MT-UHPC OVERVIEW AND BEST PRACTICES

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, commercially available/proprietary mixes can be quite expensive, costing significantly more than conventional concrete. In an effort to reduce the costs of using UHPC and open the door to using this material more regularly in Montana, the Montana Department of Transportation (MDT) funded several research efforts at Montana State University (MSU) focused on developing and testing a nonproprietary UHPC. This document provides a brief summary of the research projects that have been completed at MSU thus far, followed by best practices that should be followed to implement this material in Montana bridge projects.

Summary of Completed Research

Phase I: Development of Non-proprietary Ultra-High Performance Concrete [1]

The overall objective of this research was to develop and characterize economical non-proprietary UHPC mixes made with materials readily available in Montana. This objective was achieved by first identifying and obtaining suitable/economical materials to be used in UHPC. Specifically, the materials identified and used in this research were simply Type I/II portland cement, class F fly ash, fine masonry sand, silica fume, and high range water reducer. UHPC mixes were then developed/characterized/optimized by using a statistical experimental design procedure (response surface methodology). An optimal mix that provided desired workability and strength was selected for further evaluation through a suite of mechanical and durability tests, which clearly demonstrated the exceptional performance of this material. The mixes developed as part of this research obtained compressive strengths of approximately 20 ksi with flows of 8-11 inches. The mechanical properties tested in this research were compressive and tensile strength, elastic modulus, and shrinkage. Durability tests included alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze- thaw resistance, and scaling.

Phase II: Feasibility of Nonproprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Field Application [2]

The overall objective of this phase of research was to further develop and characterize the MT-UHPC developed in Phase I. Specifically, this research focused on (1) investigating the potential variability in performance related to differences in constituent materials, (2) investigating issues related to the field batching/mixing of these UHPC mixes, and (3) testing rebar bond strength and studying how this will affect requisite development lengths.

Based on this research, it was determined that, while variations in the source of the constituent materials had some effects on performance, the effects were fairly minor, with all recorded flows and 28-day compressive strengths exceeding 6 inches and 16 ksi, respectively. Further, in regard to the effects of mixing/batching conditions, only temperature was observed to have a significant effect on performance, with flows and set times decreasing with increasing temperature. Regarding the pullout tests, all the specimens that met the minimum embedment depth requirements specified by the FHWA yielded prior to concrete bond failure, indicating the suitability of these recommendations for the MT-UHPC developed in this research.

Phase III: Feasibility of Nonproprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Implementation [3]

The focus of this phase of research 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 (Figure 1). 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.

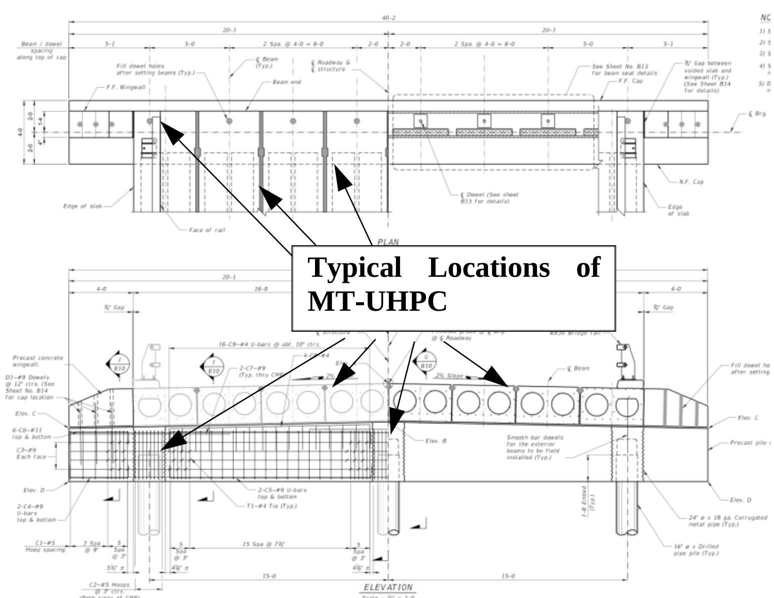

Figure 1: Trail Creek Bridge Structural Drawings

Phase IV: Exploration of UHPC Applications for Montana Bridges [4]

The focus of this research was on investigating additional applications of UHPC in bridges, specifically its use as a bridge deck overlay. A material-level evaluation was performed on three UHPC mixes, primarily focusing on workability, compressive strength, tensile strength, and tension and shear bond strengths. Based on this material-level evaluation, a thixotropic version of a proprietary mix was chosen for subsequent structural testing due to its ability to be batched in large quantities. Five slab specimens were tested to determine the effects that including a UHPC overlay would have on the overall behavior of the slab. The testing demonstrated that including UHPC overlays increased the ultimate moment capacity of the slabs, even with the specimens that had a weak substrate concrete. Test results were also compared with ACI 318 predictions, which demonstrated that these methods were conservative for predicting the flexural capacity of concrete slabs, underpredicting the capacity by 18-33%. Overall, the results were promising and shed light on how a UHPC overlay may improve the overall performance of an existing bridge decks.

Materials, Batching, and Mixing

This section will present a summary of materials used in MT-UHPC, followed by a description of the batching, mixing, placing and finishing processes.

Materials

The requisite materials for making the Montana UHPC are water, portland cement, fly ash, silica fume, high range water reducer, steel fibers, and fine aggregates. The mix design for 1 cubic yard of the MT-UHPC are provided in Table 1.

Table 1: UHPC Mix Design (1 cy)

Item	Amount (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

The following provides a brief discussion of each material used in MT-UHPC. More detailed information can be found in the references cited above.

Cement: the cement primarily used in this research was a Type I/II/V cement from the GCC cement plant in Trident MT, although any Type I/II cement should suffice. That being said, slight modification to the mix design may be required if another cement source is used.

Fly Ash: any class F fly ash should be suitable for use in the MT-UHPC, as several class F fly ashes were tested throughout the research and all performed well within the MT-UHPC. However, as was the case with varying the portland cement source, the mix design may need to be slightly modified.

Silica Fume: The only silica fume tested in this research was supplied by BASF, and is readily available from this company.

HRWR: Only CHRYSO Premia 150 water reducer should be used in MT-UHPC. Other water reducers were tested in the original mix development, but CHRYSO Premia 150 was chosen because it provided adequate flows with the least amount of entrapped air.

Steel Fibers: The steel fibers used in MT-UHPC were 13 mm long, had a diameter of 0.2 mm, and had a specified yield stress of 285 ksi. While these fibers are available from several suppliers, only fibers from HiPer Fiber are domestically produced and meet Buy America requirements.

Fine Aggregate: The fine aggregate should be a finely-graded masonry sand, as this type of sand was found to perform well within this mix. Further, this sand should be oven dried so that no moisture content correction needs to be made during mixing. Further, as was done in the Trail Creek bridges, the contractor opted to premix all dry components of the mix (i.e., cement, fly ash, silica fume, and sand) prior to arriving at the job site, and therefore having no moisture in the sand is imperative. A sand that meets these specifications is readily available from the QUIKRETE supplier in Billings.

Table 2 provides a summary of the materials used in MT-UHPC along with potential suppliers in Montana.

Table 2: Materials

Material	Type	Supplier
Portland Cement	Type I/II	GCC Trident Cement Plant
Fly Ash	Class F	QUIKERETE/Prairie State
Silica Fume	MasterLife SF 100	BASF
High Range Water Reducer	CHRYSO Fluid Premia 150	CHRYSO Inc.
Steel Fibers	Type A: Straight Steel Fibers	HiPer Fiber Solutions
Fine Aggregate	Dried Masonry Sand	QUIKRETE Billings

Batching and Mixing

MT-UHPC is mixed with high-shear horizontal mortar mixers similar to one shown in Figure 2. It should be noted that the capacity of this type of mixers can be quite small (10-27 ft^3) relative to a conventional concrete mix truck (10 yd^3). Further, mixing MT-UHPC is quite demanding on the mixer and thus the batch sizes of UHPC are limited to around 3-10 ft^3, depending on the capacity of the mixer. Throughout MSU's research, IMER Mortarman 360s were used to mix MT-UHPC, which could reliably mix batch sizes of around 3 ft^3.

The mixing procedure for MT-UHPC is as follows:

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

Upon completion of the procedure above, the UHPC should be placed as soon as possible, and UHPC left in the mixer should be continuously mixed on low until placed.

To save time during construction and to ensure proper proportions, the dry ingredients (cement, fly ash, silica fume, and sand) can be weighed, premixed, and bagged prior to arriving on the job site, as was done during the Trail Creek field demonstration project discussed in the introduction. During this project, 3-ft^3 batches of MT-UHPC were premixed according to the procedures outlined above and placed into sling bags. Once mixed, the sacks of MT-UHPC were stored in a shipping container shown in Figure 3. 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. During construction, the premixed dry ingredients were added to the mixer by hoisting a premixed sack and depositing it in the mixer through the hole in the bottom of the sack, as shown in Figure 2. The HRWR and mix water were weighed on site, and then added to the mixer, at which point the procedure outlined above was followed. After this mixing was complete, the MT-UHPC was removed from the mixer and placed.

Figure 2: Sack of dry mix being added to the mixer

Figure 3: Sacks of MT-UHPC in storage container

Temperature Effects

Temperature can have a significant effect on the performance of MT-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 concrete. To counteract the negative effects of casting MT-UHPC at high temperatures, ice can be used to directly replace a portion of the mix water (a replacement of 50% was successfully used in this research). Low temperatures can delay reactions during the mixing process causing the mix to fail, and will delay the cure time and strength gain of the concrete.

During the Trail Creek project, 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. However, as expected these varied environmental conditions did affect the behavior/performance of the UHPC, but the effects on the mixing and placement of the UHPC were fairly minor, and the effects on strength gain were accounted for by using the maturity method.

The maturity method was shown to be 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.

Placement, Finishing, and Grinding

Because of limited batch sizes for MT-UHPC, governed by the capacity of the high shear mixers, the use of MT-UHPC is limited to smaller applications such as connections of precast elements, and repairing localized damage in bridge decks and girders. The initial research phases conducted at MSU focused primarily on its use in field-cast joints between precast elements.

In applications in which the surface of the MT-UHPC is to be exposed, special procedures must be followed to ensure a clean, consolidated surface. As is common with all UHPC, air within the mix can get entrapped near the top surface during the initial set. Therefore, the MT-UHPC must be cast ½ inch above the surface of the concrete to facilitate grinding of this surface after setting (Figure 4). Further, if the specimen is sloped, top-forming may be required to ensure even placement within the joint (Figure 5). If this top forming is not present, the MT-UHPC will overflow the formwork on the low end of the specimen and not completely fill the joint on the high end. After setting and removal of the formwork, the MT-UHPC should be ground to the desired height. This grinding should not take place until the MT-UHPC reaches a strength of at least 3 ksi.

Expected Properties and Test Methods

The methods and materials discussed herein should produce MT-UHPC with compressive strengths of around 18 ksi, be self-consolidating with flows around 9-10 in, and have durability properties that far exceed those of conventional concrete. The test procedures outlined in ASTM C1856 should be used to determine the flow and mechanical properties of the MT-UHPC. These procedures specify that compressive strength of UHPC should be determined by testing 3 inch by 6 inch cylinders. Because of the high strengths expected for UHPC, standard caps (e.g., neoprene, sulfur) cannot be used when testing these specimens, and therefore a cylinder end grinder must be used to prepare the cylinders for testing. MSU's research clearly demonstrated the efficacy of using the maturity method to determine the strength of UHPC, which was especially helpful in determining the early strength of MT-UHPC in the field.

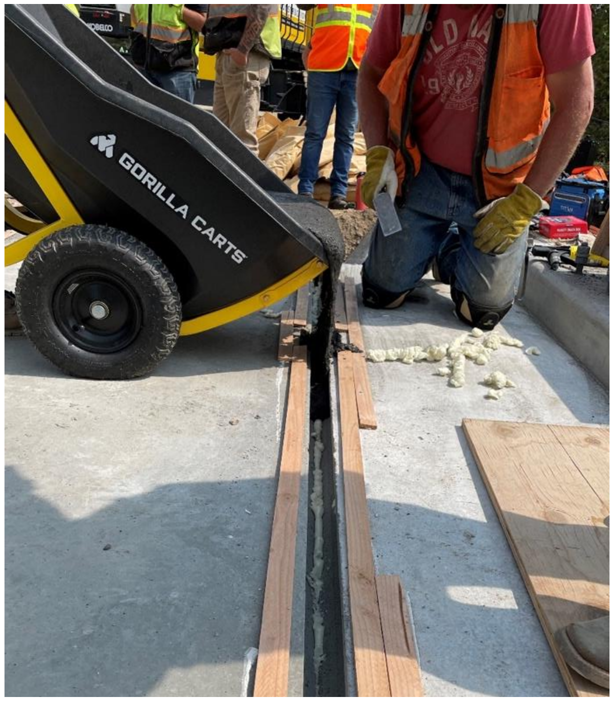

Figure 4: UHPC directly added to keyway with ½-in strip for overcasting

Figure 5: Keyways with top forming

Conclusion

This work has resulted in a cost-effective and locally optimized UHPC that has shown promise for enhancing Montana's infrastructure with a material that balances performance and affordability. The successful use of MT-UHPC in projects, including the Trail Creek bridges, underscores its potential for varied applications across the state. This initiative not only offers a practical solution for Montana's construction needs but also provides insights that could be valuable for the development of other advanced materials and subsequent applications, contributing to the evolving landscape of sustainable construction practices.

References

1. Berry, M., R. Snidarich, and C. Wood, *Development of Non-Proprietary Ultra-High Performance Concrete*. 2017, Montana Department of Transportation.

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. Berry, M., E. Hendricks, and K. Matteson, *Final Report: Feasibility of Non-Proprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Phase III Implementation*. 2023, Montana Department of Transportation.

4. Starke, J., K. Matteson, and M. Berry, *Final Report: Exploration of UHPC Applications for Montana Bridges*. 2024, Montana Department of Transportation.