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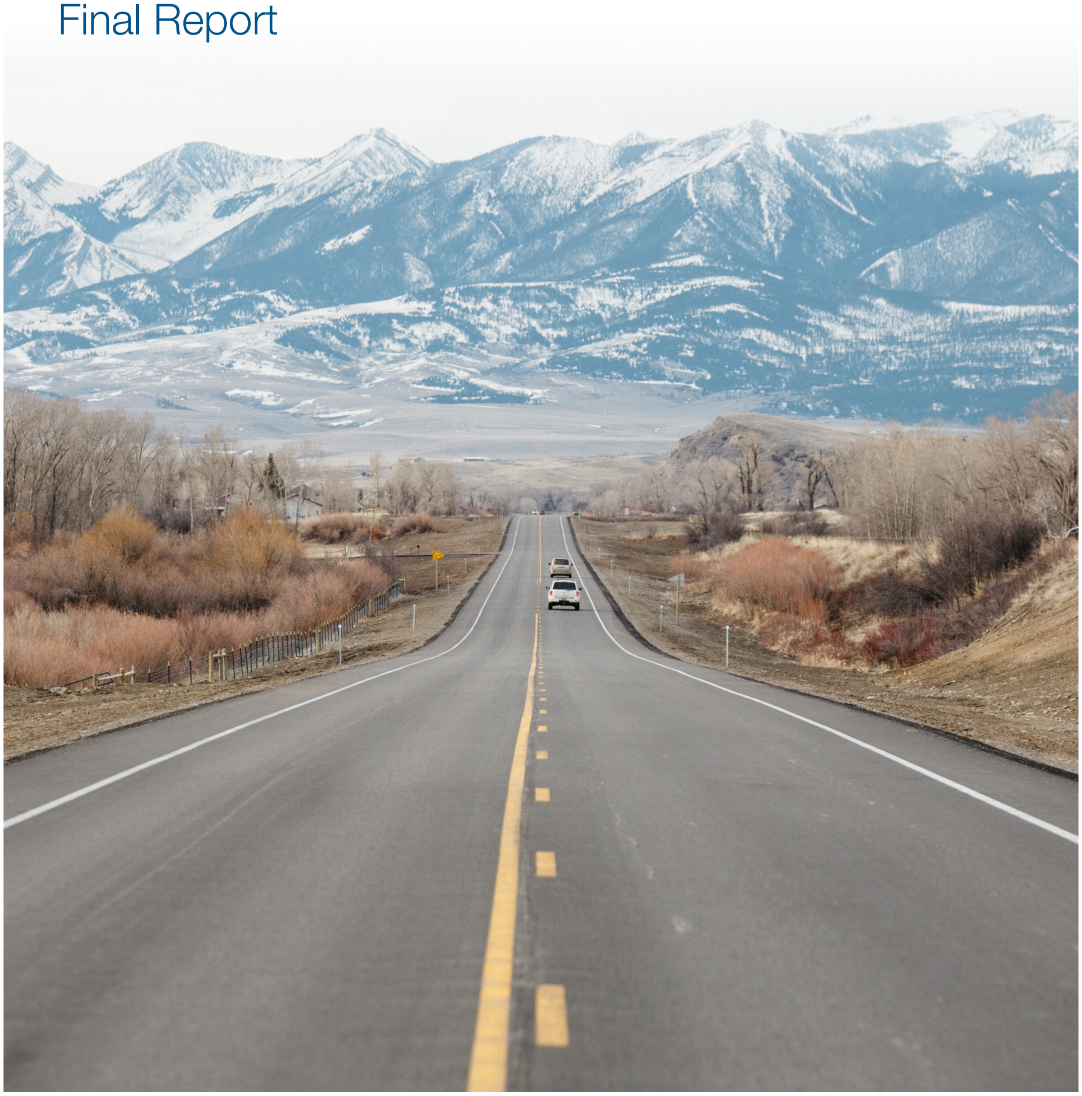
Research

FEASIBILITY OF NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) FOR USE IN HIGHWAY BRIDGES IN MONTANA: IMPLEMENTATION

FHWA/MT-23-002/9925-818

Final Report



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FEASIBILITY OF NON-PROPRIETARY ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) FOR USE IN HIGHWAY BRIDGES IN MONTANA: PHASE III IMPLEMENTATION

Final Report

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16. Abstract

Previous research conducted at MSU developed a nonproprietary UHPC mix design (MT-UHPC) that is significantly less expensive than commercially available mixes and is made with materials readily available in Montana. The focus of the research discussed herein was on the field implementation of MT-UHPC. Specifically, MT-UHPC was used in all field-cast joints on two bridges spanning Trail Creek on Highway 43 outside of Wisdom, MT. This project began with an extensive literature review focused on previous field applications of UHPC. Subsequently, implementation research was performed with the intent of filling several research gaps related to the field application of MT-UHPC. This research investigated the effects that mixing process, batch size, and temperature have on the performance of MT-UHPC. It also developed maturity curves to be used in estimating the early strength gain of MT-UHPC. Trial batches were then conducted on site and placed into joint mockups to confirm and improve the construction methods to be used on the actual bridge project. In this exercise MT-UHPC was mixed using the same methods and under the same environmental conditions expected on the day of construction. MT-UHPC was then used in the Trail Creek bridges to connect the precast concrete bridge elements.

Overall, this project was a successful demonstration of using a nonproprietary UHPC in field-cast joints for an accelerated bridge construction (ABC) project. All placed UHPC had adequate flows, gained strength quickly, and reached the required minimum compressive strengths. This was accomplished despite an accelerated construction schedule, and despite mixing and placing the material in the field under varied environmental conditions.

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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 MSU [1, 2] included (1) the development of nonproprietary UHPC mixes that are significantly less expensive than commercially available mixes and are made with materials readily available in Montana, (2) an investigation into several items related to the field batching of these mixes, (3) an exploration into the potential variability in performance related to differences in constituent materials, and (4) the investigation of rebar bond strength and the subsequent effect this has on development length. This previous research was successful and clearly demonstrated the feasibility of using MT-UHPC in Montana bridge projects.

The focus of this project was on the field implementation of MT-UHPC. Specifically, MT-UHPC was used in all field-cast joints on two ABC bridges spanning Trail Creek on Highway 43 near Lost-Trail Pass outside of Wisdom, MT.

1.2 Objective and Scope

The primary objective of this project was to successfully implement nonproprietary MT-UHPC in the field-cast joints of the replacement Trail Creek bridges. This report documents the tasks conducted to realize this objective.

- A comprehensive literature review was conducted to evaluate the state-of-the-practice and recent advances in UHPC. In particular, this review focused on the implementation of UHPC in actual bridge applications. It was aimed at learning from the mistakes made in prior UHPC applications and utilizing techniques found to be successful.
- Constituent material sources were selected by the contractor and approved by MSU for use in the MT-UHPC. The properties of the materials were documented and compared to materials previously used by MSU.
- Implementation-related research was conducted to ensure the successful field application of MT-UHPC. Specifically, mixing methods and temperature effects were investigated, and a maturity curve was developed to predict early strength gain in the field.
- Trial batches of MT-UHPC were performed and placed in mockup bridge joints. This was done on site using the same methods and under the same environmental conditions expected on the day of construction.
- Montana UHPC was successfully implemented in the replacement of the Trail Creek bridges. It was used for all field-cast connections, including the pile to pile cap connections, the connections between the beams and caps, the wing walls, and the longitudinal shear-keys between adjacent beams.

2 LITERATURE REVIEW

The literature review in this research is focused on topics specifically related to field implementation of UHPC. An extensive literature review focused on UHPC in general and the development of nonproprietary UHPC mixes was conducted during the first two phases of research [1, 2].

2.1 FHWA Report on the Design and Construction of Field-Cast UHPC Connections

In 2014 the FHWA published a report with guidance on the design and field implementation of UHPC connections [3]. This report highlights techniques and considerations learned from previous research and previous applications of UHPC in the field. The following subsections highlight some of the key takeaways from this report.

2.1.1 Surface Preparation for Bond Between UHPC and Precast Concrete

Surface preparation of precast components is critical to ensure durability and long-term performance. UHPC can bond exceptionally well to conventional concrete if the surface is prepared properly. Lack of bond can affect the structural integrity of the connection and can allow water infiltration that may accelerate rebar deterioration. Successful bonding has been demonstrated between precast conventional concrete and UHPC if the surface of the precast element is roughened as shown in Figure 1. This can be created by applying a gelatinous retarder to the formwork. Additionally, it was found that pre-wetting the interface to an SSD condition improves bonding. This can be achieved by spraying the bonding surface with water while preventing too much water pooling in the forms. Additionally, wetting the surface will limit dehydrating effects between a dry surface and the freshly placed UHPC.

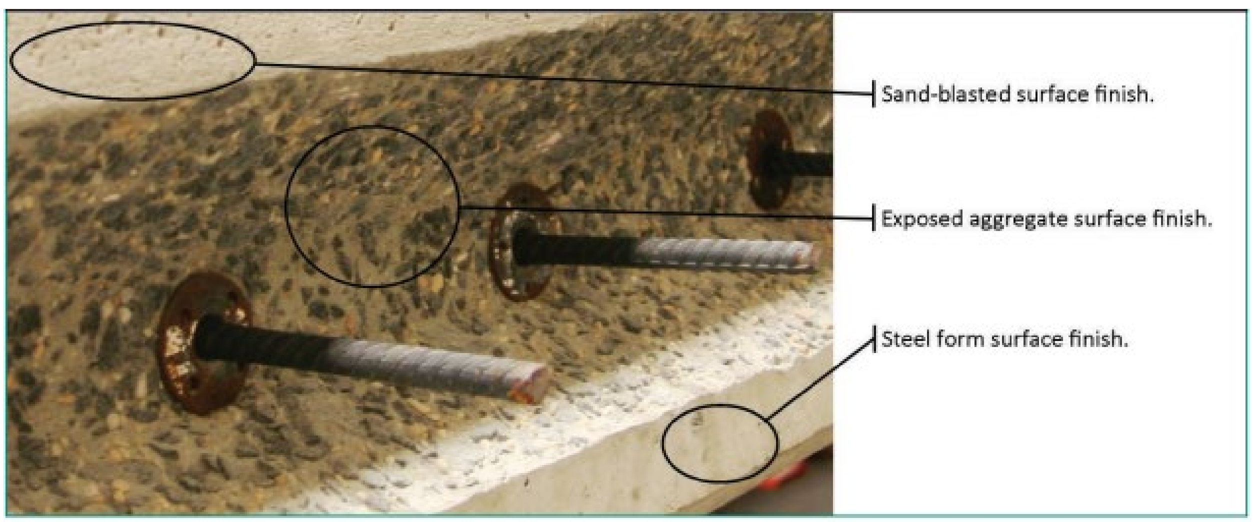

Figure 1: Exposed aggregate surface finish on a precast concrete component [3]

2.1.2 Formwork for UHPC Elements/Connections

UHPC is typically self-consolidating and more fluid than conventional concrete; therefore, the use of UHPC results in higher form pressure, which needs to be accounted for during formwork design. Additionally, the formwork needs to be fully sealed to ensure UHPC does not leak from the forms. To ensure a proper seal, contractors have checked seals with water prior to UHPC placement. A pathway for air must also be provided during placement to avoid entrapping air within the formwork. Similar to grout, UHPC should be placed starting at the low end of the pour and working towards the high end. Additionally, if the bridge has a slope, the formwork should be capped to prevent material from flowing over the joint at the low end, and intermittent holes should be included as a pathway for entrapped air to escape. Further, UHPC should be cast higher than the surface of the field-cast joint so that it can be ground to remove the air bubbles near the surface of the UHPC.

2.1.3 UHPC Mixing Considerations

UHPC is sensitive to mixing conditions including temperature and the mixing process/procedure. Mixing UHPC involves an exothermic reaction, which can cause water loss due to evaporation, especially if mixing takes place at elevated temperatures. Therefore, it is best to mix UHPC at cooler temperatures, somewhere between 50-60˚F, and out of direct sunlight and protected from wind. It has been found that fluidity is significantly reduced if the mix reaches a temperature of 80˚F, so mix temperature should be monitored. To reduce temperature effects, replacing water with cubed ice has been found to be effective.

The UHPC mixing process can strain the mixer being used. Specifically, after the mix water is added, the mix tends to stiffen up significantly prior to turning over, which can cause the mixer to bog down. Therefore, mixing UHPC requires high-capacity high-shear mixers that can handle the increased demands of mixing UHPC, or smaller batches must be used. As a target, the quantity of UHPC that can be mixed is approximately half the volume that could be mixed with conventional concrete or grout. It is recommended that contractors perform trial mixes prior to the project to ensure proper batch sizes and mixing procedures.

2.1.4 Placing and Finishing UHPC

Traditionally, wheelbarrows or the like are used to transport the UHPC from mixer to the field joint (Figure 2). It is possible to pump or chute UHPC; however, these methods should be carefully coordinated in advance to ensure feasibility of transporting material to the connections. Traditional concrete finishing practices are not applicable to field-cast UHPC. Bleed water is virtually eliminated by the low water-to-cement ratio. Typically, the UHPC is placed in a closed form with the top form in contact with the material to minimize surface dehydration. If the surface will be visible to the public, the connection is frequently overfilled and ground to match the adjacent surfaces. Contractors have reported that grinding is easier if completed before the material reaches full strength. It is important that the UHPC doesn’t freeze before reaching a compressive strength of 10 ksi. Although cooler temperatures are ideal for mixing and placing, warmer temperatures increase the rate of strength gain. Supplemental heat sources can be used externally with ground heating mats or internally with resistance heating wires. However, heat sources that force heated air on the material should not be used on surfaces of freshly placed UHPC. Formwork is then finally stripped after a compressive strength of 14 ksi. This is also when traffic and live loads are allowed on the structure.

Figure 2: Longitudinal connections placed using a wheelbarrow [3]

2.2 Commercial Production of Nonproprietary Ultra-High Performance Concrete (Michigan)

Previous research at the University of Michigan focused on the development and characterization of nonproprietary UHPC mixes [4]. This research resulted in a viable nonproprietary UHPC mix; however, the use of this material in an actual field application was not successful. A follow-on study was performed to investigate why this recently developed mix did not successfully scale up to field implementation [5]. Based on the findings of this investigation, the mixing process was then adjusted accordingly and the UHPC mix was successfully used in a bridge application project [5]. This section summarizes the key findings from this investigation.

2.2.1 Reasons for Failed Field Implementation

The nonproprietary mix developed at the University of Michigan [4] performed exceptionally well in the laboratory, but it could not be successfully mixed during several field trials. Several factors contributed to this. It was determined that the silica fume used in the field had a high carbon content that drove up water demand, and the dosage rate of high range water reducer (HRWR) was too low to compensate for this higher water demand. Also, the silica fume used in the field trial was densified, which posed a challenge for the mixer to disperse during dry mixing. Finally, the field mixer did not have the capacity to induce turnover in the wet mix. Essentially, it was found that a proper dose of HRWR is key in successfully mixing UHPC.

2.2.2 Mixing Protocol:

Field mixing, in contrast to laboratory mixing, has some limitations. Large capacity mixers generally have lower mixing speeds than smaller lab mixers, which can lead to the formation of silica sand clumps that hinder mixing action. Further, as stated previously, mixing large UHPC batches can strain the mixer, and therefore mixes should be limited in size and be appropriate for the size of mixer being used. A procedure was developed to minimize these effects. Specifically, they found it beneficial to withhold half of the sand until after the mix water had been added and the mix had turned over.

2.2.3 Successful Field Implementation

UHPC was implemented on a bridge repair on the Pine River in Kenockee Townhill, MI. This repair entailed using UHPC to replace the joints connecting the reinforced concrete slabs. Mixing was achieved using two Mortarman 360 MBP pan mixers with capacity of 8 cu ft. However, each mix was limited to 5.5 cu ft. Once the mix turned over, the material was discharged into wheelbarrows to be transported to the pour location.

The mixing process took place on a hot day with forecast ranging from 73˚F to 89˚F. The first batch was mixed at an ambient temperature of 75˚F. The maximum mix temperature was 80˚F and the spread was 9.4 in. However, the second batch was mixed at 77˚F ambient temperature, and the mix temperature rose to 95˚F, resulting in a 7.4 in spread. To address this issue, cubed ice was added as a replacement for 40% of the water to keep the mix temperature below 85˚F. Mixes that rose above this temperature seemed to result in significant drop in spread.

The UHPC was cast at a rate slow enough to minimize flow lengths and the resultant preferential alignment of steel fibers. Specifically, the UHPC was placed at a speed comparable to the flow speed of the fresh mix. Additionally, the forms and surface of concrete and rebar were pre-wetted to prevent the mix from losing water to dry surfaces. Once casting was finalized, top forms were added to reduce surface dehydration.

(a) Pre-wetting surfaces and placement of UHPC (b) Top forming after placement

Figure 3: Longitudinal joints during and after UHPC placement [5]

The formwork was stripped after one day and the top surface was observed to have small holes and shrinkage cracks. However, the underlying material was examined and was found to be in good shape. No grinding or overpouring was performed in this application.

2.3 First Application of UHPC Bridge Deck Overlay in North America

Researchers at Iowa State University evaluated the use of ultra-high-performance concrete (UHPC) as a bridge deck overlay [6]. This was the first time this was attempted in North America. The research was first focused on developing and characterizing a thixotropic UHPC mix design. Typical UHPC mixes have high flows and are not suitable for applications on slopes, and therefore a thixotropic mix is required for the proposed application. A UHPC mix suitable for applications on slopes of up to 7% was developed in cooperation with LafargeHolcim. The feasibility of this mix was then tested in the structural engineering laboratory at Iowa State University by placing the overlay mix on inclined slabs with varied surface preparations. The results from the laboratory investigation demonstrated the feasibility of its use in this application and were used to determine proper surface roughness and overlay thickness.

After the initial phases of this research, the thixotropic UHPC mix design was used as an overlay on the Mud Creek Bridge on Buchanan County Road D48 near Brandon, Iowa. This bridge is 102 ft long and 30 ft wide, and is a continuous concrete slab bridge with two lanes. For this project, the top 0.25 in of the deck surface was first removed, and the deck was then grooved along the bridge length with an amplitude of roughness ranging from 1/12 in to 1/8 in. All batching and placing of the UHPC was performed on site by the contractor. A pair of high-shear pan mixers were used to mix the concrete. Each mixer had the capacity to mix 0.65 yd^3 (17.55 ft^3) of material. Loading and batching of the UHPC took approximately 20 minutes per batch. An overlay thickness of 1.5 in was compacted and maintained by using a vibratory truss screed. All the mixing was done at one end of the bridge and transported using a mini concrete dumper. Grinding and grooving of the UHPC deck surface took place 4 days after placement (Figure 4), at which point the compressive strength had reached 12.3 ksi. Finally, the deck was evaluated using pull-off tests to quantify the bond strength between the UHPC and the substrate material.

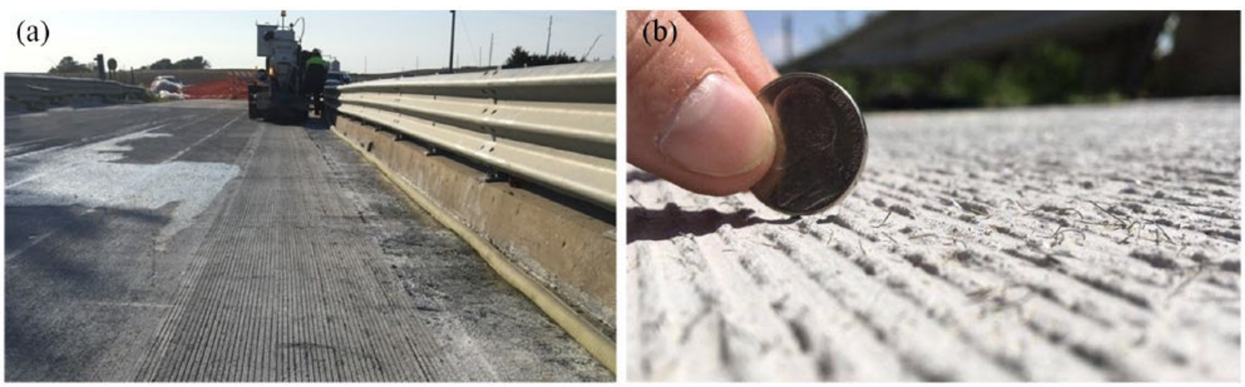

Figure 4: UHPC overlay on Mud Creek Bridge deck: (a) grooving of the surface; (b) closeup of finished surface [6]

This project was deemed successful, and the experience revealed areas for improvement on future UHPC projects. Batching the material with two mixers was satisfactory, but a sufficiently large, trained crew is also necessary. The consistency of the thixotropic UHPC mix was such that placing was difficult using racks and shovels. The crew needed for placing and screeding the overlay was about twice that required for a normal overlay. It was also found that lightly misting the UHPC in front of the vibrating screed helped consolidation and sticking issues. Additionally, the use of a curing compound was recommended to keep the moisture within the UHPC layer immediately after consolidation. It was determined that for this project, the total cost of the UHPC overlay was approximately \$45/ft^2, including batching, placing, and grinding of the deck surface.

2.4 Utilization of Ultra-High Performance Concrete (UHPC) in New York

The New York State Department of Transportation's (NYSPDOT) has used UHPC in 30 construction projects involving prefabricated bridge elements with field-cast UHPC joints [7]. An example of one such project is shown in Figure 5. This section briefly reviews some of the key findings from this experience.

- First, overall, they found precast construction with UHPC joints to be an economical solution when accelerated construction is needed.
- The nonproprietary performance-based UHPC specification has performed well for NYSDOT.
- In terms of construction, in order to improve bonding of UHPC they recommend providing an exposed aggregate finish on the mating surface of the precast component.
- Additionally, they determined that it is critical to prewet the precast surfaces before filling the joints.
- They recommend overfilling the joints by at least ¼ in to deal with consolidation settlement of the UHPC.
- All formwork should be leak proof to ensure that the highly flowable UHPC does not leak out of the forms.
- The use of maturity meters is recommended to determine strength when accelerated curing is required.
- It was found that the contractor often didn't provide sufficient labor for the project, which led to some inefficiency. With more experience, DOT staff was able to guide contractors in later projects with compressed schedules to provide sufficient labor.
- Sufficiently large UHPC mixers are recommended to speed construction.
- Overall, all bridges using precast elements with UHPC joints are performing well.

Figure 5: Example precast UHPC project in progress

3 MATERIALS

This chapter discusses the materials that were used by the contractor for the UHPC implemented in the Trail Creek bridges. The materials used were the same general materials recommended by previous MSU research, but the source of some of these materials differed from what was used previously. Specifically, this research used Portland cement, fly ash, silica fume, fine aggregate, HRWR and steel fibers. The source and material properties for each constituent material are reported in the following sections.

In summary, the cement was a Type I/II/V from the GCC cement plant in Trident, MT. The fly ash was a Class F ash sourced from Prairie State Energy Campus in Marissa, IL. The fine aggregate was a masonry sand processed and packaged by QUIKRETE near Billings, MT. The silica fume was MasterLife SF 100 from BASF. The high range water reducer (HRWR) was CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. The steel fibers were sourced by Hiper Fiber and were 13 mm long, had a diameter of 0.2 mm and a tensile strength of 285 ksi. The mix proportions for a 1 yd^3 batch of these materials are shown below in Table 1.

Table 1: Mix proportions for 1 yd^3

Item	Weight (lbs)
Water	298.7
Portland Cement	1299.5
Fly Ash	371.3
Silica Fume	278.4
HRWR	64.4
Steel Fibers	262.9
Fine Aggregate	1556.4

3.1 Portland Cement

The cement utilized by the contractor was sourced from Trident. The Trident cement was a Type I/II/V cement from the GCC cement plant in Trident, MT, and was used in original mix development. Chemical and physical properties of the cement are included in Table 2, along with the applicable C150 limits.

Table 2: Cement chemical properties

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

3.2 Fly Ash

Prairie State fly ash was chosen by the contractor after some difficulty in finding a fly ash supplier. The chemical and physical properties of the fly ash are provided in Table 3, along with the ASTM C618 limits.

Table 3: Chemical and physical properties of fly ash

Chemical Properties	**C168 Limit**	**Prairie State**
SiO_2 (%)	NA	54.3
Al_2O_3 (%)	NA	17.57
Fe_2O_3 (%)	NA	11.34
Sum of Constituents	50.0 min	83.21
SO_3 (%)	5.0 max	1.15
CaO (%)	18.0 max/>18.0	8.00
MgO (%)		1.45
Na_2O (%)		1.24
K_2O (%)		2.57
Moisture (%)	3.0 max	0.03
Loss on Ignition (%)	6.0 max	1.10
Available Alkalis, as Na_2O (%)	Not Required	0.79
Physical Properties		
Fineness (% retained on #325)	34% max	25.13
Fineness Uniformity	±5 max	1.59
Strength Activity Index		
7 day, % of control	75% min	81.0
28 days, % of control	75% min	87.0
Water Requirement (% control)	105 % max	96.0
Autoclave Soundness (%)	0.8% max	-0.01
True Particle Density (g/cm^3)	NA	2.36
Density Uniformity (%)	±5 max	1.35

3.3 Silica Fume

The silica fume used by the contractor in field implementation 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 4.

Table 4: 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

3.4 Fine Aggregate

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. The aggregate source, location and key physical properties are provided in Table 5. Included in the gradation curve are the upper and lower ASTM limits for the aggregate.

Table 5: Fine aggregate source 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

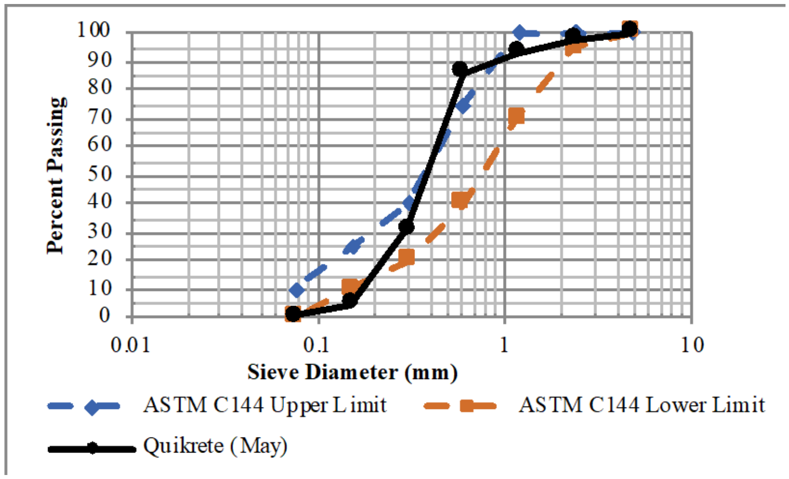

Figure 6: Particle size distribution of concrete sands

3.5 High Range Water Reducer (HRWR)

This application 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 shown to provide the best workability and least amount of entrapped air.

3.6 Steel Fibers

The contractor chose Hiper Fiber as the supplier for the steel fibers, which are domestically produced and comply with Buy America requirements. The physical properties of the fibers used are shown in Table 6.

Table 6: Steel fiber properties

Properties	Hiper Fiber
Length (mm)	13
Diameter (mm)	0.2
Aspect Ratio	65
Tensile Strength (ksi)	285
Elastic Modulus (ksi)	29000
Coating	Copper

4 IMPLEMENTATION RESEARCH

This chapter discusses the findings of preliminary mixes that were aimed at ensuring the successful field implementation of MT-UHPC. Specifically, this task investigated the effects of varying the mixing process, batch size, and mixing and curing temperatures. It also included the development of a maturity curve to be used in determining the strength of the UHPC in the field.

Table 7 provides a brief summary of the mixes conducted as part of this task. It should be noted that the recorded strengths were obtained from the average of three 3-by-6 in cylinders tested in accordance to the methods discussed in [2]. Each of these mixes will be discussed in greater detail in the following sections.

Table 7: Summary of MT-UHPC mixes

Mix Number	Description	Batch Size (cuft)	Ambient Temp (˚F)	Cure Temp (˚F)	24-hr Strength (ksi)	28-day Strength (ksi)
1	Baseline mix using materials sourced from the contractor	2.5	48	70	6.9	18.4
2	First of two consecutively mixed batches	2.5	67	70	6.8	16.4
3	Second of two consecutively mixed batches	2.5	67	70	7.3	17.8
4	First 4.5-ft^3 batch	4.5	57	70	7.7	17.1
5	Mix that investigated a new mixing method of adding 2/3rd of dry material with water, then adding the remaining dry material after turnover	4.5	61	70	9.53	17.4
6	A failed 4.5-ft^3 mix that stiffened up in the mixer	4.5	63	70	6.5	13.7
7	Mix that investigated the effects of curing cylinders under varying temperatures	3	67	70	7.3	17.2
				Varying (56-93)	8.7	---
8	Mix investigating replacing 40% of the mix water with ice to combat temperature effects	3	86	70	7.9	20.1
9	Mix investigating temperature effects by curing cylinders in hot, cold and room temperature conditions for varying amounts of time.	3	45	34	0.4	12.4
				70	5.9	17.8
				100	11.8	18.6

4.1 Mixing Methods

The effects that several mixing and batching procedures have on the performance of the MT-UHPC were investigated in this research. Each bridge will require approximately 5 yds^3 of UHPC, which will amount to approximately 30-45 batches per bridge (depending on batch size) using the mixers available for this work (Imer-Mortarman 360s). Obviously, batching and mixing this quantity of mixes will be time consuming, and any effort to reduce this time should be investigated. This research specifically investigated the effects of conducting consecutive batches without washing out the mixers, and the effects of varying the batch size. The results of these trial batches are summarized below.

4.1.1 Consecutive Batches

All previous research on the MT-UHPC was conducted on single batches of UHPC with a clean mixer. This research investigated the effects of conducting consecutive mixes, without cleaning the mixer between batches. In this investigation, two mixes were performed in succession, and turnover time, flow, and strength gain were recorded. The first mix (initiated in a clean mixer) turned over at approximately 3 minutes and had a flow if 11.25 in. The second mix (initiated in a mixer with residual UHPC from the previous mix), had a turnover time of approximately 7 minutes and a flow of 11 in. While there is some variation in turnover time, this variation is in the range of what was observed throughout this research. The recorded strengths from each mix are provided in Figure 7. These results indicate that conducting consecutive mixes has a very minor effect on the performance of the MT-UHPC, and therefore this may be a viable option to reduce the total time required to cast the MT-UHPC on the bridge projects. However, it should be noted that only two batches were conducted consecutively, and the effects of conducting more than two batches was not investigated. That being said, nothing in the process indicated that this would be a problem. Further, to prevent buildup on the mixers, they should be inspected and cleaned accordingly throughout the process.

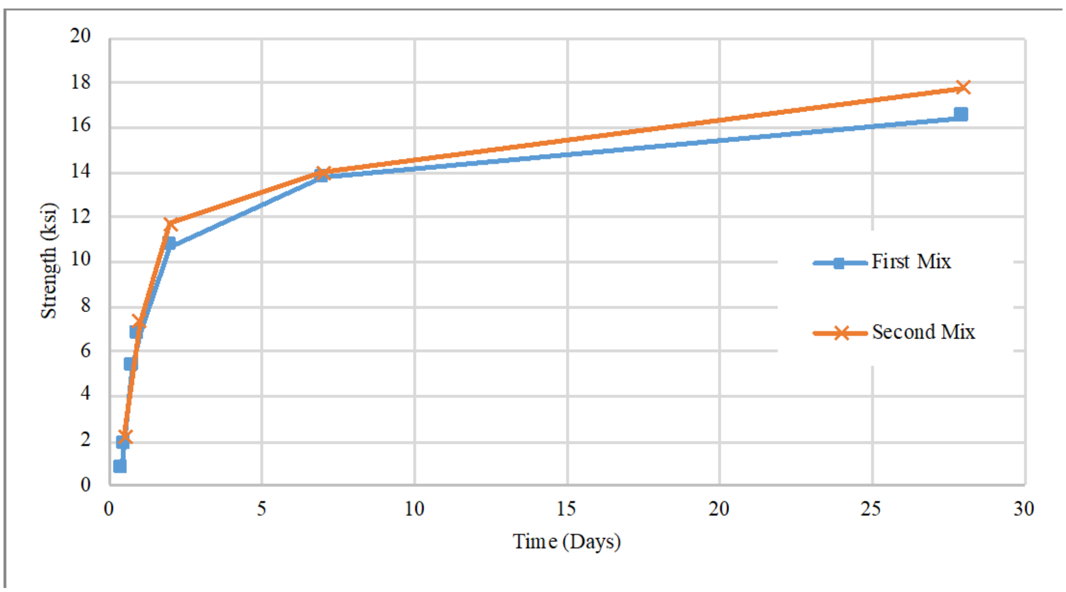

Figure 7: Strength gain of consecutively mixed batches

4.1.2 Batch Size

UHPC is typically mixed in high-shear pan mixers, and requires a significant amount of power during the mixing process. The mixer can bog down and possibly stall after water is added to the dry ingredients and before the mix turns over and becomes fluid. Therefore, UHPC is typically mixed in smaller batch sizes than are required for conventional concrete, and as an approximation, Graybeal [8] recommends using a batch size in a particular mixer that is half the capacity of what would be used for conventional concrete or grout.

As mentioned previously, this research and the bridge projects will use Imer Mortarman 360 high-shear pan mixers for mixing the MT-UHPC. These mixers have a stated capacity of 9 ft^3; however, as discussed above it would not be feasible to mix this amount of UHPC in these mixers. Previous research at MSU conducted several trial batches using these mixers with varying volumes of MT-UHPC (from 2.5 to 4 ft^3), and determined that batch size did not have a significant effect on the performance of the mix, with no clear trends in flow or compressive strength [2]. That being said, they do note that the materials in the 4-ft^3 batch were near the top of the mixer prior to the mix turning over and that larger batches may be possible, but modifications to the mixing process may need to be explored. This current task investigated the feasibility of scaling the batch size up to 4.5 ft^3 (half of the mixer capacity), to reduce the number of batches required in the bridge projects and subsequently the amount of time required for placement.

As part of this investigation several 4.5-ft^3 batches were mixed in the lab, and the flow and resultant compressive strengths were obtained. The first 4.5-ft^3 batch conducted in the lab performed well during the mixing process, with no major issues. Although, the mixer did bog down some, and the constituent materials were slightly overflowing from the mixer after the water was added and prior to the mix turning over (Figure 8). The resultant flow was 11.25 in and the 28-day compressive strength was 17.1 ksi. The strength gain profile for this mix is compared to that of a typical 2.5-ft^3 batch in Figure 10, and the results are consistent.

Figure 8: Mix constituents nearly overflowing during a 4.5-ft^3 batch

An additional 4.5-ft^3 mix was performed to confirm that this batch size would be suitable for the bridge projects. However, this additional mix did not perform well. The mixer bogged down and stalled during mixing, which led to the mix prematurely stiffening up in the mixer. The mix became too stiff to cast cylinders and was not suitable for placement. Figure 9 shows a beam being cast with the successful 4.5-ft^3 mix (left) compared to the stiffened unsuccessful mix (right).

(a) successful 4.5 ft^3 batch being placed (b) unsuccessful 4.5 ft^3 batch being placed

Figure 9: First two 4.5-ft^3 batches being placed into beam molds

While the larger batch size was determined to be a major factor in this failed mix, elevated temperatures may also have contributed. As will be discussed in greater detail in the following section, elevated temperatures can be beneficial to UHPC in regards to strength gain, but it is well documented that mixing UHPC at elevated temperatures can be problematic [2, 5, 9]. It is worth noting that this failed mix was attempted on June 9th at 7 pm, when the outside temperature was 82°F, and the water and dry-mix materials were around 70°F. This is a higher temperature than any previous trial batch conducted in this research, and most likely contributed to the failure of the mix. It should also be noted that the temperature of the mix increased substantially while it was stiffening up due to the premature exothermic reactions taking place within the mix.

To further investigate the feasibility of using a batch size of 4.5 ft^3, two additional 4.5-ft^3 batches were conducted in the lab. It should be noted that both mixes were conducted early in the morning to avoid elevated temperatures being a factor. The first of these mixes investigated a modified mixing procedure intended to reduce the strain on the mixer. This procedure involved (1) adding 2/3rd of the dry mix (cement, fly ash, silica fume, and sand), (2) adding all water and HRWR, and (3) adding the remaining 1/3rd of the dry mix after the mix turned over. This process was successful at reducing the initial strain on the mixer. After the initial portion of dry mix and water/HRWR were added, the mix quickly turned over without bogging the mixer down. That being said, once the additional dry mix was added, the mix appeared to revert back to the pre-turned over state for several minutes before once again turning over and becoming fluid. During this phase of the process, the mixer did bog down some, but it did not stall out as it did during the previous mix. The resultant flow and compressive strengths for this mix were adequate. The resultant compressive strengths are included in Figure 10. However, this process did not completely alleviate the strain on the mixer and would be labor intensive on the job site.

The final 4.5-ft^3 mix was conducted using the standard mixing procedure, during the early morning when temperatures were less than 65°F. This mix was not successful, once again stiffening up and stalling the mixer before the mix turned over. It should be noted that once again the temperature of the mix increased substantially while it was stiffening up due to the premature exothermic reactions taking place within the mix. Additional water was added to the mix in an attempt to increase the flow, but this was unsuccessful. The mix was workable enough to cast cylinders, but the resultant 28-day strengths were the lowest recorded in this research, 13.65 ksi.

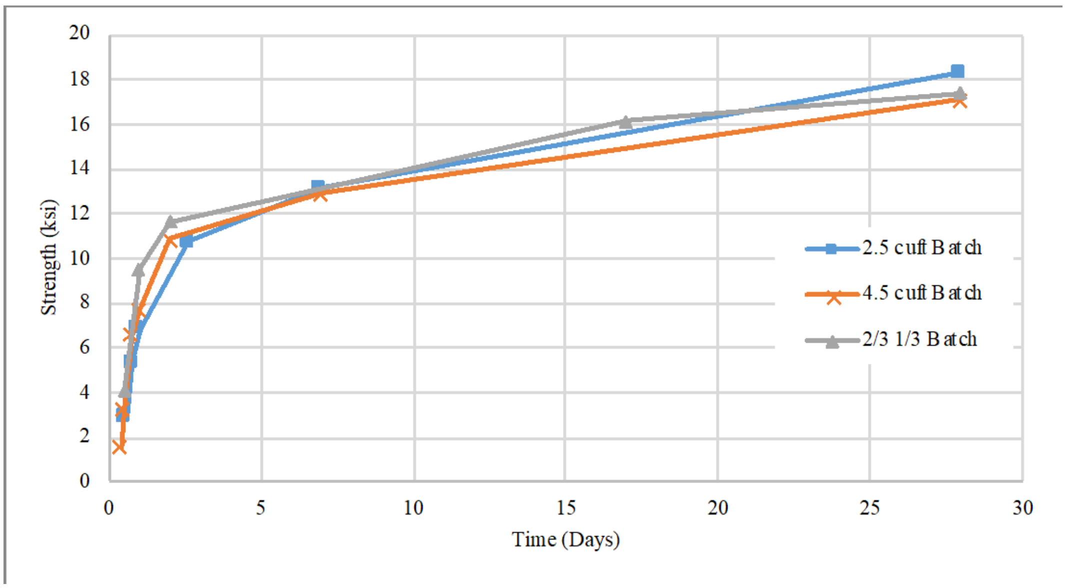

Figure 10: Comparison of compressive strengths from different batch sizes and mixing methods

After these mixes, the decision was made to limit the MT-UHPC batch size in the Imer-Mortarman 360 mixers to 3-ft^3 to avoid premature setting/stiffening and to limit strain on the mixers. It should be noted that while the modifications we made to the mixing process (withholding 1/3rd of the dry mix until turnover) did alleviate some (not all) of the strain on the mixers, this process would be labor intensive and be counteractive to the benefits of larger batch sizes. A method was proposed and successfully used by Michigan [5] in which a portion of the sand was withheld from the mix until the mix turned over. This method is not appropriate for the bridge projects in this research, as all of the dry ingredients will be premixed prior to arriving on site.

4.2 Temperature Effects

As stated in the previous section, temperature can have a significant effect on the performance of UHPC. High temperatures during the curing process can be beneficial relative to strength gain, but detrimental during the mixing process as elevated temperatures can cause increased evaporation of the limited mix water, and prematurely initiate the reactions within the UHPC. Issues with elevated temperatures were first encountered with the second 4.5-ft^3 batch discussed in the previous section (Figure 9), which was conducted outside at a temperature of 82°F. The construction of the bridge is scheduled to take place in the summer/early fall in Wisdom, MT where temperatures can vary significantly throughout the day. Therefore, it is imperative to determine a range of outside temperatures suitable for mixing MT-UHPC and quantify the effects that curing temperature has on strength gain of MT-UHPC.

4.2.1 Temperature Range for Batching MT-UHPC

Previous research at MSU investigated the effects of mixing MT-UHPC at low temperatures (40°F), and determined that there were no issues with workability and resultant compressive strengths at this low temperature [2]. While batching the MT-UHPC at a lower temperature is most likely possible, it was not specifically investigated in this research.

Elevated temperatures can negatively affect the batching of MT-UHPC, causing the mix to stiffen up significantly due to increased evaporation and premature reactions within the mix. Previous research at MSU investigated the effects of mixing MT-UHPC at an outside temperature of 75°F, when the constituent dry materials were at 90°F [2]. While this mix worked, its flow was significantly less than that of typical mixes conducted at lower temperatures (6.25 in vs. 10-11 in). Further, as discussed above, one of the mixes in this research was conducted at an outside temperature of 82°F, when the constituent materials were around 70°F. This mix stiffened up prematurely in the mixer, making it difficult to cast test cylinders and perform a flow test.

Previous research has successfully used ice to replace a portion of the mix water to allow casting UHPC at elevated temperatures [5, 9]. To evaluate the effectiveness of using ice to replace a portion of the mix water in MT-UHPC, a 3-ft^3 mix was conducted at MSU in the evening when the outside temperature was 86°F. For this mix, the dry material was stored outside in the shade for approximately 5 hours prior to mixing when temperatures were in the low 90s, and at the time of mixing, the dry-mix materials were 77°F. The mix water was 67°F, and 40% of the mix water was replaced with cube ice obtained from a local gas station. The mixing was carried out in the shade. The mix performed well, did not set prematurely, had a flow of 10 in, and had adequate strength gain (shown in Figure 11 in comparison to the MT-UHPC mix conducted at lower temperatures). That being said, it did take a few more minutes to turn over, as it took some time for the ice to melt and contribute to the mix. Further, the mix did begin stiffening up after turnover more quickly than previous UHPC mixes conducted at lower temperatures. Also, it was observed that the UHPC taken into the air-conditioned lab to cast specimens remained workable longer than the UHPC that remained outside of the lab at elevated temperatures. This quicker setting phenomenon may be an issue when trying to place UHPC into the keyways of the slab (where flow is important) if the slab temperature is elevated due to direct sunlight.

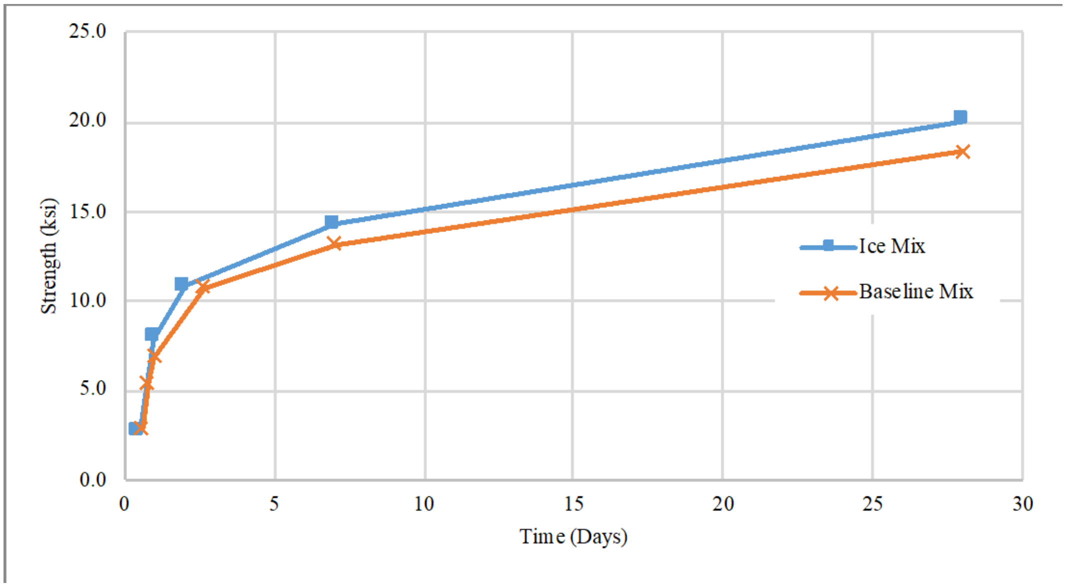

Figure 11: Compressive strengths of ice mix versus conventional mix

The MT-UHPC should be placed at lower outside temperatures and when material temperatures are low. If MT-UHPC is to be placed at higher temperatures, care should be taken to reduce the risk of the mix prematurely setting. The current specifications for the MT-UHPC states that it should not be placed when outside temperatures are above 80°F. While this limit is a good starting point for dealing with elevated temperatures, other factors should also be considered and mitigated. For example, the MT-UHPC dry-mix material should be protected from the sun and elevated temperatures prior to mixing. Further, the mixers should also be protected from the sun, as their temperatures can far exceed the outside temperatures when exposed to direct sunlight. Additionally, the use of ice to replace a portion of the mix water could be used (as discussed above) to keep temperatures within the mix low.

4.2.2 Preliminary Investigation on the Effect of Curing Temperature on Strength Gain

A preliminary investigation was conducted to study the effects that curing temperature has on initial strength gain. In this investigation, cylinders were cured for the first 48 hours under two conditions. After casting at room temperature, one set of cylinders was cured outside of the lab in the sunlight where the ambient temperatures varied from 56˚F to 93˚F. The other set of cylinders was cured in the lab at a constant temperature of 70˚F. The strengths from these mixes are compared in Figure 12. As can be observed in this figure, the cylinders cured outside exposed to elevated temperatures, gained strength significantly faster than the cylinders cured at 70˚F. At 10 hours, the outside cylinders had a compressive strength of 5.7 ksi, while the cylinders cured inside were only at 0.5 ksi. At 48 hours, the difference in strengths was significantly less, but the outside-cured specimens were still higher (11.6 ksi vs. 10.5 ksi).

Following this preliminary investigation, the effect of curing temperature on strength gain (including long-term effects) was systematically investigated, as is discussed in the following subsection.

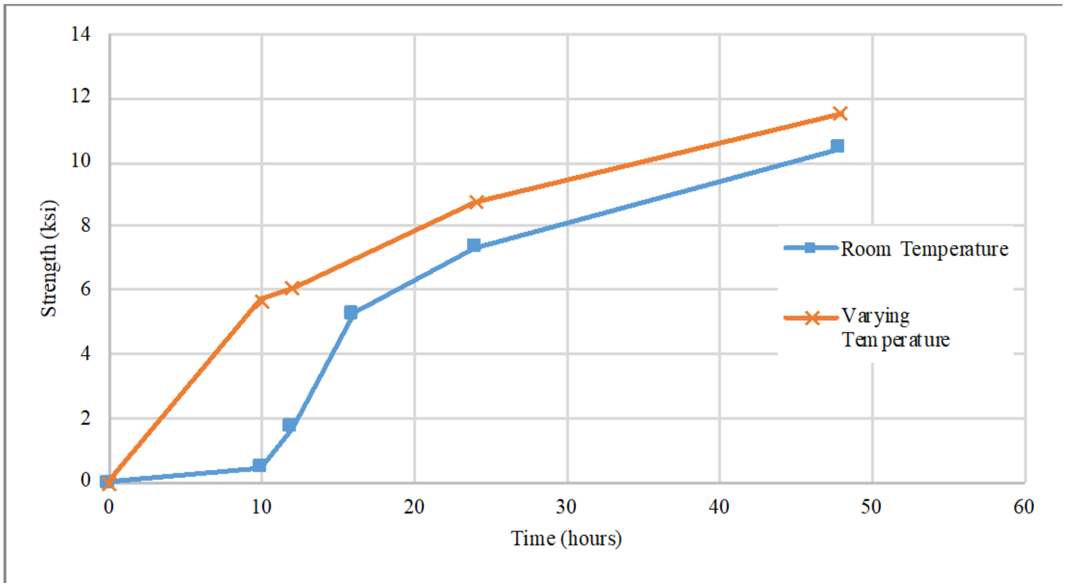

Figure 12: Compressive strengths from preliminary curing temperature study

4.2.3 Systematic Investigation on the Effect of Cure Temperature on Strength Gain

This study systematically investigated the effect of curing temperature on the strength gain of MT-UHPC over the first 28 days. In this study, a 3-ft^3 batch of MT-UHPC was mixed at room temperature within the lab and a total of 72 cylinders were cast. These cylinders were then separated into groups of 12, and cured at 3 different temperatures (34˚F, 70˚F, and 100˚F) for either the first 48 hours or for the full 28 days. For example, one group of 12 cylinders was cured at 34˚F for the first 48 hours and then transferred to the cure room for the remaining 26 days, and another group was cured at 34˚F for the full duration. Compressive strengths were obtained at 24 hours, 48 hours, 7 days, and 28 days (3 cylinders x 4 test days = 12 cylinders). The test matrix and the resultant strengths (averages of 3 specimens) are summarized in Table 8. It should be noted that the cylinders cured at 34˚F were placed within a temperature-controlled freezer in the Subzero Research Laboratory at MSU, the cylinders cured at 70˚F were cured in the concrete materials lab, and that the cylinders cured at 100˚F were placed within an oven in the concrete materials lab. Moisture was not provided or controlled for the specimens cured outside of the cure room.

Table 8: Summary of test results for systematic temperature study

Cure Condition (Initial 48hr)	Cure Condition (After 48hr)	24-hr strength (ksi)	48-hr strength (ksi)	7-day strength (ksi)	28-Day strength (ksi)
Freezer (34˚F)	Cure Room (70˚F)	0.37	3.57	14.43	17.00
Lab (70˚F)	Cure Room (70˚F)	5.93	9.57	14.37	17.77
Oven (100˚F)	Cure Room (70˚F)	11.77	13.43	14.07	16.10
Freezer (34˚F)	Freezer (34˚F)	0.37	3.57	9.90	12.40
Lab (70˚F)	Lab (70˚F)	5.93	9.57	13.87	16.87
Oven (100˚F)	Oven (100˚F)	11.77	13.43	14.73	18.60

The average compressive strengths for the cylinders cured at various temperatures for the first 48 hours and then moved to cure room for the remaining 26 days are shown in Figure 13. As can be observed in this figure and Table 2, curing temperature has a significant effect on initial compressive strength, with 24-hour strengths ranging from 0.37 ksi at 34˚F to 11.77 ksi at 100˚F, and 48-hour strengths ranging from 3.57 ksi at 34˚F and 13.43 ksi at 100˚F. However, after the cylinders are transferred to the cure room, this trend of increasing strength with increasing initial cure temperature is not present. The strengths at 7 days are nearly identical to each other (around 14 ksi), and at 28 days the specimens cured at 100˚F actually have the lowest strength. The latter indicates that the early strength gain observed for the 100˚F may come at a cost of slightly lower long-term strengths.

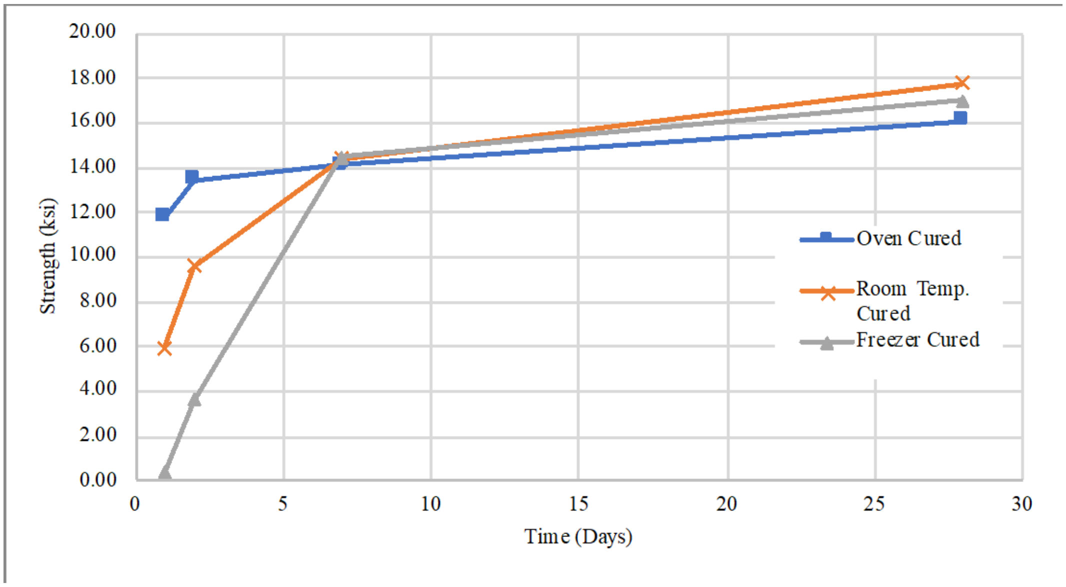

Figure 13: Compressive strengths from cylinders cured at various temperatures for first 48 hours before being moved to cure room

The average compressive strengths for the cylinders cured at various temperatures for the full 28 days are shown in Figure 14. As can be observed in this figure, and as expected, curing temperature has a significant effect on compressive strength throughout the testing period. At 28 days, the average compressive strengths were 12.4, 16.9, and 18.6 ksi at 34˚F, 70˚F, and 100˚F, respectively. It should be noted that the 28-day strength at 34˚F (12.4 ksi) was the lowest observed in this phase of research, while the 28-day strength at 100˚F (18.6 ksi) was the highest.

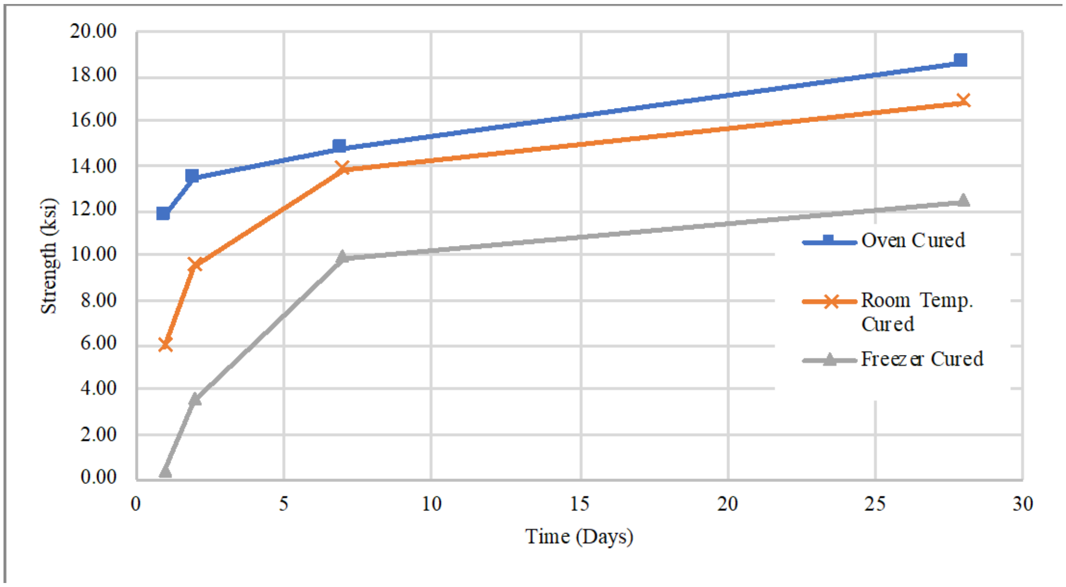

Figure 14: Compressive strengths from cylinders cured at various temperatures for duration of testing

4.3 Estimating Early Strength Gain with Maturity Method

As will be discussed in a later chapter, each bridge to be constructed using MT-UHPC has a construction window of only 96 hours (including demolition of the existing bridges), and certain phases of the construction cannot proceed until the MT-UHPC has reached the minimum design strength. Therefore, it is imperative to estimate the early strength gain of the MT-UHPC, including the effects of curing temperature, as this was shown to have a significant effect on early strength gain in the previous section. This was achieved using the maturity method prescribed in ASTM C1074. Maturity curves were developed for several of the mixes discussed above (Mix 2, 3, 7, and 9 in Table 8), which were exposed to various curing conditions, and include the mixes focused on evaluating the effects of curing temperature. Maturity was monitored using a Humboldt Model H-2682 maturity meter, using the Temperature Time Factor (TTF) and an assumed temperature datum of 0˚C (recommended by ASTM C1074). The curves were obtained by monitoring the TTF and corresponding compressive strengths of the mixes systematically throughout the curing process.

The resultant maturity curves for these mixes are shown in Figure 15 for the first 48 hours, and Figure 16 for the full duration of testing (assuming a datum of 0˚C). As can be observed, the data for all of the mixes sans the mix cured at 34˚F fell along the same general curve. While this good fit is promising, the outlying data for the 34˚F specimens is somewhat concerning. This data shows that the strengths of the 34˚F-specimens are significantly higher than what would be predicted with the other curves developed in this study, indicating hydration is taking place faster than anticipated at this temperature. This finding suggests that the assumed datum temperature of 0˚C may not be appropriate for the MT-UHPC. To investigate this further, the recorded TTF values were adjusted to account for a datum value of -5˚C rather than 0˚C. The adjusted maturity curves using a datum of -5˚C are provided in Figure 17 for the first 48 hours, and Figure 18 for the duration of testing. As can be observed, the maturity curves for the first 48 hours are now in better agreement, although the 34˚F-curve is still predicting slightly higher strengths than the other curves. Referring to long-term strengths (Figure 18), all curves are again very similar, although the 28-day strengths for the 34˚F-specimens are lower than anticipated, with recorded strengths of around 12.5 ksi rather than the 13.5 ksi predicted by the other curves. While the adjusted datum temperature of -5˚C provides closer agreement between the curves, the datum temperature should be investigated further using the methods outlined in ASTM C1074 Appendix 1.

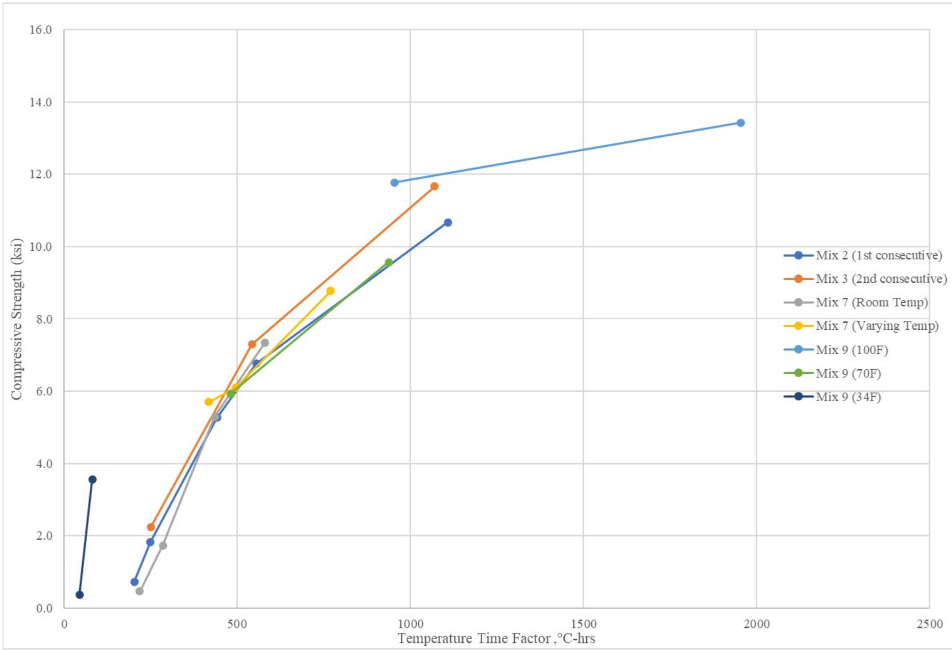

Figure 15: Maturity curves over first 48 hours (0˚C Datum)

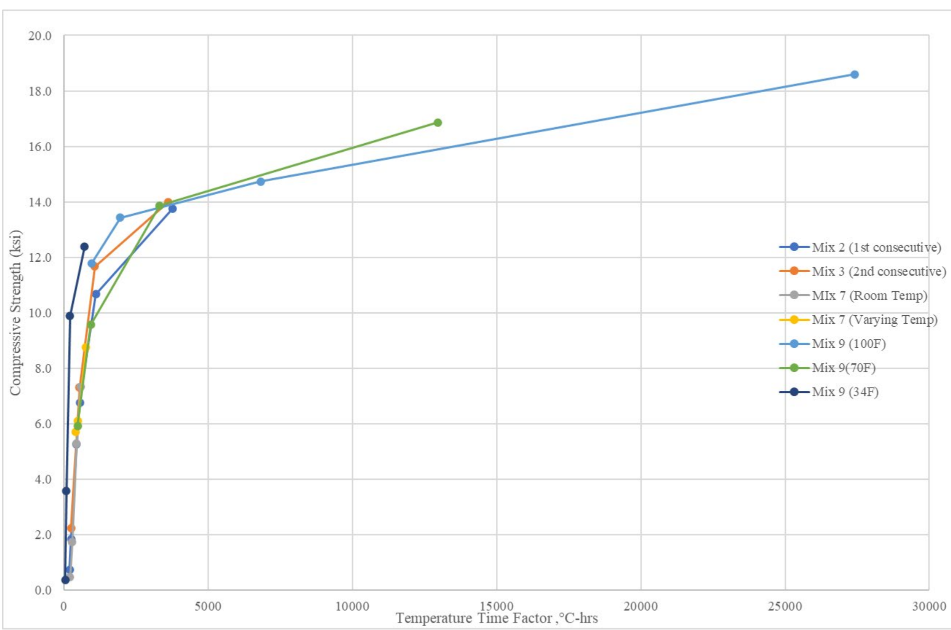

Figure 16: Maturity curves over duration of testing (0˚C Datum)

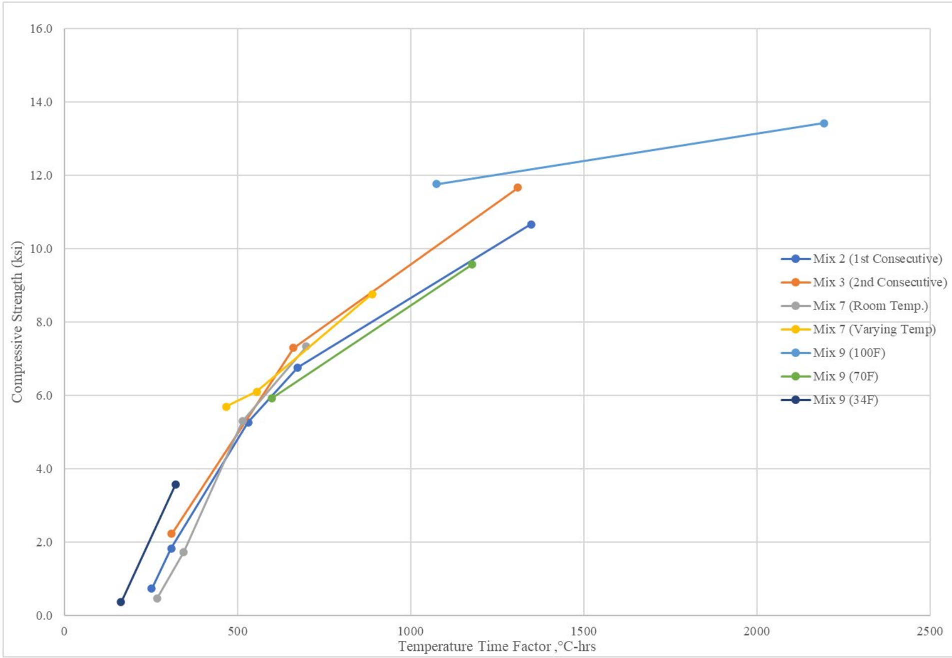

Figure 17: Maturity curves over first 48 hours (-5˚C Datum)

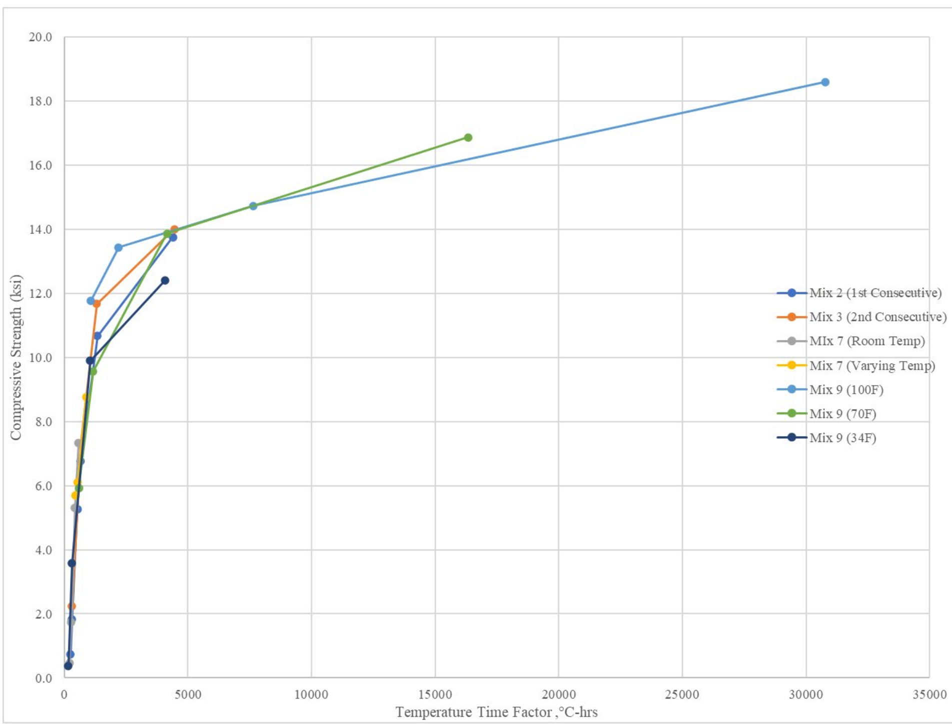

Figure 18: Maturity curves over duration of testing (-5˚C Datum)

4.4 Summary of Implementation Research and Key Findings

This task was focused on filling several research gaps related to the field application of MT-UHPC. Specifically, this research investigated the effects of the mixing process, batch size, and temperature on the performance of MT-UHPC. It also developed maturity curves to be used in estimating the early strength gain of MT-UHPC. Key findings from this task follow.

- MT-UHPC batches can be mixed consecutively in the same mixer without cleaning the mixer between batches. Residual material and moisture in the mixer had little effect on the flow and strength gain. However, the mixers should be inspected and cleaned accordingly throughout the projects.
- Batch sizes should be limited to 3 ft^3 when mixing MT-UHPC with Imer Mortarman 360s. Batch sizes of 4.5 ft^3 using these mixers were problematic in this research, with two out of four batches prematurely stiffening-up within the mixers due to inadequate mixing energy. However, larger batch sizes may be possible in these mixers if modifications are made to the batching process.
- MT-UHPC should be placed at lower temperatures and when material temperatures are low. Elevated temperatures can negatively affect the batching of MT-UHPC, causing the mix to stiffen up significantly due to increased evaporation and premature reactions within the mix. If MT-UHPC is to be placed at elevated temperatures, care should be taken to reduce the risk of the mix prematurely setting (e.g., using ice to replace a portion of the mix water, storing constituent materials and mixers in the shade).
- Cure temperature should be accounted for when estimating the compressive strength of the material in the field (e.g., using the maturity method), as temperature was observed to significantly affect strength. Compressive strengths were observed to increase with increasing cure temperature, with this effect being most prominent in early strengths (first 48 hours).
- The maturity curves developed in this research may be used to estimate compressive strength of MT-UHPC in the field. These curves were developed under varying curing conditions and were all very similar to each other, especially when using a datum temperature of -5˚C. Further research into an appropriate datum temperature may be warranted.

5 TRAIL CREEK STRUCTURES OVERVIEW AND MT-UHPC SPECIAL PROVISIONS

This chapter provides details on the location and state of the Trail Creek structures to be replaced with precast elements using MT-UHPC field-cast joints. It also documents the general procedures used in these bridges to batch, store, and field-mix the MT-UHPC. This chapter concludes with a discussion of the Special Provisions used to prescribe the field implementation of MT-UHPC on the Trail Creek bridges, and the quality control strategies used during construction.

It should be noted that the contractor responsible for the construction of the bridges was Dick Anderson Construction out of Helena, MT. Dick Anderson was a subcontractor to the primary, Schellinger Construction out of Columbia Falls, MT.

5.1 Bridge Overview

The two Trail Creek bridges selected for replacement are located in Southwest Montana on Highway 43, about 17 miles west of Wisdom, MT near the May Creek Campground, as shown in Figure 19 and Figure 20. The bridges were significantly deteriorated, and in need of replacement. One of the bridges is shown in Figure 21, highlighting the deteriorated state of the bridges prior to replacement.

From Wisdom, there are no convenient detours around this location, and therefore Highway 43 must be shut down to through-traffic during construction of each bridge. The average daily cost to the traveling public resulting from this road closure was estimated to be $2,500 per hour, and thus an accelerated bridge construction (ABC) procedure was chosen for the bridge replacements with a specified 96-hour construction window for each bridge. Specifically, the chosen procedure consisted of precast elements assembled on-site with MT-UHPC used for all field-cast joints. A monetary incentive/disincentive was applied to the contract to incentivize the timely construction of the bridges.

Figure 19: General location of Trail Creek bridges

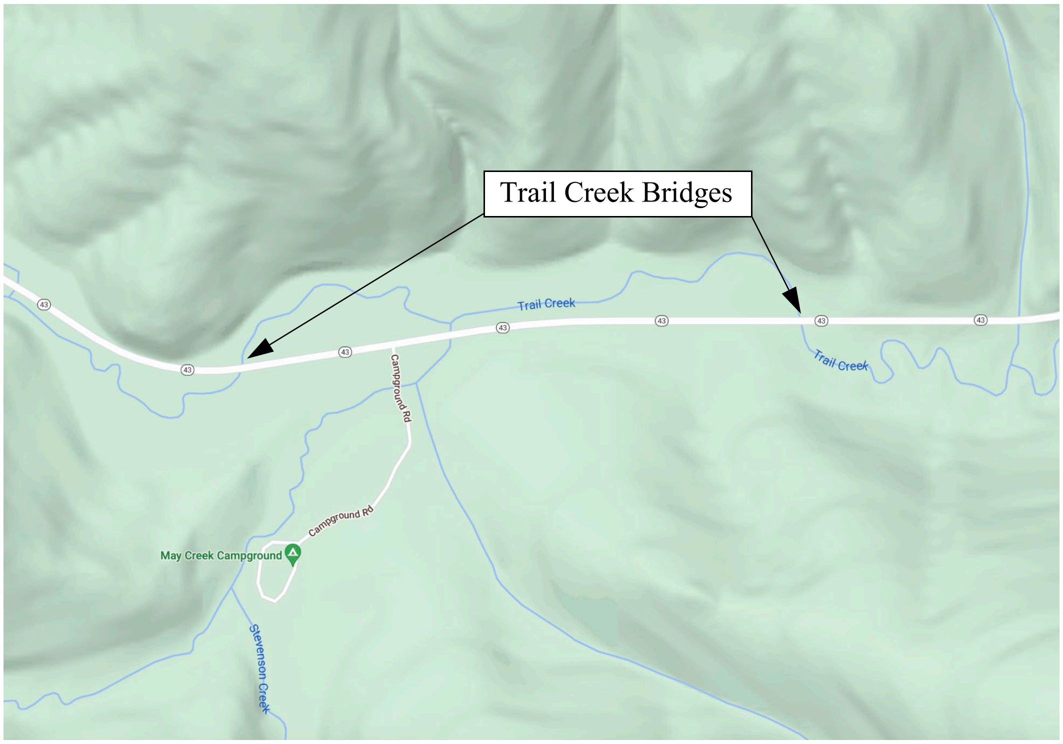

Figure 20: Specific location of Trail Creek bridges


Figure 21: One of the Trail Creek bridges prior to replacement

Each replacement bridge had a single span of approximately 60 ft, and was constructed with precast elements connected with MT-UHPC. An overview of the plans is provided in Figure 22. The support structure for each bridge consisted of two precast pile caps, each cast with three 24-in diameter connection sockets (constructed with embedded corrugated metal pipes) at the locations of the piles. The main span and riding surface of the bridge consisted of eight precast/prestressed hollow-core beams placed directly on top of the pile caps adjacent to each other. These beams each had small sockets on either end to be placed on top of embedded dowels on the pile caps. The bridges also included four precast wingwalls to be connected to the pile caps via embedded dowls on the caps. MT-UHPC was used for all field-cast connections, including the pile to pile cap connections, the connections between the beams and caps, the wing walls, and the longitudinal shear-keys between adjacent beams, as shown in Figure 22.

The following sections provide details on the batching, storage, and mixing of the MT-UHPC.

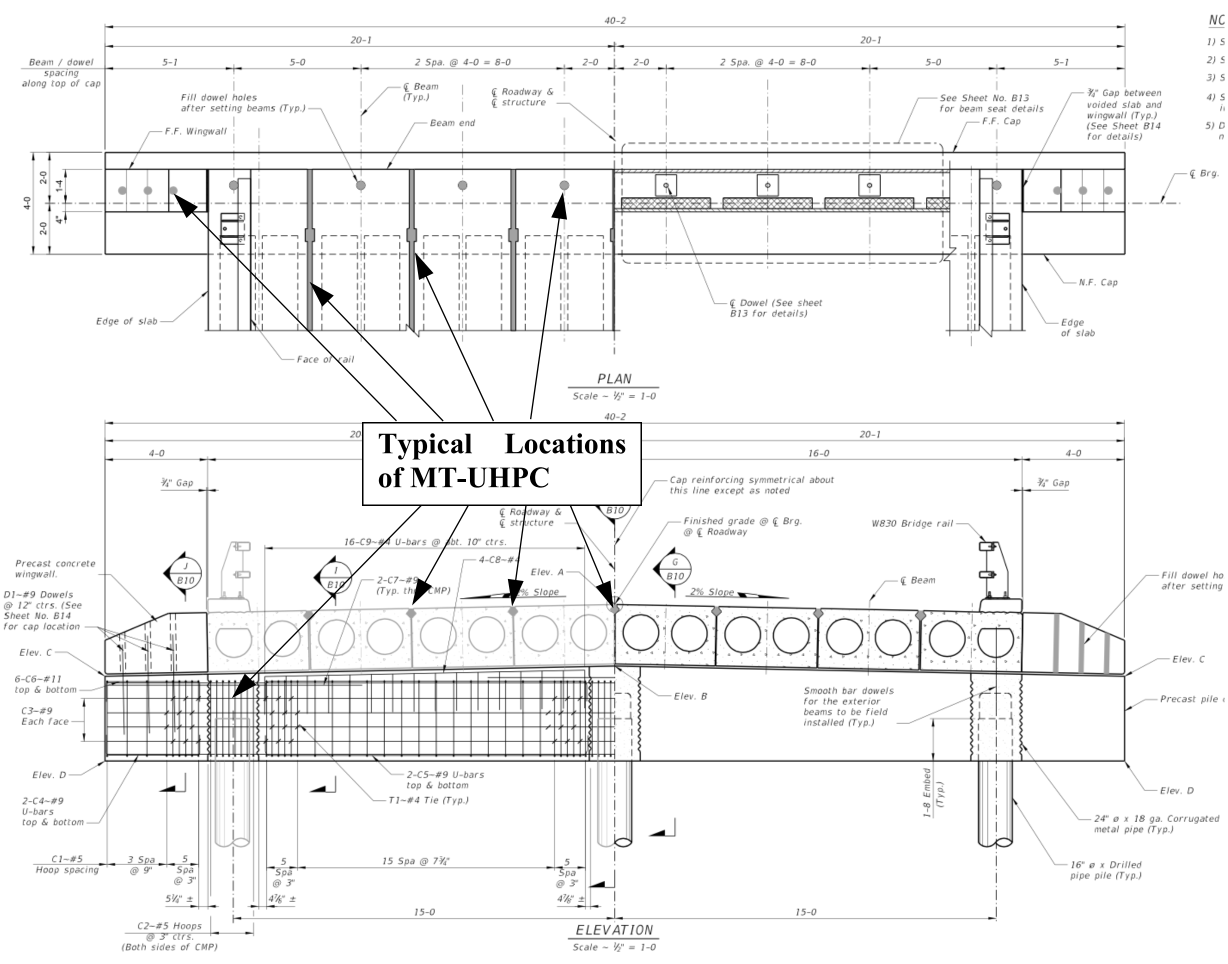

Figure 22: Structural plans for Trail Creek bridges

5.2 MT-UHPC Batching and Mixing Procedures

The mix proportions used in the MT-UHPC are provided in Table 9. It should be noted that these mix proportions reflect a 2.5% increase in the water and HRWR relative to the mix proportions used in previous research. The water and HRWR were increased during bridge construction to help the UHPC turn over, and improve its workability. More details on the specific materials used in this project are provided in Chapter 3; however, a brief summary of the materials is included here. The cement was a Type I/II/V from the GCC cement plant in Trident, MT. The fly ash was a Class F ash sourced from Prairie State Energy Campus in Marissa, IL. The fine aggregate was a masonry sand processed and packaged by QUIKRETE near Billings, MT. It should be noted that the fly ash, cement, and sand were all purchased from QUICKCRETE and delivered in 1-yd^3 sling bags. The silica fume was MasterLife SF 100 from BASF. The high range water reducer (HRWR) was CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. The steel fibers were sourced by Hiper Fiber and were 13 mm long, had a diameter of 0.2 mm and a tensile strength of 285 ksi.

Table 9: Mix proportions for 1 yd^3

Item	Weight (lbs)
Water	306.2
Portland Cement	1299.5
Fly Ash	371.3
Silica Fume	278.4
HRWR	66.0
Steel Fibers	262.9
Fine Aggregate	1556.4

It was estimated that each structure would require approximately 5 yd^3 of MT-UHPC for the field-cast joints. After acquiring enough materials to cast a total of 10 yd^3 of UHPC, and several months prior to the bridge construction, the dry ingredients were batched and premixed to save time on the jobsite. The constituent dry materials (i.e., cement, fly ash, silica fume, and sand) were weighed out in proportion to 3-ft^3 batches then premixed and bagged in sling bags. The premixing was done using the IMER Mortarman 360 in accordance with the methods recommended in previous MSU research. Once mixed, the 3-ft^3 sacks of MT-UHPC were stored in a shipping container shown in Figure 23. This shipping container contained approximately 100 sacks of MT-UHPC, and provided a convenient method of protecting the material from the elements and transporting it to the jobsite. On the jobsite, these sacks were removed from the storage container and transported to the mixing location on a flatbed, as seen in Figure 24.

During construction, two IMER Mortarman 360s were used to mix the MT-UHPC. First the premixed dry ingredients were added to the mixer by hoisting the sack and depositing it in the mixer through the hole in the bottom, as shown in Figure 25. The HRWR and mix water were weighed on site (Figure 26), and then added to the mixer. The dry premix, water, and HRWR were then mixed until the MT-UHPC turned over (approximately 5-10 minutes) and became fluid. Once turned over, the steel fibers were added (Figure 27), and the MT-UHPC was mixed for approximately 5 additional minutes to evenly distribute the fibers. After this mixing was complete, the MT-UHPC was removed from the mixer and placed in the field-cast joints. Details on the placement of the field-cast joints are discussed in the following chapters.

Figure 23: Sacks of MT-UHPC in storage container

Figure 24: Sacks of MT-UHPC dry material on the jobsite

Figure 25: Sack of dry mix being added to the mixer

Figure 26: Water, HRWR, and steel fibers being weighed on site

Figure 27: Steel fibers being added to the mixer

5.3 MT-UHPC Special Provisions

As part of this research, in coordination with MDT, Special Provisions were created to prescribe the procedures and requirements of the MT-UHPC. These Special Provisions outline all key aspects of the MT-UHPC, and the key components are included in Appendix A. Some key takeaways from these provisions are itemized below.

- The constituent materials and mixing methods recommended by previous MSU research must be used.
- The minimum compressive strength of the MT-UHPC prior to backfilling around pile caps, operating compaction equipment near the structures, or placing beams on the pile caps is 4,000 psi.
- The minimum required 28-day compressive strength of the MT-UHPC is 12,000-psi.
- The state will supply two IMER Mortarman 360 mixers.
- The MT-UHPC may not be placed at air temperatures below 40°F nor above 80°F.
- The cure time of the MT- UHPC must be established to meet the project schedule and compressive strength requirements defined in the specification.
- A trial pour and joint mockups must be completed. This exercise will simulate conditions for mixing, placing, curing, and surface finishing the MT-UHPC for the pile to pile cap connection and the longitudinal deck joint.
- The grinding procedures are prescribed, which require a minimum compressive strength of 3 ksi prior to grinding.
- The quality control testing procedures are prescribed.
- The basis for payment is established.

It should be noted that although these provisions outline the required quality control testing procedures, these procedures were modified prior to the construction project, and are discussed in the following section.

5.4 Quality Control Testing Procedures

The quality control procedures outlined in the Special Provision were modified in an effort to reduce the amount of MT-UHPC required for testing during construction, and to provide a more efficient means of monitoring early strength gain. Specifically, the requirements used for strength testing were as follows.

- Five 3x6 in cylinders from 3 batches of MT-UHPC were obtained from each application of the material, equating to 15 total cylinders per placement.
- The sets of 5 cylinders were pulled from batches of MT-UHPC near the beginning, middle, and end of each placement.
- From the sets of 5 cylinders, 2 were cured on site in a cure box (provided by MDT), transferred to MSU at the end of construction, cut and ground by MSU, placed in MSU's cure room, and then transferred to MDT for 28-day acceptance testing.
- The remaining 3 cylinders from each batch were field cured next to the bridge for 24-48 hours, and transferred, prepped, cured, and tested by MSU.

The maturity method (Section 4.3) was used to predict the early compressive strength of the concrete, and subsequently determine when the joints reached the minimum strength of 4 ksi required for backfilling around pile caps, operating compaction equipment near the structures, placing beams on the pile caps, and opening the bridges to traffic. The maturity curves discussed in Chapter 4 (developed using these exact materials) were used for this method. Using these maturity curves, it was determined that this 4 ksi minimum strength threshold would be expected to occur at a Temperature Time Factor (TTF) of around 375°C-hrs. The TTF was monitored on site using maturity meters with embedded thermocouples in all pile cap and keyway joints.

6 TRIAL BATCHES AND BRIDGE JOINT MOCKUPS

Prior to placement of the MT-UHPC in the actual bridges, trial batches were conducted near the location of the bridges where MT-UHPC was placed in mockup field-cast joints. During these trials, MT-UHPC was mixed on site using the same methods and under the same environmental conditions expected on the day of construction. After mixing, the MT-UHPC was placed into three replica field-cast joints. Specifically, the MT-UHPC was placed into a mockup pile to pile cap connection (Figure 28) and two keyways (Figure 29).

Figure 28: Mockup pile to pile cap connection

Figure 29: Mockup keyway connections

6.1 UHPC Batching, Mixing, and Results

The mockup trial pours took place on June 3, 2021 at the contractor's yard in Wisdom, MT, where the temperatures were around 65°F at the time of the first mix (around 9 am), and climbed to 88°F throughout the day. Figure 30 shows the MT-UHPC dry mix being added to the mixer during the first batch, and Figure 31 shows the water and HRWR being added. Two mixes were conducted during the trial. Both mixes performed well, with spreads of around 10 inches (Figure 32) and 28-day compressive strengths of 15.1 and 17.1 ksi, for first and second mix, respectively. A summary of results from these mixes is provided in Table 10.

Table 10: Summary of mockup mix results

Mix	Application	Spread (in)	24-hr strength (ksi)	48-hr strength (ksi)	7-day strength (ksi)	28-day strength (ksi)
1	Keyway	10	9.4	9.2	11.5	15.1
2	Pile Cap	10	10.3	10.7	13.4	17.1

Figure 30: Dry mix being added to mixer

Figure 31: Water and HRWR being added to mixer

Figure 32: Flow test of MT-UHPC during mockup

6.2 Joint Mockups

As mentioned above, the MT-UHPC was placed into two keyway mockups, shown in Figure 29. One of these keyways was sloped to simulate the expected conditions of the actual bridges. As is common with most UHPC, air within the mix gets entrapped near the top surface during initial set. Therefore, the MT-UHPC was cast ½ inch above the surface of the deck to facilitate grinding of this top surface. This overcasting of UHPC was implemented using ½-inch thick wood strips glued to the top surface of the deck around the keyways, as shown in Figure 33. Also, foam sealant was used at the bottom of the keyway to ensure that the MT-UHPC did not flow out the bottom of the connection, shown in Figure 33b.

After mixing, the MT-UHPC was placed into the keyways using buckets, as shown in Figure 34. This method worked well for these mockups, and the UHPC easily flowed into the joints with no need for vibration. However, the sloped specimen highlighted the need for top-forming of the connection. In this specimen, as expected, the MT-UHPC overflowed the formwork on the low end of the specimen and did not completely fill the joint on the high end. Both the flat and sloped specimens after placement of the MT-UHPC are shown in figures 35 and 36, respectively. It should be noted that thermocouples were embedded in the keyway to estimate early strength gain and assist in determining the proper time for grinding.

a) full specimen b) inside keyway showing foam sealant

Figure 33: Keyway mockup

Figure 34: MT-UHPC being placed into keyway mockup

Figure 35: Flat keyway mockup after MT-UHPC placement

Figure 36: Sloped keyway mockup after MT-UHPC placement

After placement and initial curing, the surface of the UHPC needed to be ground down to the top surface of the deck elements. The initial grinding occurred over a portion of one of the mockups after approximately 6 hours with a TTF of 173°C-hrs, which corresponded to a compressive strength of less than 1 ksi. This grinding was carried out using a handheld angle grinder with a concrete grinding wheel. While the top surface was easily ground at this low strength, it was determined that this was too early since the steel fibers were being pulled from the UHPC during the process. More grinding occurred the following morning at approximately 20 hours, with better results. However, the maturity meter had been removed from the specimens prior to this grinding, and therefore the estimated strength of the UHPC was unknown during this grinding. It should be noted that the Special Provisions specify that the MT-UHPC reach 3 ksi before grinding. Figure 37 shows a specimen being ground, while Figure 38 shows a specimen after grinding at 6 hours.

Figure 37: UHPC being ground around keyway

Figure 38: UHPC surfaces ground after a 6-hr cure time

In regards to the pile cap connection mockup, the UHPC was simply added to the connection with buckets, as shown in Figure 39. There were no issues with this process, and this connection required no grinding of the top surface since this concrete will be covered by the longitudinal beam elements in the actual bridge project.

Figure 39: UHPC being added to the pile cap connection mockup

6.3 Discussion of Results

Some key takeaways from the trial pours and joint mockups are as follows:

- MT-UHPC was successfully batched and mixed in the field using the exact materials, mixers and methods to be used in the actual bridge project. The flows of the trial mixes were around 10 inches, and the compressive strengths exceeded the minimum specified 28-day strength of 12 ksi, with an average strength of 16.1 ksi.
- The methods used to form and place the UHPC in the connection mockups were primarily successful. However, the UHPC in the sloped-keyway mockup demonstrated the need for top forming the keyways, as the UHPC in these connections overflowed at the low end and fell short on the high end.
- Grinding the UHPC before it reaches a strength of 1 ksi resulted in a rough surface on the UHPC and steel fibers being pulled from the material. It is recommended that the MT-UHPC reach at least 3 ksi prior to grinding, as is specified in the Special Provisions.

7 BRIDGE CONSTRUCTION

This chapter discusses the construction process used for the Trail Creek bridges and highlights the application of MT-UHPC in the field-cast joints of the bridge. It should be noted that both bridges followed the same process described below and had identical structural systems.

7.1 Demolition and Site Preparation

As stated previously, each bridge had a 96-hour shutdown window for construction. The shutdown period began with applying containment methods to prevent the pollution of Trail Creek, and the demolition of the existing bridge. The bridge site after demolition is shown in Figure 40, which also shows the timber piles from the old bridge and the containment methods in place. The old bridge after removal is shown in Figure 41. It should be noted that the rebar was removed from the old bridge and recycled (Figure 42).

Figure 40: Bridge site after removal of existing bridge

Figure 41: Demolished bridge after removal

Figure 42: Reclaimed rebar from demolished bridge

7.2 Pile Caps

For each bridge, 6 drilled steel pipe piles (3 on each side of the span) were placed and covered prior to the beginning of the shutdown window. After the banks of the river were prepared for erosion control, these drilled piles were uncovered, and the soil around the piles was prepared for the placement of the pile caps. This soil preparation included achieving proper compaction and elevations. The uncovered piles are shown in Figure 43, along with one of the precast pile caps being moved into position for placement. As can be observed in this figure, an expanding foam sealant was placed on the ground at the locations of the sockets to prevent the UHPC from potentially flowing out of the base when being filled.

Once the surface was prepared, the pile caps were then placed on top of the piles, bearing on the compacted soil. Figure 44 shows a pile cap being placed. Thermocouples were then placed within the sockets to monitor the maturity and subsequent strength of the MT-UHPC. MT-UHPC was then used to complete the connection between the piles and the pile caps. Figures 46-48 show MT-UHPC being directly added into the connections. Figure 50 shows the pile cap after the placement of the MT-UHPC, just before the placement of the beam elements.

It should be noted that UHPC placement commenced for both bridges early in the morning when outside temperatures were around 25°F. With the exception of the first mix on the first bridge, there were no issues mixing and placing the UHPC at this low temperature. On the morning of the first bridge, both mixers had small amounts of ice accumulated in their drums (Figure 49). One of these mixers was warmed up in order to remove this ice, and the other was not. The UHPC in the mixer that had not been warmed up took too long to turn over, and this mix began setting within the mixer. Whereas, the mix that was placed in the warmed-up mixer worked well, with no issues. The remainder of mixes worked well in both mixers.

Therefore, on the second bridge, both mixers were first warmed up by simply adding water to the mixer for several minutes prior to initiating mixing for the day.

Figure 43: Uncovered pile caps and prepared surface prior to cap placement

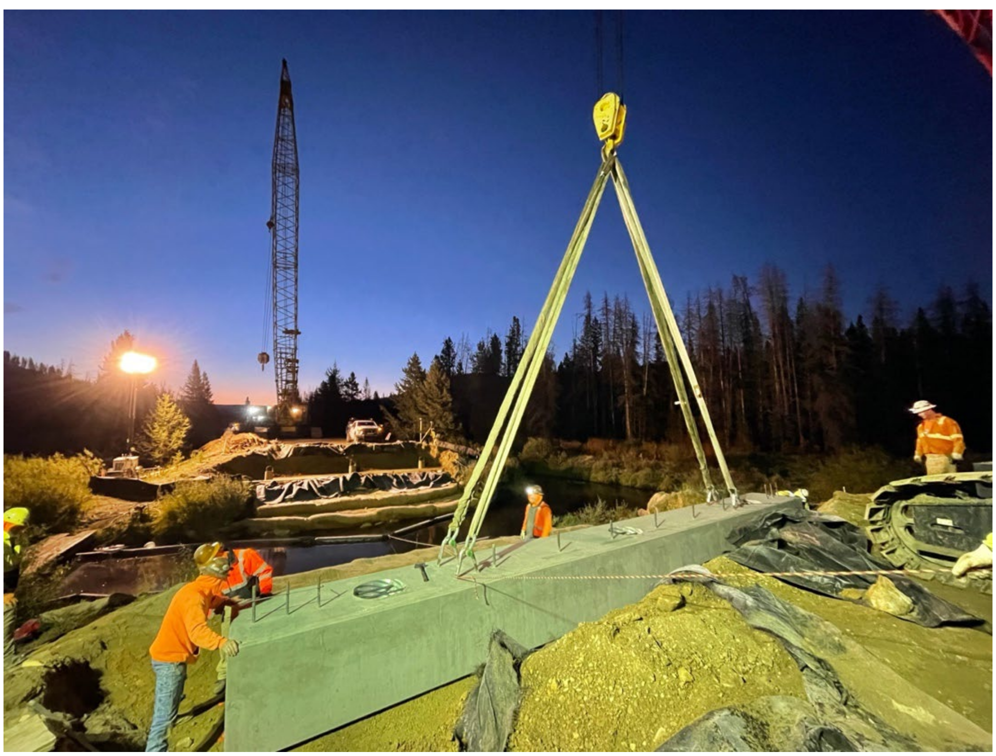

Figure 44: Pile cap being placed on steel pipe piles

Figure 45: Pile cap void to be filled with UHPC with thermo-coupling wires installed

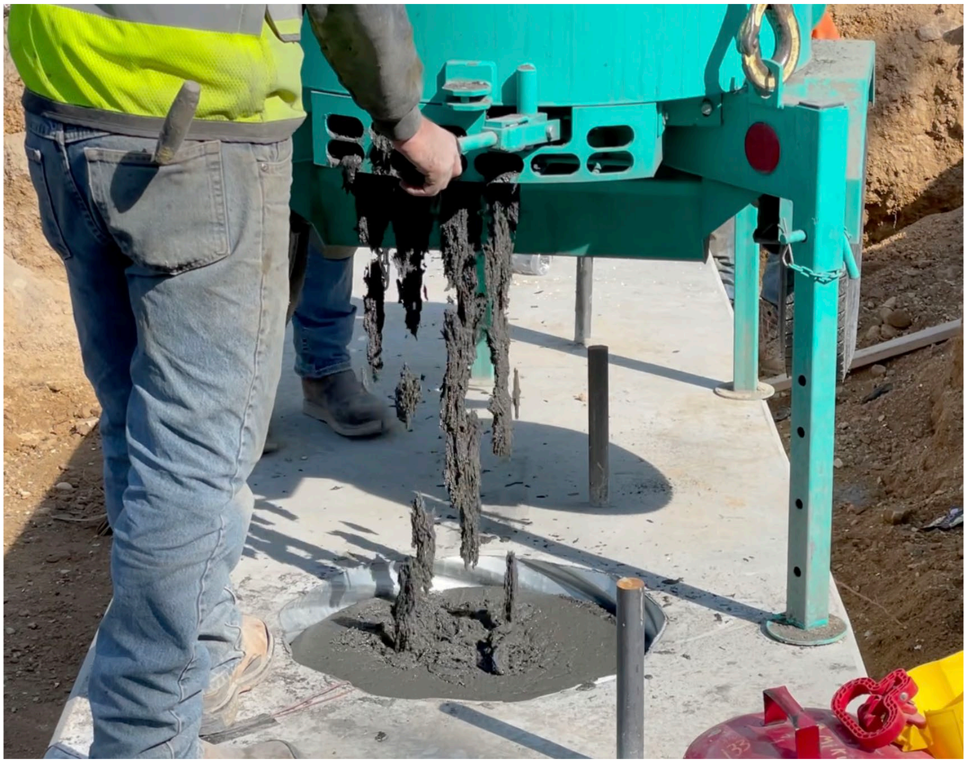

Figure 46: MT-UHPC being placed into pile cap sockets

Figure 47: MT-UHPC placement on pile cap

Figure 48: MT-UHPC dry mix being added to mixer on pile cap

Figure 49: Ice formed in the bottom of the mixer prior to the start of construction

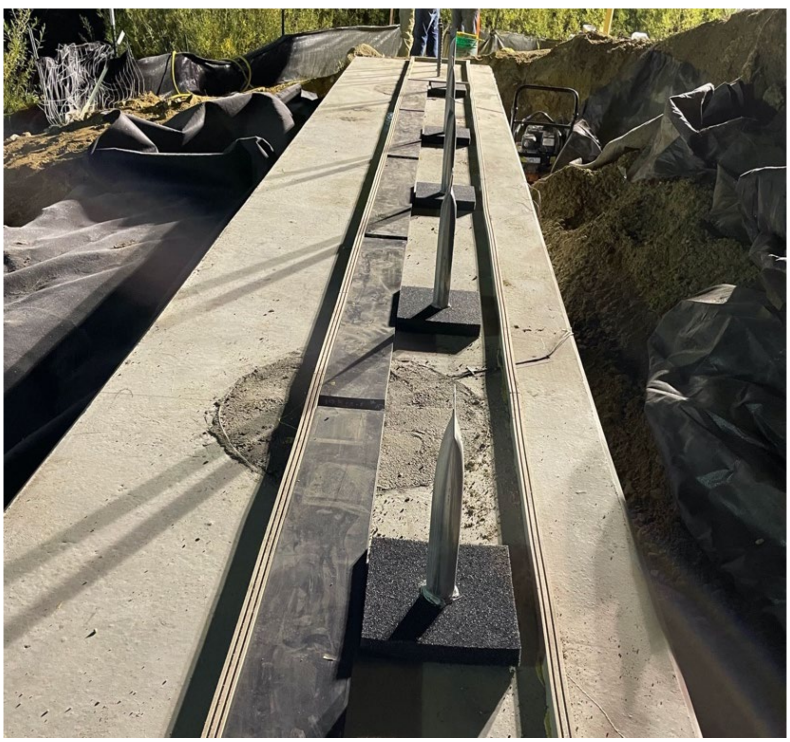

Figure 50: Pile cap after UHPC placement, just prior to the beam placement

7.3 Longitudinal Beam/Deck Elements

After the MT-UHPC was determined to reach the required strength of 4 ksi (via the maturity method), the 8 precast/prestressed hollow-core beam elements were placed on top of the pile cap, aligning the holes in the beams with the embedded dowls on the cap. This process is shown at various stages in figures 51-54.

Figure 51: First longitudinal beam element being placed

Figure 52: Second beam element being placed on pile caps

Figure 53: First two beam elements after placement, with visible keyway

Figure 54: Final longitudinal deck element being placed

After the beams were placed, some adjustments (Figure 55) were made to ensure that there were not excessive differences between the tops of adjacent beams. The contractor began these adjustments with the middle beam and then worked towards the edge of the bridge. Once a beam was adjusted, the shear tabs within the keyways were welded. Figure 56 shows these stainless-steel shear tabs just prior to welding.

Figure 55: Longitudinal beam elements being leveled

Figure 56: Shear tabs just prior to welding (left), and shear tab connection without tab (right)

Before the placement of MT-UHPC within the keyways, ½ in wood slats were glued to the surface of the bridge deck around the keyways, as shown in Figure 57. This was done, as is common in all UHPC applications, to allow for over casting of the MT-UHPC. The top surface of UHPC contains a large amount of entrapped air due to a skin forming on the surface of the concrete, which will be ground down in a later step. MT-UHPC was then placed into these keyways, and top formed to ensure that the UHPC evenly fills the sloped keyways.

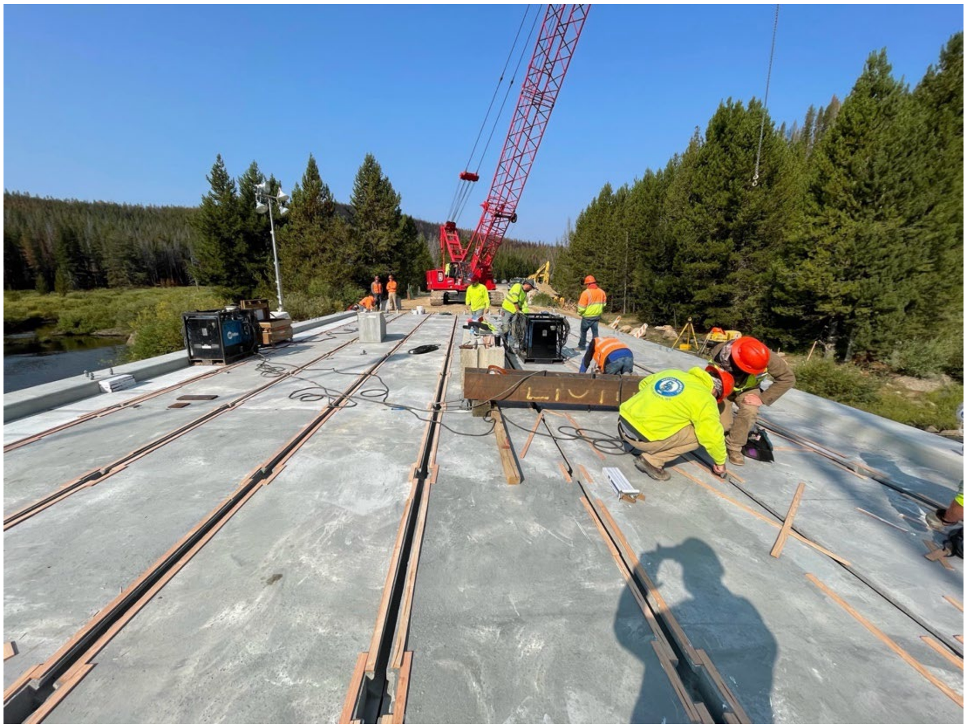

Figure 57: Wood slats glued to the top surface of beams around keyways

For the keyway placement, the UHPC was batched at the end of the bridge and then transported to the keyway for placement using a wheelbarrow. At first, the MT-UHPC was placed directly into the keyway as shown in Figure 58a. However, it was determined that using a trough (shown in Figure 58b) was more efficient. Placement of MT-UHPC in the keyways began at the low end of the bridge and finished at the high end. The trough was slowly moved along the length of the keyway at a rate slow enough to allow the UHPC to disperse evenly within the joint. As the material was placed, it was immediately top formed behind the trough. This involved workers standing on the top-forming boards until fasteners were installed to maintain pressure on the material moving forward. It should also be noted that during this step, UHPC was also placed into the wingwall and beam dowel holes, as shown in Figure 59. One of the bridges with completed UHPC and top forming is shown in figures 60 and 61.

a) UHPC directly added to keyway b) UHPC being added to keyway using trough

Figure 58: MT-UHPC being placed into keyways

Figure 59: UHPC being placed into beam dowel hole, connecting it to pile cap

Figure 60: Keyways with top forming

Figure 61: Complete bridge with keyways after UHPC placement and top forming

7.4 Keyway Grinding

Once the MT-UHPC was determined to have reached an appropriate strength for grinding, the forms were stripped from the top of the keyways and the MT-UHPC was ground to the top surface of the beam elements. The stripped UHPC prior to grinding is shown in Figure 62, the grinding process is shown in Figure 63, and the bridge immediately after grinding is shown in Figure 64.

Figure 62: Keyways after removal of wood slats, just prior to grinding

Figure 63: Bridge during grinding process

Figure 64: Bridge deck immediately after keyway grinding

At several locations across the bridge, the top surface of the UHPC contained a significant amount of air pockets after grinding, which was most likely due to insufficient depths of UHPC in these locations. Therefore, the decision was made by MDT to epoxy-coat the top surface of the UHPC. The finished keyways before and after the application of epoxy are shown in Figure 65 and Figure 66, respectively. The bridge with all keyways epoxied is shown in Figure 67.

The strength of the MT-UHPC within the keyways was monitored via the maturity method and embedded thermocouples throughout the keyways. Once the keyways reached the required minimum compressive strength of 4 ksi, the earthwork (e.g., backfilling and compaction) was completed on the approaches, and the bridges were opened to traffic. These approaches were paved at a later time and did not prohibit the opening of the bridge. Figure 68 shows the first vehicle to cross the first bridge after the keyways came to strength. The following section discusses the timeline for both bridges.

a) keyway b) keyway with air pockets

Figure 65: Keyways after grinding

Figure 66: Finished keyway after epoxy application

Figure 67: Bridge deck after epoxy application on all keyways

Figure 68: First vehicle to cross bridge after keyways reached required strength

7.5 Timeline of UHPC Related Activities

The total project timeline for each bridge spanned approximately 96 hours. The first 24 of which included the demolition of the old bridge and preparation of the site for the pile cap placement. This section specifically documents the UHPC implementation and related tasks, which took place over the course of approximately three days. The timeline for both bridges after demolition and site preparation are presented in figures 69 and 70. In these figures, the cure time for the MT-UHPC to reach the required 4 ksi compressive strength are highlighted in yellow.

As can be observed in these figures, the placement of MT-UHPC in the pile cap connections took 5-6 hours on both bridges, while placement in the keyways took approximately 3 hours. This difference in time is due to the fact that more material was placed in the pile caps (3 yd^3) than was placed in the keyways (2 yd^3). In regards to cure time, the pile caps took 11-13 hours to reach the required 4 ksi for construction loads, while the keyways took 20-23 hours to reach this strength. This contrast in cure time between the pile caps and keyways was largely due to variations in temperatures during curing. The pile cap connections were placed in the morning and were exposed to elevated daytime temperatures during curing, with direct sunlight exposure. Whereas, the keyways were placed in the afternoon and cured overnight at significantly lower temperatures (in the 20s °F). Further, the pile cap connections had a larger mass of concrete enclosed in the connection, where heat of hydration elevated the temperatures during curing. The keyways were significantly thinner and more exposed to the open air and lower temperatures. Longer cure times observed for the keyways resulted in a slight delay in the construction schedule. This could possibly be avoided in future applications by using heated blankets if low temperatures are expected.

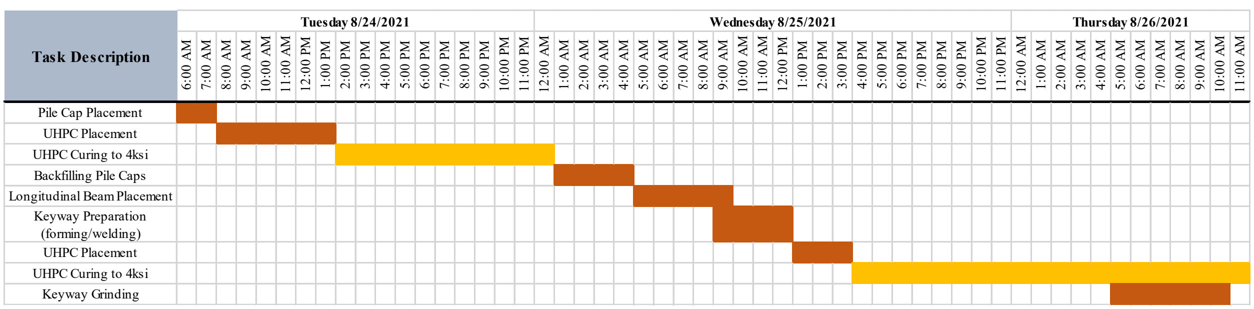

Figure 69: Timeline of UHPC related activities on the first bridge

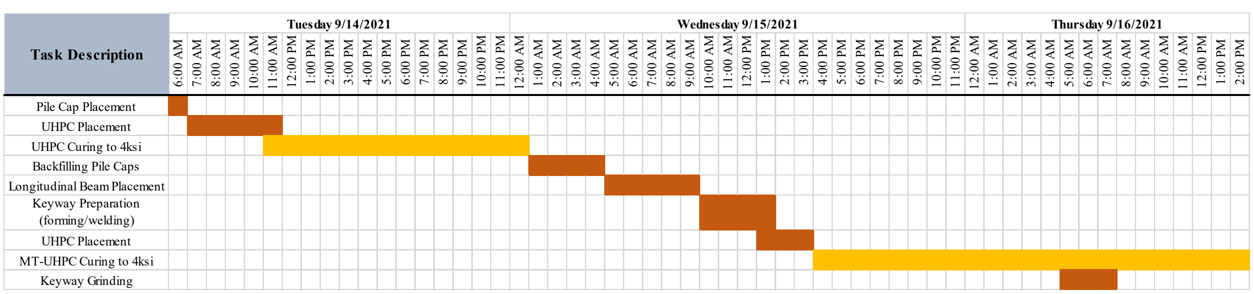

Figure 70: Timeline of UHPC related activities on the second bridge

7.6 Summary of UHPC Strengths

The results from the quality control testing of the MT-UHPC are provided in Table 11 for the first bridge and Table 12 for the second bridge. Included in both tables are the ambient air temperatures at the time of sampling, and included in Table 12 are the internal UHPC temperatures at the time of sampling. The compressive strengths reported in these tables are the averages of 2 cylinders that were obtained from mixes near the beginning, middle, and end of each day of UHPC placement. These cylinders were cured in a cure box on site until being transferred to the cure room at MSU. The quality control testing procedures are discussed in Section 5.4.

As can be observed in these tables, all MT-UHPC mixes reached the minimum specified compressive strength of 12 ksi at 28 days, with average strengths of 17.6 ksi and 17.5 ksi for bridge 1 and 2, respectively. All flows were greater than 10 in on the first bridge, while the flows on the second bridge had several samples with 9.5 in flows and one with 8.75 in. The decreased flows on the second bridge are most likely due to the increased wind observed at the job site during the construction of this bridge. However, all flows were within what was required for placement on the bridge.

As can be observed in both tables, temperature had a significant effect on the flow of the UHPC. That is, the flow was observed to decrease as the ambient and internal temperatures increased, whereas there is no clear trend in compressive strength with varying ambient or internal temperatures.

Table 11: Compressive strength and flow results from first bridge

Time Sampled	Date	Application	Spread (in)	Ambient Temp. (˚F)	28-day Strength (ksi)
8:45 AM	8/24/21	Pile cap	11	49	18.4
10:50 AM	8/24/21	Pile cap	11	61	18.8
1:05 PM	8/24/21	Pile cap	10.25	72	16.6
1:45 PM	8/25/21	Keyway	10.5	74	18
2:35 PM	8/25/21	Keyway	10	82	18.2
3:20 PM	8/25/21	Keyway	10	88	15.7

Table 12: Compressive strength and flow results for second bridge

Time Sampled	Date	Application	Spread (in)	Ambient Temp. (˚F)	Internal Temp. (˚F)	28-day Strength (ksi)
7:50 AM	9/14/21	Pile cap	11	42	61.6	18.5
10:00 AM	9/14/21	Pile cap	10.5	55	67.9	17.7
11:15 PM	9/14/21	Pile cap	10	62	71.9	16.7
1:45 PM	9/15/21	Keyway	8.75	82	78.4	17.6
3:00 PM	9/15/21	Keyway	9.5	84	75.4	16.5
3:50 PM	9/15/21	Keyway	9.5	84	76	17.8

7.7 Cost

The cost of using MT-UHPC in this project are provided in Table 13. These costs were estimated by the contractor after the completion of the project in November 2021. As can be observed in this table, the cost of the constituent materials was \$1550/yd^3, with the most expensive component being the steel fibers, which accounted for approximately half the total cost. These material costs include the freight from the source to the contractor's yard in Helena. The premixing and bagging of the dry mix was estimated to cost \$850/yd^3. This brings the total cost for the materials to \$2400/yd^3, including pre-bagging. The grinding of the UHPC after placement was estimated at \$370/yd^3, while the placement was estimated at \$1,790/yd^3, bringing the total cost of using MT-UHPC on this project to \$4560/yd^3.

Table 13: Cost of MT-UHPC per cubic yard

Item	Cost/cy
Cement	\$ 237
Silica Fume	\$ 174
High Range	\$ 204
Fly Ash	\$ 68
Steel Fibers	\$ 790
Sand	\$ 77
Materials Subtotal	**\$ 1,550**
Mixing/Packaging	\$ 850
Total Material Cost	**\$ 2,400**
Grinding	\$ 370
Placement	\$ 1,790
Total	**\$ 4,560**

8 MONITORING BRIDGE PERFORMANCE

The Trail Creek bridges were visited on October 28th, 2022, approximately 13 months after their completion. During this site visit, the bridges were inspected for general signs of damage, such as cracking, spalling, and debonding. As can be seen in the following figures (Figure 71-Figure 76), no significant damage was observed in the UHPC connections. It should be noted, that the UHPC cap-to-pile connections cannot be inspected due to their location under the deck panels. The only sign of deterioration in the bridges was the rusting of the steel fibers on the surface of the UHPC (Figure 72), and surficial rusting of several embedded pipes used in the connections between the deck specimens and the pile caps (Figure 75). It has been shown in previous research that the rusting surface fibers will eventually break and fall off, and due to the impermeable nature of this material, this rust will not propagate into the concrete and cause more rusting on the interior fibers.

Figure 71: Overview of east bridge

Figure 72: Closeup view of keyway joint in east bridge

Figure 73: Another closeup of keyway joint from east bridge

Figure 74: Overview of west bridge

Figure 75: Rusting of embedded pipe on deck-to-cap connection

Figure 76: Keyway overview from west bridge

9 SUMMARY AND CONCLUSIONS

This project began with an extensive literature review focused on previous field applications of UHPC. Subsequently, implementation research was performed with the intent of filling several research gaps related to the field application of MT-UHPC. This research investigated the effects of the mixing process, batch size, and temperature on the performance of MT-UHPC. It also developed maturity curves to be used in estimating the early strength gain of MT-UHPC. Trial batches were then conducted on site and placed into joint mockups to confirm and improve the construction methods to be used on the actual bridge project. In this exercise MT-UHPC was mixed using the same methods and under the same environmental conditions expected on the day of construction. MT-UHPC was then successfully used in two ABC bridges on Highway 43 around 17 miles west of Wisdom, MT. The MT-UHPC was used in the field-cast joints connecting the precast concrete bridge elements. Specifically, MT-UHPC was used in the: (1) connection between the piles and pile caps, (2) connection between the precast/prestressed longitudinal beam elements and the pile caps, (3) keyways between the beam elements, and (4) connections between the wing walls and pile caps. Based on this research, the following conclusions can be made.

Conclusions from the preliminary implementation research.

- MT-UHPC can be batched consecutively without cleaning the mixer in between batches.
- Batch sizes should be limited to 3 ft^3 when mixing MT-UHPC with IMER Mortarman 360s.
- MT-UHPC should be placed at low temperatures and when material temperatures are low to reduce the risk of the material stiffening and premature setting (which was observed to occur at elevated temperatures).
- Cure temperature should be accounted for when estimating the compressive strength of the material in the field, as temperature was observed to greatly affect the rate of strength gain. Specifically, increased temperatures resulted in a higher rate of strength gain and decreased temperatures delayed strength gain.
- Maturity curves developed in this research may be used to accurately estimate compressive strength of MT-UHPC in the field, regardless of cure temperatures.

Conclusions from the trial batches and joint mockups.

- MT-UHPC was successfully batched and mixed in the field using the exact materials, mixers, and methods to be used in the actual bridge project. The flows of the trial mixes were around 10 inches, and the compressive strengths exceeded the minimum specified 28-day strength of 12 ksi, with an average strength of 16.1 ksi.
- The methods used to form and place the UHPC in the connection mockups were primarily successful. However, the UHPC in the sloped-keyway mockup demonstrated the need for top forming the keyways, as the UHPC in these connections overflowed at the low end and fell short on the high end.
- Grinding the UHPC before it reaches a strength of 1 ksi resulted in a rough surface on the UHPC and steel fibers being pulled from the material. It is recommended that the MT-UHPC reach at least 3 ksi prior to grinding, as is specified in the Special Provisions.

Conclusions from bridge construction

- Pre-mixing and bagging the dry constituent materials (i.e., cement, fly ash, silica fume, and sand) was an effective/efficient strategy for the implementation of MT-UHPC in the field.
- The on-site batching and mixing methods worked well. However, the use of larger mixers should be investigated. The 3-ft^3 limit per batch resulted in an excessive number of mixes per application, which slowed progress on the bridge.
- The MT-UHPC was successfully mixed, batched, placed, and cured under varied environmental conditions. Specifically, temperatures ranged from the low 20s to the upper 80s (°F), and moderate winds were present. That being said, these varied environmental conditions did affect the behavior/performance of the UHPC. Specifically, low temperatures were observed to cause issues with mixing if the mixers were not warmed up prior to batching, and were observed to increase cure times. Whereas, elevated temperatures can cause mixes to setup prematurely in the mixer, and can cause mixes to stiffen up quickly during placement. Wind was observed to reduce workability during placement.
- The maturity method provided an efficient and accurate means for estimating the early strength of the MT-UHPC in the field, significantly reducing the number of cylinders required for testing and allowing for a more rapid indication of when the UHPC reaches the required strength for construction loads, which is especially important in accelerated bridge construction projects such as this.
- The top-forming method used on this project could be improved. The method used resulted in several locations with an insufficient depth of UHPC, requiring epoxy coating after grinding.
- The Special Provisions developed for this project were a good starting point for implementing MT-UHPC in a bridge construction project in Montana. However, they should be updated and modified for future projects to incorporate some of the key findings from this inaugural project.
- It was imperative to establish a good working relationship with the contractor and establish good lines of communication. The contractor on this project, Dick Anderson Construction, was a pleasure to work with, making this project possible.

Overall, this project was a successful demonstration of using a nonproprietary UHPC in field-cast joints for an accelerated bridge construction project. All placed UHPC had adequate flows, gained strength quickly, and reached the required minimum compressive strengths.

10 REFERENCES

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2. Berry, M., K. Matteson, and R. Scherr, *Feasibility of Non-proprietary Ultra-High Performance Concrete (UHPC) For Use in Highway Bridges in Montana: Phase II Field Application*. 2020, Montana Department of Transportation.

3. Graybeal, B., *Design and construction of field-cast UHPC connections.* 2014.

4. El-Tawil, S., et al., *Development, Characterization and Applications of a Non-Proprietary Ultra High Performance Concrete for Highway Bridges*. 2016, Univeristy of Michigan.

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6. Sritharan, S., et al., *First Application of UHPC Bridge Deck Overlay in North America.* Transportation Research Record, 2018. **2672**(26): p. 40-47.

7. Royce, M., *Utilization of Ultra-High Performance Concrete (UHPC) in New York*, in *First International Interactive Symposium on UHPC*. 2016.

8. Graybeal, B., *Construction of Field-Cast Ultra-High Performance Concrete Connections*. 2012, Federal Highway Adminstration, FHWA-HRT-12-038.

9. Graybeal, B., *Design and construction of field-cast UHPC connections*, C. Turner-Fairbank Highway Research, Editor. 2014.

APPENDIX A: UHPC SPECIAL PROVISIONS

The special provisions related to the application of MT-UHPC on the Trail Creek bridges are included below. These special provisions were created to prescribe the procedures and requirements of MT-UHPC for the project. The full-length special provisions can be found on the project website.

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(b) Consider all loads on the bridge including axle loads, outriggers, equipment dynamic forces, and wind forces on the load, the boom, and the equipment. Consider deflection and secondary force effects. Include traffic live load if the structure will carry traffic during equipment operations.

(c) Investigate different loading combinations for all configurations. Include the distribution of dead load and changing center-of-gravity of the equipment with and without load at different boom extensions, rotations, and elevations.

(2) Structural Effects. Identify critical members. Determine any conditions under which the equipment cannot safely operate.

b) Written Report. Provide a report containing a narrative summarizing the results of the analysis. Describe special measures necessary to protect the structure through all phases of the equipment's positioning and use. Include drawings as necessary and indicate any minimum equipment clearances to relevant portions of the structure and to traffic flow. Estimate the work's duration.

c) MDT will consider equipment submitted under this contract for addition to the ACEL.

D. Method of Measurement. Work associated with this provision is not measured for payment.

E. Basis of Payment. Include all costs associated with the requirements of this provision in the cost of other items.

47. CONCRETE – CLASS MT-UHPC [STPP 46-2(16)9]

A. Description. This work includes furnishing, forming, placing, curing, and finishing a Montana sourced Ultra-High Performance Concrete (MT-UHPC) for the pile-to-pile cap connections, longitudinal deck joints, and dowel joints as specified in the plans.

B. References.

1) MSU MT-UHPC Research Team as defined in this specification:

a) Contact: Dr. Michael Berry
Phone: 406-994-1566
Email: berry@montana.edu

b) Contact: Dr. Kirsten Matteson
Phone: 406-994-6125
Email: Kirsten.Matteson@montana.edu

2) The MT-UHPC material in this specification is based on MDT research: "Feasibility of Non-Proprietary Ultra-High Performance Concrete (UHPC) for Use in Highway Bridges in Montana". Additional information is available at: https://www.mdt.mt.gov/research/projects/mat/high_performance_concrete.shtml.

3) Information relating to implementation, materials, and mixing requirements is available at: https://www.mdt.mt.gov/other/webdata/external/research/DOCS/RESEARCH_PROJ/BRIDGE_UHPC_2/Materials-and-mixing.PDF.

C. Materials.

1) Use ultra-high performance concrete for connection locations shown on the plans. Source, mix, and place the MT-UHPC as directed by the MSU MT-UHPC Research Team.

2) The minimum compressive strength of the MT-UHPC prior to backfilling around pile caps, operating compaction equipment near the structures, or placing beams on the pile caps is 4000-psi. The minimum required compressive strength at 28-days is 12,000-psi.

3) Furnish material constituents for the MT-UHPC in accordance with 551 except where specified directly by the MSU MT-UHPC Research Team.

4) Furnish high carbon steel fibers with a minimum tensile strength of 290-ksi. The steel fiber reinforcement is to be steel chord type Bekaert DRAMIX® OL 13 / .20.

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5) Source, handle, and store all required materials as directed by the MSU MT-UHPC Research Team.

6) Develop a mix design based on the requirements herein and according to the MSU MT-UHPC Research Team's instructions.

D. Submittals. Submit the following items for approval by the Project Manager:

1) The proposed mix design which includes the sources of the constituents, the batch proportions, the mixing procedure, and compression strengths at intervals described in this specification.

2) Quality control plan that includes:

a) mixing protocol as required by direction from the MSU MT-UHPC Research Team and as defined during the mockup work detailed in this specification,

b) placement procedures, and

c) curing procedures.

3) Proposed equipment including buggies, grinding equipment, and any other equipment that will be used to place, cure, and finish the field joints.

4) Method of forming the joint pours in accordance with recommendations by the MSU MT-UHPC Research Team.

5) Pour sequence plan including staging areas for materials and equipment as well as the anticipated total time to complete the work.

6) Grinding procedure, if applicable.

E. Construction Requirements.

1) The State will furnish two high shear pan mixers required for mixing the MT-UHPC. Two UHPC mixers on site is a minimum requirement for continuity of material supply and for redundancy purposes. Additional mixers are not required, but if utilized, are the responsibility of the Contractor and must be approved by the Project Manager.

2) Concrete Mixers. Transport the two State furnished mixers from the Structures Laboratory at Montana State University - Bozeman to the construction site. Contact the MSU-MT Research Team and Tyler Steffan at (406) 444-7800 or Nathan Haddick at (406) 444-9400 a minimum of 10 days before transportation and return delivery of the concrete mixers. Upon completion of the final usage of the mixers on the project, return to the Structures Laboratory at Montana State University - Bozeman. Provide the equipment necessary to load and unload the concrete mixers.

3) The Contractor is responsible for the condition of the UHPC concrete mixers. Any damage incurred due to mishandling during loading, handling, transport, incorrect usage, or subjecting to inappropriate operation is the responsibility of the Contractor and must be repaired at the Contractor's cost prior to return to the Department. The concrete mixers must be used and cleaned per the equipment manufacturer's instructions and any additional recommendations provided by the MSU MT-UHPC Research Team.

4) Temperature limitations. Do not place UHPC at air temperatures below 40oF nor above 80oF.

5) Cure times and Compressive Strengths. Establish the cure time of the MT-UHPC required to meet the project schedule and compressive strength requirements defined in this specification.

6) Joint Mockup.

a) Construct a mockup to simulate conditions for mixing, placing, curing, and surface finishing the MT-UHPC for the pile-to-pile cap connection and the longitudinal deck joint. The mockup for the longitudinal deck joint (i.e. keyway) should be a minimum of 10-ft. If necessary, modify operations and/or the mix design as approved by the Project Manager to successfully place and cure the mockup field joints per this specification and plan set.

b) Demonstrate the ability to mix and place the MT-UHPC, to provide formwork to contain the concrete within the joints, and establish cure times to meet the project schedule and all requirements defined in this specification, and as directed by the Project Manager.

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c) Use the same staff, equipment, forming, mixing, placing, and curing procedures as will be used for the production bridge joints.

d) Perform the field trial batch under the same ambient conditions (time of day, weather, temperature, etc.) as expected during construction for each joint location (the pile-to-pile cap connection and the longitudinal deck joints). If the ambient conditions are expected to be similar for both bridges, a single successful mockup is adequate.

e) Include in the mockup a demonstration of grinding, or other finishing methods, of the MT-UHPC that will be used for the longitudinal joints of the bridge.

f) Notify the Project Manager a minimum of 72 hours prior to the mockups. The Project Manager will coordinate with the Bridge Bureau and Montana State University researchers to be on-site for the mockup demonstration.

g) If desired results are not achieved as determined by the Project Manager in consultation with the technical representatives from MDT and Montana State University, modify the process accordingly and complete another UHPC test pour. Continue until a UHPC test pour is completed successfully. Document the procedures, tools, forms, and any other equipment implemented in this successful completion. Use the same methods in completing final UHPC closure pours.

h) Support and provide access to MDT and/or the MSU Research Team for obtaining the results of temperature, slump, and unit weight measurements for a minimum of two independent samples.

i) Provide concrete for compressive strength testing for the MT-UHPC mix used in the mockup pours. Use 3-in by 6-in cylinders with three cylinders tested for each compressive strength result. Cure and test all test samples using the same method of curing and testing as specified during construction.

7) Forms. Construct watertight forms that are coated to prevent absorption of water similar to approved methods established during the mockups and approved by the Project Manager.

8) Quality control.

a) Follow the approved procedures and methods developed, defined, and approved during the mockup work detailed in this specification.

b) Make five sets of 3-in x 6-in compressive strength test samples for each day of placement. Three cylinders are to be tested and averaged for each compressive strength result. Cure all sets in an environment similar to the material and application they represent.

c) Except for the curing requirements, perform the following tests in accordance with ASTM C39 to establish early and final compressive strength requirements for acceptance. Grind the loading surfaces of the cylinders to ensure end planeness within 1/10 of a degree. Test all cylinders by a testing lab approved by the Project Manager and the MSU MT-UHPC Research Team. Unless otherwise specified by the MSU MT-UHPC Research Team or as approved by the Project Manager:

(1) Test the first set for compressive strength at 12-hours. These cylinders will be field cured.

(2) Test the second set for compressive strength at 36-hours. These cylinders will be field cured.

(3) Test the third set at 28-days. These cylinders will be cured in accordance as recommended by the MSU MT-UHPC research team or the Project manager.

(4) The fourth and fifth sets will be collected and cured by MDT as applicable.

9) Concrete Placement. Comply with the recommendations and procedures established during the mockup pour and approved by the Project Manager. Limit free fall height to 2-feet to prevent segregation of steel fibers. Fill the joint at a speed comparable to the flow speed of the fresh mix and as directed by the MSU MT-UHPC research team. Place the UHPC joint in a continuous operation. Unless otherwise approved by the Project Manager, fill the joint

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0.5-in higher than the top surface of the deck to allow entrapped air to rise in this zone during curing.

10) Curing. Cover and cure the UHPC as established during the joint mockup and as approved by the Project Manager. Do not place any loading on the UHPC joint until the UHPC has achieved a minimum compressive strength of 4000-psi. Construction loading on the bridge during UHPC placement and curing are the responsibility of the Contractor.

11) Grinding. Once the UHPC has obtained 3-ksi compressive strength, or as further determined during the mockup joint work and approved by the Project Manager, grind the UHPC surface flush with the adjacent voided slab deck segments. A 1/8-in variation in the top of the UHPC joint and the adjacent voided slab deck surface is considered acceptable if an overlay is provided over the entire deck surface. Suspend grinding operations if significant steel fiber pullout is observed. Do not resume grinding until directed by the Project Manager.

F. Testing and Acceptance. The MT-UHPC material acceptance will be based on compressive strength requirements and surface finish requirements as provided in this specification. Other standard material properties will be measured and monitored based on research requirements but will not be considered in the acceptance criteria. Extra material and test data such as, but not limited to, slump, air voids, or unit weight for the fresh MT-UHPC must be made available by the contractor to assist in this effort.

G. Method of Measurement. Concrete – Class MT-UHPC as defined in this specification is measured in accordance with Standard Specification 552.04.

H. Basis of Payment. This item, and all incidental items required to provide this item, per contract documents including labor, materials, equipment, trial batches, up to two mockups, and testing are to be included in the unit price bid for Miscellaneous Items. The first two mockups are incidental and any beyond 2 will be measured and paid for under Miscellaneous Work.

48. <u>PRESTRESSED VOIDED SLAB BEAMS [STPP 46-2(16)9]</u>

A. Description. The beams specified on the plans are precast, prestressed concrete voided slabs that provide the structural support and the riding surface for the bridge.

B. Materials. Use Concrete - Class Pre that includes between 5% to 8.5% entrained air. Maximum f'_c for design is 7.5ksi.

C. Construction Requirements.

1) Contractor Dry Fit.

a) Dry fit the prestressed voided slab beams, precast pile cap substructure, and wingwalls prior to shipment to the project site. Provide continuous support beneath the precast pile caps during the dry fit, not to exceed 1ft on center.

b) Erect the precast elements to the final grades shown on the drawings and verify the fit to within the specified tolerances. All precast members must be deemed acceptable during the dry fit process before shipment to the project.

c) Provide the Project Manager at least 3-weeks' notice before performing the contractor dry fit of precast elements to allow for inspection.

2) Silane Sealer. Apply a silane sealer to the grouted keyways a minimum of 14-days after grouting the beam keyways.

3) Weld Ties. Use stainless steel meeting the requirements of ASTM A276; Type 304 for all plates, rods, and anchors for welded tie beam connections. All welding must be in conformance with AWS D1.6 and welders certified to use a 308 rod.

D. Method of Measurement. Prestressed voided slab beams are measured by the Linear Foot of beam installed and accepted.

E. Basis of Payment. Payment for the completed and accepted quantities at the contract unit price is full compensation for all necessary resources required to complete the items of work in accordance with the contract.