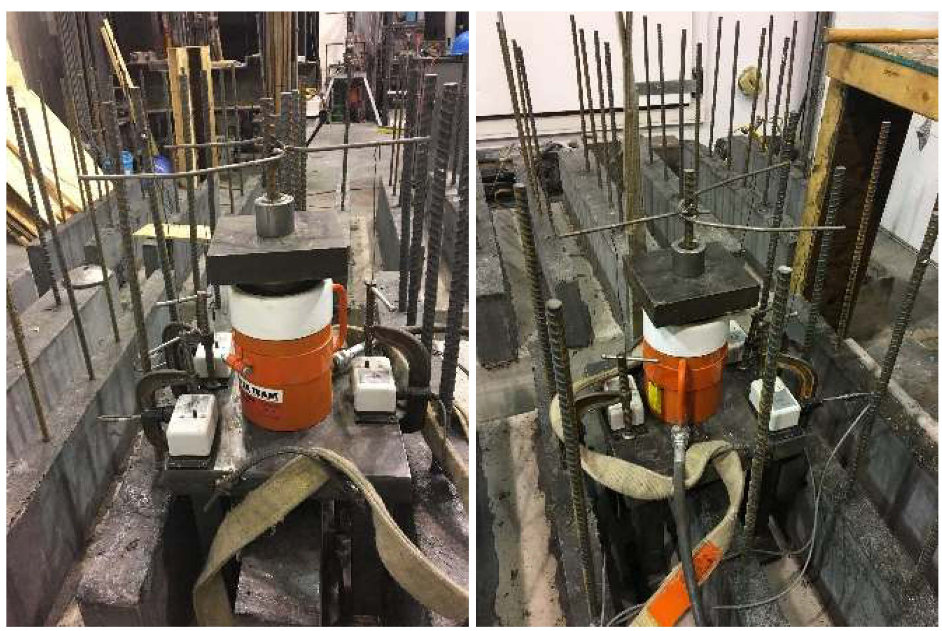


Figure 24: Actual Test Setup and Instrumentation

7.2 Construction of Test Specimens

Each slab was approximately 4 ft x 8 ft x 11.5 inches deep. The formwork for the bottom slab was constructed out of plywood and 2x12 timber members. The slab was reinforced in both directions with No. 3 rebar with a 1-inch clearance from the bottom of the slab. The No. 8 bars (to be embedded in the curbs) were placed in the form and held in place with 2 in x1 in member spanning across the slab. The slab formwork and reinforcement can be seen in Figure 25. The slab consisted of conventional concrete supplied by a local batch plant and was placed into the forms with a front-discharge ready mix truck. The placement of the slabs is shown in Figure 26.

Figure 25: Slab Formwork and Reinforcement

Figure 26: Placement of the Slabs

The curb formwork was constructed out of plywood and 2 in x 4 in timber members, as shown in Figure 27. As can be observed in this figure, the rebar to be embedded into the UHPC curb was held in place with a member spanning across the top of the curb.

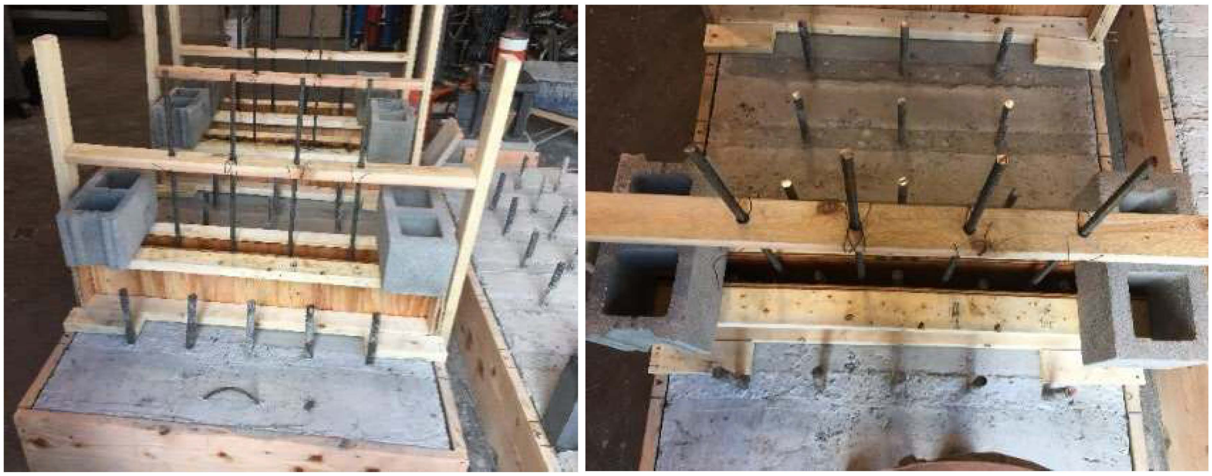


Figure 27. UHPC Pullout Curb Formwork

The curbs were cast with UHPC mixes prepared in 3.5 cu. ft batches using the IMER Mortarman 360 mixer. A total of 7 UHPC batches were required to construct all of the testing curbs. The UHPC was placed in the curb formwork with clean, dry 5-gallon buckets. The UHPC was placed starting at the middle of each curb and care was taken to evenly distribute the UHPC by adding UHPC at each end of the curbs as needed. The UHPC was placed quickly to avoid any premature setting of the concrete before the curbs were completed. A flow test was conducted, and test cylinders were prepared for each batch of concrete. Formwork remained on the curbs for a minimum of 48 hours before it was removed, and the UHPC cured for 28 days before testing.

7.3 Test Matrix and Results

A total of 56 pullout tests were conducted as part of this research. Forty of these specimens included systematic variations to bar size, embedment depth, clear spacing, and clear cover to isolate the effects of these parameters. The other 16 of these specimens were designed to meet the minimum embedment depth requirements recommended by the FHWA [9] for UHPC. These 16 tests are of utmost importance to this project as they will demonstrate that these recommendations can be used for Montana UHPC, a necessary step before this mix can be used in the desired application. Therefore, this chapter will only focus on the results of these 16 specimens. The total test matrix and summary of results is provided in Appendix A.

The 16 FHWA-compliant specimens included 4 duplicate specimens of 4 bar sizes, and are summarized in Table 16. The bar sizes investigated were No. 4, 5, 6 and 7 and were all Grade 60 conventional reinforcement. The embedment length, side cover, and bar spacing were determined from the FHWA requirements. These requirements state that the minimum embedment depth should be taken as 8 times the diameter of the reinforcing bar for bars with a minimum cover greater than or equal to three times the diameter of the bar (for bars with yield strength less than 75 ksi).

Using the test setup described in the previous section, each bar was loaded until failure while monitoring the applied load and resultant deflection. Typical stress-deformation curves for each bar size are provided in Figure 28, and the max recorded stress and resultant failure mechanism are provided in Table 16. As can be observed, all embedded reinforcing steel failed due to yielding of the reinforcement, the desired failure mechanism. In almost all cases, the bars were loaded beyond yielding and into the strain hardening region before the test was stopped (as can be observed in Figure 28 a, b, and c). It should be noted that the tests were stopped after yielding, but before the reinforcement ruptured to ensure the safety of the researchers in the lab, and therefore the maximum stresses recorded in the table do not indicated the ultimate failure stress. It is also worth noting that none of the specimens in this subset failed due to bond failure prior to, or after reinforcement yielding. These results are promising and indicate that the FHWA embedment depth recommendations may be suitable for use in bridge closure pours made with the UHPC mix developed in this research.

Table 16: Pullout Test Matrix and Results for FHWA Recommended Development Length

Flow (in)	f'c, ksi	Bar Size	l_d, in	ls, in	c_{so}, in	c_{si}, in	Max. Stress (ksi)	Failure Mechanism
11.0	17.34	4	4	2	1.5	3	80.79	Yielding
							69.44	Yielding
							92.08	Yielding
							69.95	Yielding
9.5	16.59	5	5	3	1.875	3.1875	77.12	Yielding
							73.45	Yielding
							73.37	Yielding
							63.53	Yielding
11.0	17.34	6	6	4	2.25	3.125	77.35	Yielding
							66.41	Yielding
							86.34	Yielding
							48.49	Yielding
9.5	16.59	7	7	5	2.625	3.0625	76.45	Yielding
							77.31	Yielding
							72.8	Yielding
							102.65	Yielding

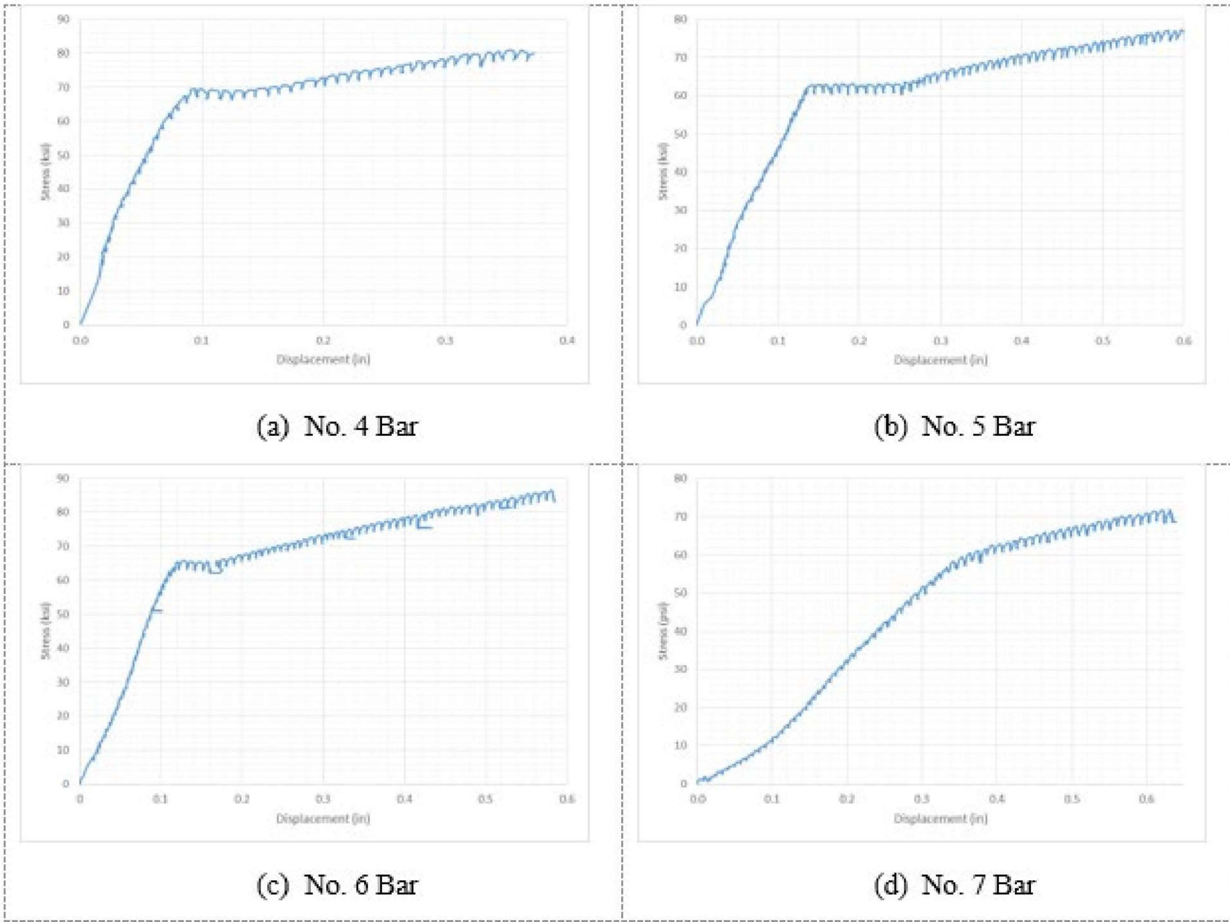


Figure 28: Typical Stress vs. Displacement Plots for FHWA Pullout Tests

8 SUMMARY AND CONCLUSIONS

The primary objective of the research discussed herein was to further investigate and develop a non-proprietary UHPC mix for use in Montana. Specifically, this research (1) investigated the potential variability in concrete performance related to differences in constituent materials, (2) investigated issues related to the field batching/mixing of these UHPC mixes, and (3) tested rebar bond strength and its effects on requisite development lengths. The following conclusions can be drawn from this investigation:

- While variations in the source of the constituent materials (e.g., cement, fly ash, aggregate) had some effects on UHPC performance, the effects were fairly minor. Further, it should be noted that the same base mix design was used in all of the materials investigated in this research, and some of the differences in performance could be eliminated if the mix design was adjusted accordingly to account for the variations in the material.
- As expected, the flow of the UHPC mixes generally increased with increasing aggregate moisture content, and the 7- and 28-day compressive strengths generally decreased. However, adjusting the mix water to account for the variations in aggregate moisture contents did not significantly affect the observed flow of the mixes, but generally did improve the observed compressive strengths.
- The recommended MT UHPC mix demonstrated high early strengths, with compressive strengths of around 10 ksi at 24 hours. The mix continued to gain strength over time, ultimately reaching compressive strengths of around 20 ksi at 182 days.
- Batch size did not have a significant effect on flow or compressive strength; however, it was observed that the larger scale mixes used in this phase of research required 10% more water and HRWR to obtain the same performance observed for the smaller batches used in the material sensitivity study (when size was increased from 0.2 cu. ft. to 2.5 cu. ft. or larger).
- Temperature was observed to have an effect on several parameters. Specifically, flow was observed to decrease with increasing temperature, while the compressive strengths for the hot mix were consistently the lowest. These results indicate that care should be given while batching and mixing UHPC mixes at higher temperatures.
- In regard to the pullout tests, all of the reinforcing bars that met the minimum FHWA recommendations for embedment depth and clear cover reached at least their yield stress prior to bond failure, indicating that the FHWA recommendations are suitable for use in connections made with the MT UHPC.
- Finally, despite the wide range of mixing conditions studied in this phase of research, all mixes in this study had flows between 6 and 11 inches, and respective 7- and 28- day compressive strengths of at least 13 and 16 ksi. This consistent/adequate performance under varying conditions indicates that the MT UHPC mix is suitable for field applications in Montana. However, trial batches should be performed to optimize performance and account for the variations in materials and mixing conditions.

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APPENDIX A: COMPLETE PULLOUT TEST RESULTS

This section provides the test matrices and results from all of the pullout tests conducted as part of this research effort. The parameters investigated were embedment length (l_d), clear spacing between bars (c_{si}), bar size, and bar side cover (c_{so}). Results from this test series are presented in the subsections and tables 17-20.

It should be noted that the results from this overall test series are clouded by the fact that many of the test specimens failed prematurely due to mechanisms not associated with the bond capacity of the rebar/UHPC embedment. Specifically, many of the specimens failed due to tensile failure of the top of the UHPC curb, which manifested in a longitudinal crack running along the length of the curb, as seen in Figure 29. This failure was most likely due to inadequate embedment length of the rebar extending up from the conventional concrete slab. To complicate things further, if a rebar specimen failed prematurely due to failure in the concrete, this failure had a tendency to spread to the adjacent specimen region, affecting the results of this other specimen. Future testing should extend the rebar further into the curb to prevent the tensile failure mechanism, and a joint should be included in the concrete curb to isolate the rebar specimens and prevent the spreading of the concrete failure.

The other observed failure mechanisms in these tests were yielding of the rebar (preferred mechanism) and splitting of the UHPC curb along the length of the rebar (associated with resultant hoop stresses forming around the rebar). This mechanism is more typically associated with conventional bond failure. Figure 30 shows a curb after testing where the rebar yielded prior to bond failure, and Figure 31 shows several specimens that failed due to splitting of the concrete.

It should be noted that many of the embedment length, clear bar spacing, and bar side cover variables were pushed to extremes, and therefore failure was expected and even intended in order to find the limits of this UHPC mix for its intended application. Further, while the results from this overall test series were clouded by premature failure of the UHPC due to issues not related to bond failure, the specimens that met the FHWA recommendations for embedment depth yielded prior to bond failure.

Figure 29: Side Cover tests 1 through 4 showing UHPC tension failure

Figure 30: FHWA Recommended tests 14 through 16 showing no UHPC effect as test results ended with rebar yielding

Figure 31: Bar Spacing test 7 showing UHPC splitting failure

A.1 Embedment Length

The embedment of reinforcing bars is one of the main variables that affects the strength of bond development. To evaluate the effect of embedment on reinforcing bars, No. 5 Grade 60 bars with clear bar spacing of 2 in and side cover of 2.5 in were tested. The embedment varied from 2.5 in to 6.25 in at increments of bar diameter ($2d_b$ to $5d_b$). In previous studies embedment has been found to be a strong predictor of reinforcement bond development. The results of these tests are provided in Table 17.

Table 17: Embedment Length Pullout Test Matrix

	Test ID	Flow (in)	f'c (ksi)	Bar Size	ld (in)	ls (in)	cso (in)	csi (in)	Max. Stress (ksi)	Failure Mechanism
Embedment Length	1	10.5	19.31	5	2.5	1.5	1.25	2	29.08	UHPC tension failure
	2	10.5	19.31	5	2.5	1.5	1.25	2	N/A	Pre-cracked
	3	10.5	19.31	5	3.75	2.75	1.25	2	N/A	Pre-cracked
	4	10.5	19.31	5	3.75	2.75	1.25	2	45.15	UHPC tension failure
	5	10.5	16.92	5	5	4	1.25	2	N/A	Pre-cracked
	6	10.5	16.92	5	5	4	1.25	2	64.37	Yielding
	7	10.5	16.92	5	6.25	5.25	1.25	2	N/A	Pre-cracked
	8	10.5	16.92	5	6.25	5.25	1.25	2	N/A	Pre-cracked

A.2 Clear Bar Spacing

To test the effect of clear bar spacing, No. 5 and No. 4 Grade 60 bars were tested. The No. 5 bars were embedded at either 3.75 in ($6d_b$) or 5 in ($8d_b$). The No. 4 bars were embedded at either 3 in ($6d_b$) or 4 in ($8d_b$). The side cover for both No. 5 and No. 4 bars was 3 in. Both bars were tested with a spacing of 3 in as the rest of the tests were conducted at a spacing of 2 in. The results of these tests are provided in Table 18.

Table 18: Clear Bar Spacing Length Pullout Test Matrix

	Test ID	Flow (in)	f'c (ksi)	Bar Size	ld (in)	ls (in)	cso (in)	csi (in)	Max. Stress (ksi)	Failure Mechanism
Bar Spacing	1	10.5	19.31	5	3.75	2.75	1.25	3	42.63	UHPC tension & splitting
	2	10.5	19.31	5	3.75	2.75	1.25	3	43.46	UHPC tension & splitting
	3	11.0	17.34	5	5	4	1.25	3	68.31	Yielding
	4	11.0	17.34	5	5	4	1.25	3	59.57	UHPC splitting failure
	5	10.5	19.31	4	4	3	1.25	3	65.99	Yielding
	6	10.5	19.31	4	4	3	1.25	3	72.07	Yielding
	7	9.0	15.27	4	3	2	1.25	3	57.62	UHPC splitting failure
	8	9.0	15.27	4	3	2	1.25	3	149.22	Yielding

A.3 Bar Size

To test the effect of bar size, No. 4 and No. 7 Grade 60 reinforcing bars were tested. The No. 4 bars were embedded at either 3 in ($6d_b$) or 4 in ($8d_b$). The No. 7 bars were embedded at 3.5 in ($4d_b$) or 5.25 in ($6d_b$). The clear bar spacing for both bars was 2 in. For the side cover, the No. 4 bars had 1.5 in ($3d_b$) and the No. 7 bars had 2.625 in ($3d_b$). The results of these tests are provided in Table 19.

Table 19: Bar Size Pullout Test Matrix

Test ID		Flow (in)	f'c (ksi)	Bar Size	ld (in)	ls (in)	cso (in)	csi (in)	Max. Stress (ksi)	Failure Mechanism
Bar Size	1	9.5	17.71	4	4	3	1.5	2	80.10	Yielding
	2	9.5	17.71	4	4	3	1.5	2	82.40	Yielding
	3	9.5	17.71	4	3	2	1.5	2	74.55	Yielding
	4	9.5	17.71	4	3	2	1.5	2	81.22	Yielding
	5	9.0	15.27	7	4	3	2.625	2	12.17	Pre-cracked
	6	9.0	15.27	7	4	3	2.625	2	48.50	UHPC splitting failure
	7	9.0	15.27	7	5.25	4.25	2.625	2	66.63	Yielding
	8	9.0	15.27	7	5.25	4.25	2.625	2	20.65	Pre-cracked

A.4 Side Cover

To test the effect of side cover, No. 5 Grade 60 bars were embedded at 3.75 in ($6d_b$) and had a clear bar spacing of 2 in. The side cover of the No. 5 bars varied from 1.25 in ($2d_b$) to 3.125 in ($5d_b$). The side cover was measured from the outside of the bar to the edge of the UHPC curb. The results of these tests are provided in Table 20.

Table 20: Side Cover Pullout Test Matrix

Test ID		Flow (in)	f'c (ksi)	Bar Size	ld (in)	ls (in)	cso (in)	csi (in)	Max. Stress (ksi)	Failure Mechanism
Side Cover	1	9.5	16.09	5	3.75	2.75	1.25	2	44.34	UHPC tension failure
	2	9.5	16.09	5	3.75	2.75	1.25	2	48.13	UHPC tension failure
	3	9.5	16.09	5	3.75	2.75	1.25	2	53.56	UHPC tension failure
	4	9.5	16.09	5	3.75	2.75	1.25	2	49.08	UHPC tension failure
	5	9.5	16.09	5	3.75	2.75	1.875	2	68.73	Yielding
	6	9.5	16.09	5	3.75	2.75	1.875	2	51.78	UHPC tension failure
	7	9.5	16.09	5	3.75	2.75	1.875	2	56.72	UHPC tension failure
	8	9.5	16.09	5	3.75	2.75	1.875	2	45.20	UHPC tension failure
	9	9.5	17.71	5	3.75	2.75	2.5	2	60.66	Yielding
	10	9.5	17.71	5	3.75	2.75	2.5	2	79.81	Yielding
	11	9.5	17.71	5	3.75	2.75	2.5	2	N/A	Pre-cracked
	12	9.5	17.71	5	3.75	2.75	2.5	2	75.88	Yielding
	13	10.5	16.92	5	3.75	2.75	3.125	2	81.71	Yielding
	14	10.5	16.92	5	3.75	2.75	3.125	2	N/A	Pre-cracked
	15	10.5	16.92	5	3.75	2.75	3.125	2	N/A	Pre-cracked
	16	10.5	16.92	5	3.75	2.75	3.125	2	82.29	Yielding

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