Task 2 Report – Material Sensitivity

Project Title: Feasibility of Non-Proprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Phase II Field Application

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1 Introduction

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 (Berry, Snidarich, & Wood, 2017). 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 is being conducted at MSU that will build on the non-proprietary UHPC research already completed, and focus on ensuring the successful application of this material in these field-cast joints. Specifically, this research will investigate 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 will be investigated.

The specific tasks associated with this research are as follows.

Task 1 – Literature Review

Task 2 – Material Sensitivity

Task 3 – Field Batching/Mixing

Task 4 – Bond/Development Length Characterization

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 2 – Material Sensitivity. It should be noted, that this task will continue to be updated as new results becomes available.

2 Methods

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

2.1 Mixing Procedure

The small laboratory mixtures were produced in an industrial benchtop Hobart A200 mixer in 0.20-ft^3 batches (Figure 1). 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 2). 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 and Naaman (2011) and FHWA (2013).

- 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 5-6 minutes).
- Add steel fibers and mix for approximately 3 minutes after becoming fluid.

It should be noted, that mixing UHPC 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. This will be investigated further as this research progresses.

Figure 1: Hobart A200 Mixer

Figure 2: IMER Mortarman 360 mixer

2.2 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 (ASTM, 2017). 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 3.

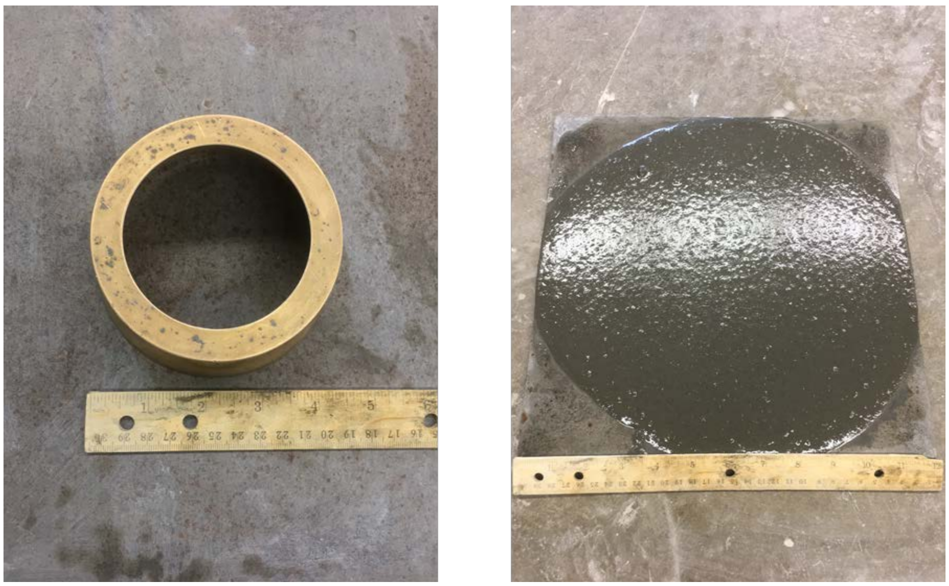


Figure 3: Spread Cone Mold & Measurement of Flows

2.3 Specimen Casting, Preparation, and Curing

For each batch, 3-by-6-in test cylinders were prepared in substantial accordance ASTM C1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete (ASTM, 2017). 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 4), and placed in a temperature-controlled cure room at 100% humidity until the respective test date.

Figure 4: Cylinder end grinder and prepared specimen

2.4 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.

Figure 5: Compression cylinder in load frame

2.5 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 (ASTM, 2018). A typical flexural specimen in the load frame is shown in Figure 6. 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 6: Flexural test specimen in load frame

2.6 Set Time Estimation

The set times of the UHPC were determined in substantial accordance to ASTM C403 -- Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance (ASTM, 2016). Set time was determined by applying the penetrometer needle at a constant pressure on the specimen surface over the course of 10 seconds until the circumscribed marker reached the specimen surface. The penetration resistance was determined via reading the pressure in pounds per second from the base of the friction ring. The accompanying time elapsed since water addition was recorded in conjunction with each penetration resistance measurement. A minimum of two penetrometer readings were taken per time interval, and penetration measurements were averaged. Penetration measurements were taken approximately every 30 minutes until the capacity of the pocket penetrometer was reached. At least four penetration measurements were taken per specimen. Penetration resistance was plotted with accompanying elapsed time. Data points were used to fit a logarithmic regression curve to measured data in order to estimate initial and final set times.

3 Materials

This section discusses the materials used in this research.

3.1 Portland Cement

Two 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 (Berry et al., 2017). 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	-

3.2 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

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

3.3 Fly Ash

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 of the 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

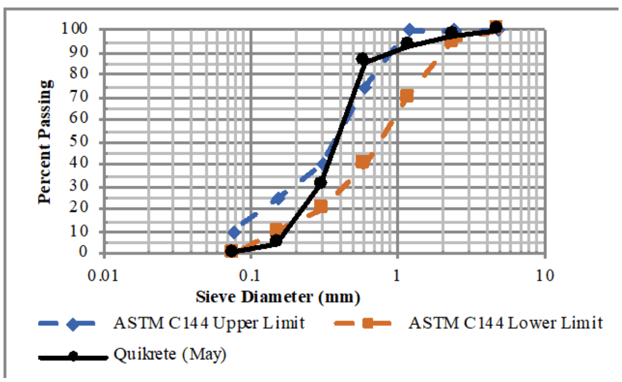
3.4 Aggregates

During the initial phase of research (Berry et al., 2017), 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.

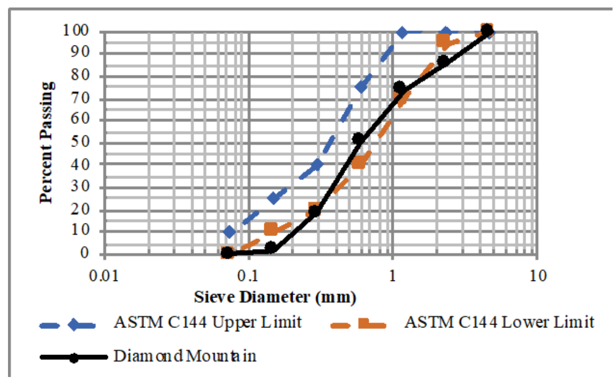
A variety of local fine aggregate sources were identified using the MDT Gravel Pit Index and obtained for use in this study. Specifically, five mason sands, four concrete sands, and two silica sands were examined during the aggregate variability study. The aggregate sources, locations, and key physical properties are provided in Table 4, while the gradation curves for each aggregate are provided in Figure 7 and Figure 8. 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

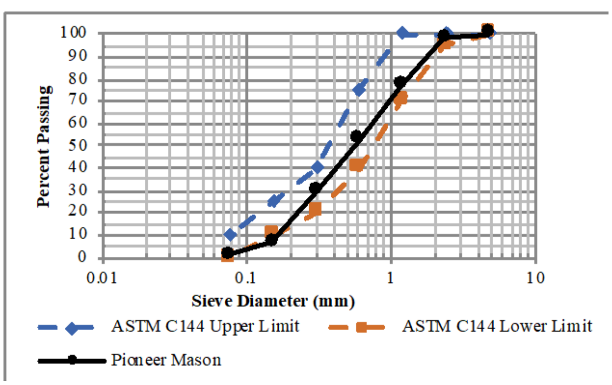
Fine Aggregate Source	Supplier	Location	FM	Absorption	OD S.G.	SSD S.G.
QUIKRETE	QUIKRETE	Billings, MT	3.32	1.87%	2.56	2.60
Diamond Mountain-Masonry	BBB&T	Frenchtown, MT	4.68	3.99%	2.45	2.60
Pioneer-Masonry	Pioneer Concrete & Fuel	Butte, MT	4.35	1.90%	2.55	2.60
S&N-Masonry	S&N Concrete & Materials	Anaconda, MT	4.50	2.46%	2.50	2.56
Helena-Masonry	Helena Sand & Gravel	Helena, MT	4.12	2.24%	2.48	2.54
Capital-Masonry	Capital Concrete	East Helena, MT	4.22	2.41%	2.54	2.60
BBB&T-Concrete	BBB&T	Bozeman, MT	4.75	1.97%	2.61	2.66
Pioneer-Concrete	Pioneer Concrete & Fuel	Butte, MT	4.75	2.09%	2.50	2.55
S&N-Concrete	S&N Concrete & Materials	Anaconda, MT	5.07	2.68%	2.48	2.55
Helena-Concrete	Helena Sand & Gravel	Helena, MT	5.30	1.67%	2.49	2.54



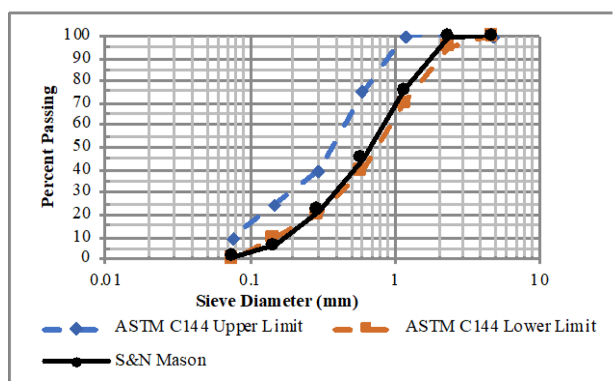
(a) QUIKRETE-Masonry



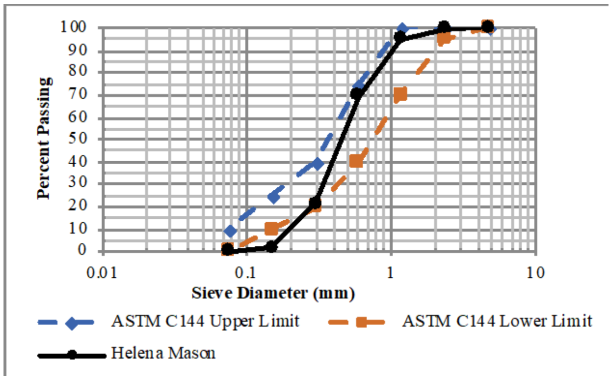
(b) Diamond Mountain-Masonry



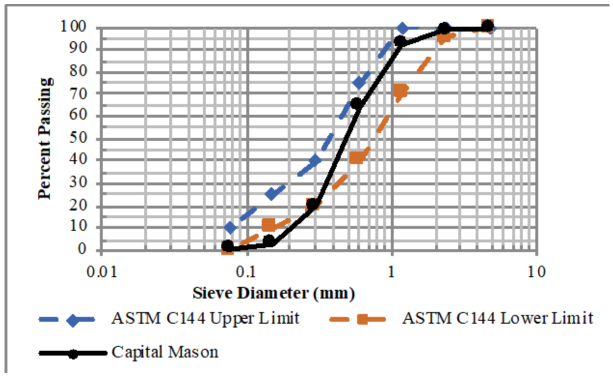
(c) Pioneer-Masonry



(d) S&N-Masonry

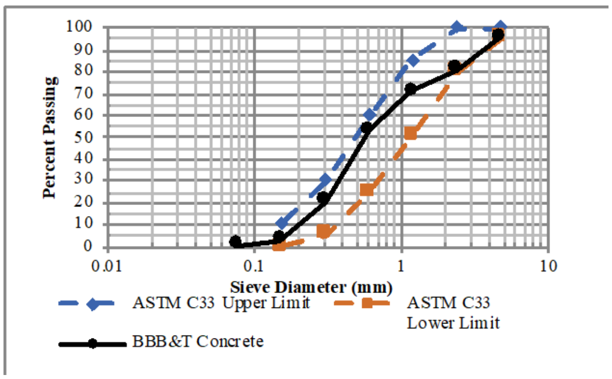


(e) Helena-Masonry

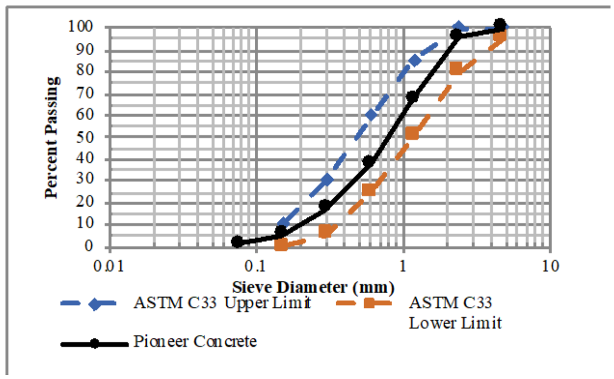


(f) Capital-Masonry

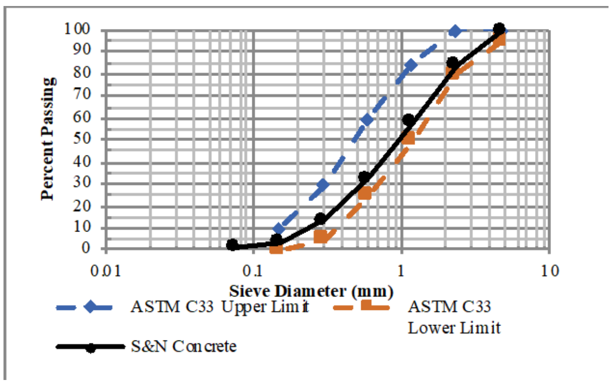
Figure 7: Particle Size Distribution of Mason Sands



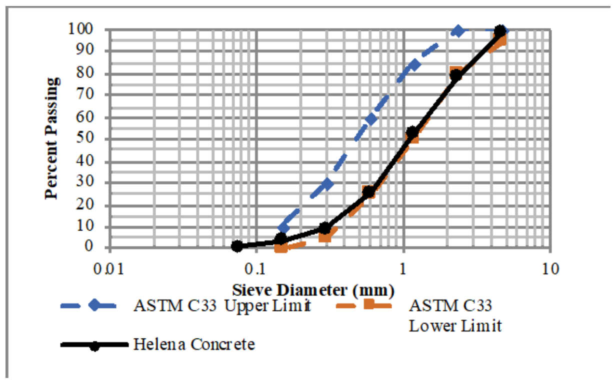
(a) BBB&T-Concrete



(b) Pioneer-Concrete



(c) S&N-Concrete



(d) Helena-Concrete

Figure 8: Particle Size Distribution of Concrete Sands

3.5 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.

3.6 Steel Fibers

The steel fibers used in the original mix development effort were 0.2 mm diameter by 13 mm in length, and were supplied by Nycon (Nycon-SF Type I "Needles"). However, the steel used in these fibers is not produced domestically, and therefore they are not permitted on federally-funded projects. The research discussed herein investigated using a domestically-produced fiber; specifically, the Bekaert Dramix OL 13/0.20. Properties of the two fibers are provided in Table 5. It should be noted that the Dramix OL 13/0.20 fibers have been proven to be a very effective fiber for use in UHPC, and are used extensively in UHPC applications nationally as they are the only domestically-produced drawn fiber of these dimensions and strength that are currently available on the market. However, at the time of writing, Bekaert has discontinued the domestic production of these fibers.

Table 5: Properties of Steel Fibers

Properties	Nycon-SF Type I	Bekaert Dramix OL 13/0.20
Length (mm)	13	13.0
Diameter (mm)	0.2	0.2
Aspect Ratio	65	65.0
Tensile Strength (ksi)	285	399.0
Elastic Modulus (ksi)	29000	29000
Coating	Copper	Copper

4 Sensitivity of UHPC to Material Variability

4.1 Base Mix Design and Proportions

The mix design recommended from the Phase I research effort (Berry et al., 2017) 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 base mix 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 Conent
0.25	0.05	1.40	0.75	0.50	0.02	0.62

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 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.

4.2 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

4.3 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 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

Fly Ash Source	Flow (in.)	Compressive strength, f'c (ksi)	
		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

4.4 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.

4.4.1 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 9. 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 concretes 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 10) and fineness modulus (Figure 11) 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 10, 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 regards 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	**Abreviation**	**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

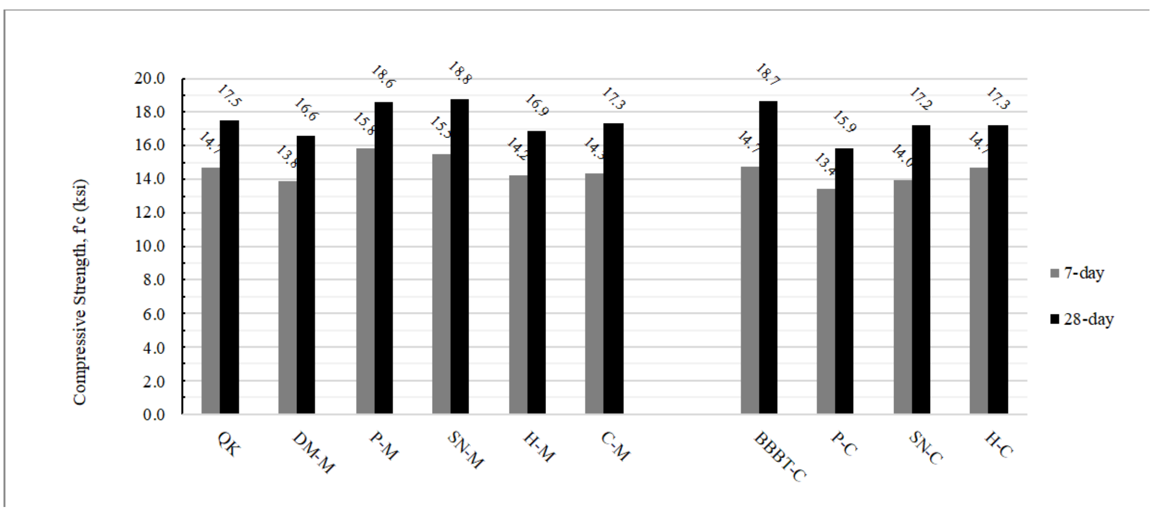


Figure 9: Compressive Strengths for Various Fine Aggregate Sources

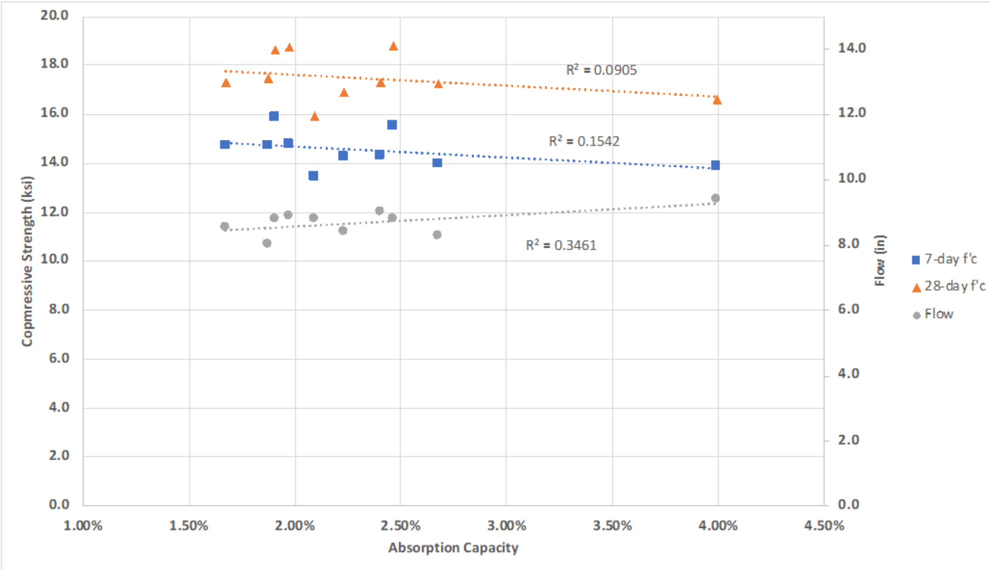


Figure 10: UHPC Properties vs Absorption Capacity

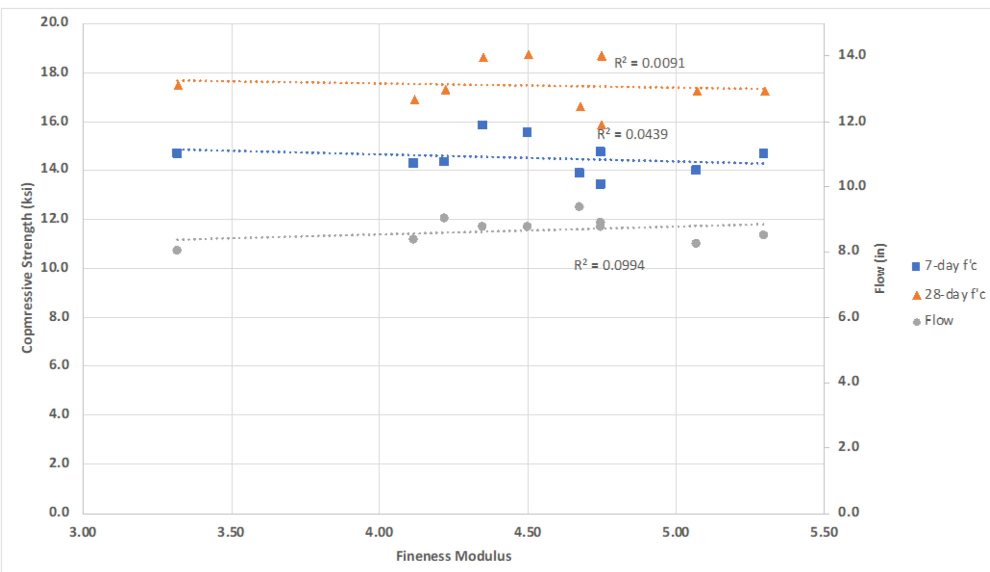


Figure 11: UHPC Properties vs Fineness Modulus

4.4.2 Moisture Content

To evaluate the effects of varying moisture content, UHPC mixes were prepared with the QUIKRETE masonry sand with varying levels of moisture: oven dried, 50% of SSD, 100% of SSD, and 150% of SSD. At this point, the UHPC mixes were not modified to account for the varying levels of moisture – no moisture content corrections were applied. The resulting flows and compressive strengths are provided in Table 11, while the flows and compressive strengths are plotted vs percentage of SSD in Figure 12 and Figure 13, respectively. Included in these figures are the least-squared best fit lines, and respective R^2 values. As can be observed in the table and figures, as expected the flow generally increased with increasing moisture content (R^2 = 80%), while the 7- and 28-day compressive strengths decreased (R^2 = 91% and 96%, respectively).

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 Figure 12 and Figure 13. 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 not observed in this study. This indicates that moisture content correcting aggregates might not be effective in UHPC mixes. It should be noted that this study is currently being reproduced with another aggregate source to validate these results.

Table 11: Flow and Compressive Strengths for Various Moisture Contents

			Compressive strength, f'c (ksi)	
Moisture Target	**Moisture Content**	**Flow (in.)**	**7-day**	**28-day**
Oven Dried	0%	9.50	15.8	18.5
50% of SSD	0.80%	9.50	15.2	18.3
100% of SSD	1.59%	10.25	14.1	17.5
150% of SSD	2.39%	10.25	14.0	17.0
50% of SSD- Corrected	0.80%	10.0	15.8	18.1
100% of SSD- Corrected	1.59%	10.0	15.1	17.6
150% of SSD- Corrected	2.39%	10.3	15.3	16.4

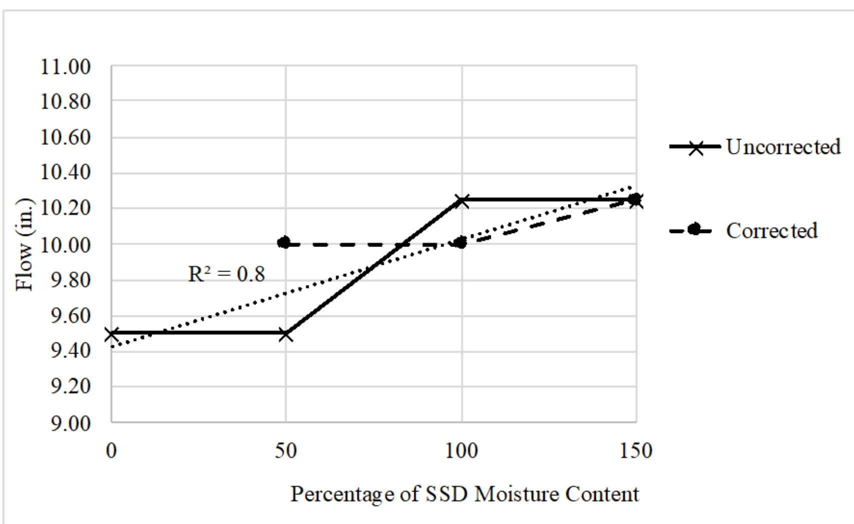


Figure 12: Effect of Moisture Content Correction on Flow

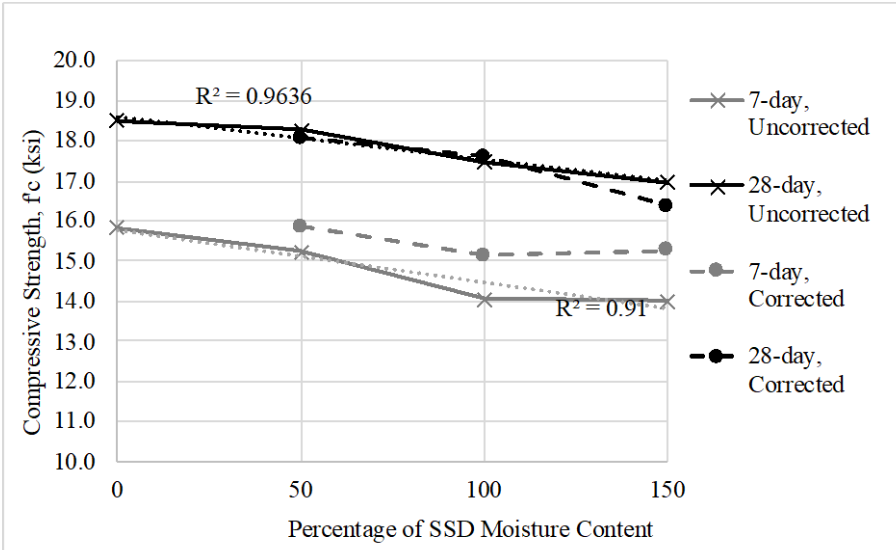


Figure 13: Effect of Moisture Content Correction on Compressive Strength

4.5 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. Tests are currently underway to evaluate the effect of the steel fibers on tensile strength, and these results will be included in the final report. 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)	
Cement Source	**Flow (in.)**	**7-day**	**28-day**
NYCON	8.5	14.7	17.5
Bekaert	10.0	13.9	17.3

5 Summary

Thus far, 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.

As indicated in earlier sections, several of these findings are currently being investigated further and findings will be updated in the final report. Currently, work is being done on Task 3, which is focused on further evaluating the behavior of UHPC mixes, and their sensitivity to mixing and batching procedures. Specifically, this work is focused on investigating: (1) the variability in strength within a batch, (2) set time and strength gain characteristics, (3) the effect of mixing time, (4) the effect of batch size, and (5) the effect temperature. Also, work is underway on designing and constructing specimens for the Task 4 bond strength study.

6 References

ASTM. (2016). *ASTM C403: Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. Retrieved from

ASTM. (2017). *ASTM C1856: Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete*. Retrieved from

ASTM. (2018). *ASTM C78: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. Retrieved from

Berry, M., Snidarich, R., & Wood, C. (2017). *Development of Non-Proprietary Ultra-High Performance Concrete* (FHWA/MT-17-010/8237-001). Retrieved from https://westerntransportationinstitute.org/wp-content/uploads/2017/12/4W5387_Concrete_FINAL_REPORT.pdf

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

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. Retrieved from <Go to ISI>://WOS:000286995400006