# Task 1 Report – Literature Review

**Project Title**: Feasibility of Non-Proprietary UHPC for Use in Highway Bridges in Montana

**Submitted By**: Dr. Michael Berry, Assistant Professor in Civil Engineering
Civil Engineering Department, Montana State University – Bozeman

**Submitted to**: Kris Christensen, Project Manager
Montana Department of Transportation, Research Programs

**Date Submitted**: July 2016

# 1 Introduction

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. Thus, elements made with UHPC have longer service lives, decreased maintenance costs, and are thinner/lighter than elements made with conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes exceeding $1,000 to $2,000 per cubic yard, which is about 10 to 20 times the cost of conventional concrete. The overall objective this project is to develop and characterize non-proprietary UHPC mixes made with materials readily available in Montana. These mixes are anticipated to be significantly less expensive than commercially available UHPC mixes, thus allowing for the use of UHPC in construction projects in Montana. In particular, the MDT Bridge Bureau is interested in using UHPC as a field-cast jointing material between precast concrete deck panels and girders and between the flanges of adjacent girders.

The specific tasks associated with this research are as follows.

Task 1 – Literature Review

Task 2 – Mix Designs and Validation of Key Properties

Task 3 – Comprehensive Determination of Material Properties

Task 4 – Analysis of Results and Reporting

This report documents the work completed as part of Task 1 – Literature Review. It should be noted that this literature review will continue to be updated as new research on this subject becomes available. This report discusses: (1) the general background of UHPC and an overview of previous research that has been conducted, (2) specific research performed on non-proprietary UHPC blends, and (3) research that has been conducted related to the proposed application.

# 2 Background

UHPC is a term used to describe concrete composites having compressive strengths in excess of 20 ksi, post-cracking tensile strength of at least 0.72 ksi, and a discontinuous pore structure that improves durability by limiting permeability. This material was initially introduced in the early 1990s and was referred to as reactive powder concrete (RPC). Early UHPC designs required the use of special mixing techniques, as well as steam curing. A significant amount of research has been conducted to develop UHPC that can be mixed and cured using more conventional methods (B. Graybeal & Tanesi, 2007; Wille, Naaman, El-Tawil, & Parra-Montesinos, 2012). The exceptional properties of UHPC are achieved with: (1) low water-to-cement ratios, (2) high particle packing density, (3) high quality aggregates and cements, (4) supplemental cementitious materials, (5) high particle dispersion during mixing, and (6) in some cases the incorporation of fiber reinforcement. As mentioned above, high particle packing density (low porosity) is one of the key principles surrounding UHPC design. Previous research has shown that there is a strong correlation between the mechanical performance of the cementitious paste and its rheological behavior, and changes in particle packing density can be indirectly evaluated with a spread test performed in accordance with ASTM C230 (Wille, Naaman, & Parra-Montesinos, 2011). Achieving the highest possible packing density of the granular constituents is one of the primary factors leading to the reduction of porosity in UHPC. This is achieved through the use of a combination of fine aggregates, silica fume, cement, and supplemental materials (Wille & Boisvert-Cotulio, 2015; Zdeb, 2013). Another important factor in the reduction of porosity of UHPC is a decrease in water-binder ratio. UHPC by definition has a very low water-binder ratio, generally ranging from 0.2 to 0.3 by weight. By increasing the particle packing density the volume of water-filled voids within the paste is reduced. By physically trapping less water in voids, more water is available to coat the surface of the particles, which leads to an overall reduction of paste viscosity. This improved rheological behavior allows the water-cement ratio (w/c) to be reduced while still maintaining adequate workability. This reduction in w/c is one of the key requirements for producing high-strength paste, and subsequently UHPC (Wille & Boisvert-Cotulio, 2015). Additionally, this low w/c helps to limit the amount of unreacted water found, thus decreasing the formation of capillary pores during the setting process and maintaining the necessary low porosity (Zdeb, 2013).

UHPC's high compressive strength, pre- and post-cracking tensile strength, and high durability make it a suitable material for use in structures. Although the initial cost of UHPC far exceeds conventional concrete mixes, the use of UHPC has been shown to reduce life-cycle costs (Piotrowski & Schmidt, 2012), as the increased durability of UHPC results in a longer service life and decreased maintenance costs. Further, the use of UHPC can result in smaller/lighter structural elements, thus using less material. Oftentimes, high strength steel fibers are required for these composites to achieve specified ductility and toughness requirements, and are commonly referred to as ultra-high performance fiber reinforced concrete (UHP-FRC) (Wille & Boisvert-Cotulio, 2015; Wille et al., 2012).

UHPC became commercially available in the U.S. through several proprietary sources around the year 2000. Since its introduction to the commercial market, the use of UHPC in various applications has been the focus of multiple research endeavors. Specifically, UHPC has been used in field-cast connections of prefabricated bridge components (Benjamin A Graybeal, 2010b), precast/prestressed girders (Jon "Matt" Rouse, 2011), precast piles (Dr. Terry Wipf, 2011; Ng, Garder, & Sritharan, 2015), and waffle-type bridge decks (S. Aaleti & Sritharan, 2014; S. R. Aaleti, Sritharan, Bierwagen, & Wipf, 2011; Honarvar, Sritharan, Rouse, & Aaleti, 2016). Additionally, the seismic performance of UHPC elements/connections has been the subject of several research efforts (Lee, Huang, Song, & O'Connor, 2014; Zohrevand & Mirmiran, 2013). It should also be noted that the use of UHPC in transportation applications has been actively researched/promoted by the Federal Highway Administration (FHWA, 2013; Goodspeed, Vanikar, & Cook, 2013; B. Graybeal, 2006a, 2006b, 2011, 2012; J. Yuan, and Graybeal, B., 2014; J. Q. Yuan & Graybeal, 2015). Of particular interest to the proposed use of UHPC, this research included a study on the bond properties of UHPC (J. Yuan, and Graybeal, B., 2014; J. Q. Yuan & Graybeal, 2015), and these findings are discussed below. Although the use of UHPC in these varied applications has been shown to be beneficial, a majority of this research has used commercially available/proprietary mixes, the cost of which has hindered its widespread use in infrastructure projects (as is the case in the proposed use discussed herein). These proprietary mixes range in cost from $1,000-$2,000 per cubic yard, which is 10 to 20 times the cost of conventional concrete.

While much of the material optimization of UHPC is done to improve its mechanical and structural behaviors, this optimization also leads to an improvement of its durability. B. Graybeal and Tanesi (2007) performed a comprehensive study focusing on the performance of UHPC subjected to standard durability tests. They found that the dynamic modulus of tested samples was 96% or greater after performing ASTM C 666 freeze-thaw cycles. After performing ASTM C 1260 tests, the results show that there is little concern for alkali-silica reaction (ASR) problems in UHPC. Unintended curing of UHPC may take place during the testing process, but due to the low permeability and high silica fume content, UHPC is not susceptible to ASR. UHPC performed exceptionally well during ASTM C 672 scaling test, as well as AASHTO T259 chloride ion penetration tests. Untreated (traditionally cured) specimens showed chloride ion penetration that ranged from very low at 28 days to negligible at 56 days when subjected to ASTM C 1202 testing.

In addition to UHPC, a fair amount of research has been conducted on engineered cementitious composites (ECC). ECC are a class of high-performance fiber-reinforced cementitious composites. They feature moderate compressive strengths (4.3 to 10.2 ksi) and high ductility while utilizing medium fiber contents. ECC can achieve tensile strain capacities from 3 to 6% compared to commercial UHPC with a tensile strain capacity of 0.1% (Ranade, Li, Stults, Heard, & Rushing, 2013). These large strain capacities are achieved by the development of multiple cracks rather than a continuous increase of crack widths (Li, 2003; Wang & Li, 2007). ECC has been successfully utilized for dam repair, bridge deck overlays, coupling beams, and various structural elements (Li, 2004) Extensive research in the development of this material has been conducted by the University of Michigan, including the testing of a full scale ECC link slab used to replace expansion joints on simply supported bridges (Lepech & Li, 2009).

## 3 Non-Proprietary UHPC Research

In 2011, Wille et al. (2011) performed research focused primarily on optimizing the proportions of UHPC constituents using materials commercially available in the U.S. In the first phase of the study, the compressive strengths and the rheological behavior of 38 paste mixtures were evaluated. These 38 mixes quantified the effects of various cement types (C), w/c ratio, silica fume (SF) types, as well as the type and dosage rate of high range water reducer (HRWR). Glass powder (GP) was used as the supplementary cementitious material (SCM) in these mixes. From this study, it was found that a proportion of C:SF:GP of 1.0:0.25:0.25 provided optimum spread values. It was also noted that adjusting these proportions resulted in very little change of observed compressive strength, but did result in changes in spread, which indicated improved particle packing density of the paste. Additionally, it was observed that by optimizing particle packing density of the powder constituents, acceptable flow values were observed with HRWR dosage rates of 1 to 8% by cement weight. Reducing the dosage rate to the lowest possible amount also resulted in higher compressive strengths. Once an optimized paste was determined, two types of fine silica sand were introduced at a proportion of 1.4 by cement weight. This ratio was used to keep the amount of cement low and therefore reduce shrinkage. Compressive strengths of 23.6 to 29.1 ksi were achieved during this phase of the study, with the largest compressive strength observed with the addition of high strength steel fibers at a ratio of 2.5% by volume. Additional research conducted by Wille et al. (2012) included more focused research on the performance of UHPFRC. By utilizing twisted high strength steel fibers at a proportion of 8% by volume, the researchers were able to achieve compressive strengths up to 42 ksi and tensile stresses up to 5.4 ksi with a peak strain of 1.1%. These values were achieved without the use of any special curing or mixing techniques.

A research study recently completed by (FHWA, 2013) demonstrated promising advances in the development of non-proprietary UHPC mixes with material costs ranging from \$355 to \$500/yd$^3$ for non-fiber-reinforced mixes (adding fiber reinforcement increases the material costs by \$470/yd$^3$). This study used a three level approach to develop suitable UHPC mix designs for various regions in the U.S. Level 1 focused on optimization of the cementitious paste. This study considered mechanical performance, durability, rheological properties, and economy. The effects of various types of SCMs were also examined. The SCMs used in this study were GP, metakaolin, fly-ash (FA), limestone powder, and ground granulated blast furnace slag (GGBS). The influences of the various SCMs were monitored using the spread value of the paste and compressive strength, and the pastes in this study were compared to the reference pastes developed by Wille et al. (2011). The second level of the study examined the performance of the cementitious matrix and the effects of different types of aggregates, the size of aggregates (fine and coarse), as well as the ratio of aggregate to cement by weight. Typical aggregate sources for three regions in the U.S. (Northeast, Upper Midwest, and Northwest) were considered, as well as pure quartz aggregate. Similar to the evaluation of the paste, spread values and compressive strengths were used to evaluate the performance of the cementitious matrix. Level three of this research examined the effects of five various commercially available fibers and their effect on the performance of the concrete composite. These fibers included both straight and deformed high strength steel fibers, straight polyvinyl alcohol fibers, and alkali resistant glass fibers. The performance of the fiber reinforced composite was determined primarily by its tensile strength. Additionally, stress-strain behavior under compressive loading was examined, as well as freeze-thaw resistance in accordance with ASTM C666. The best tensile performance was achieved with straight high strength steel fibers with a maximum tensile strength of 1.15 ksi, and after 108 freeze thaw cycles no visible deterioration was noticed. After completion of this study, four fine aggregate and three coarse aggregate UHPC mixes were recommended. The material costs of these composites range between $360 and $500 per cubic yard and $355 and $380 per cubic yard respectively (addition of steel fibers adds approximately $470 per cubic yard). Compressive strengths of 22.5 to 29 ksi were achieved with these recommended mixes, and all mixes exceeded the minimum requirement of 0.72 ksi tensile strength.

A recent study completed by the University of Michigan (El-Tawil, 2016) focused on the development of a cost-optimized non-proprietary UHPC and the evaluation of its mechanical and durability properties. Additionally, this study examined the possibility of using UHPC for field-cast joints used in prestressed bridge construction. Cost optimization was performed by investigating the relationship between the type and amount of the most expensive components (silica fume and silica powder) and the performance of the composite. Material performance was measured through compressive and tensile strength test, while durability was evaluated through freeze-thaw and chloride-ion penetration testing. The developed mix used a 50:50 blend of Portland Type I cement and GGBS as the cementitious component. This UHPC also varies from other non-proprietary UHPC developed through other research in that is uses no inert filler such as glass powder. By removing this expensive component from the composite, a 50% reduction in cost was achieved based on the reference mix developed by Wille et al. (Wille et al., 2011) while still obtaining 25.2 ksi compressive and 1.2 ksi post-cracking tensile strengths (1.5% steel fibers by volume). This study also examined bond length of reinforcing steel and joints between precast sections using UHPC, these results are discussed below.

## 4 Research Related to Proposed Application

Precast bridge elements are especially useful to facilitate accelerated construction schedules that are often desired for highway projects. One issue that arises from the use of prefabricated bridge components is their reliance on the performance of field-cast connections. These types of connections often pose constructability, durability, and structural performance issues. The use of UHPC in these field cast connections may improve their performance due to its increased durability, and increased strength, which has been shown to improve bond strength.

J. Yuan, and Graybeal, B. (2014) performed research focused on evaluating the bond of reinforcing steel within UHPC concrete, and found that UHPC has enhanced bond performance when compared to conventional high strength concretes. However, it was determined that neither $f'_c$ nor $f'^{1/2}_c$ are effective for predicting the bond strength in UHPC. A comprehensive study on bond length was also performed at the University of Michigan (El-Tawil, 2016) on the UHPC blend that was developed during their research. It was determined that this UHPC blend required significantly less bond length than what is required for normal concrete; however the authors suggest additional research be conducted as their specific results differ from those reported by J. Yuan, and Graybeal, B. (2014) discussed above.

The research conducted by El-Tawil (2016) also included tests of field-cast joints between two pre-cast bridge deck sections using UHPC, and it was determined that a 6-inch joint length could be sufficient for load transfer between the two elements. Benjamin A Graybeal (2010a, 2010b); B. A. Graybeal (2014) also tested field-cast connections and determined that the use of UHPC in such connections can mitigate some of their potential issues. As discussed above, full development of reinforcing steel can be achieved in a much shorter length when compared to traditional concrete and grout mixtures. This allows a designer to specify shorter lap splices and connection details that reduce construction complexity and associated costs. The tensile capacity of UHPC as well as its ability to bond exceptionally well to previously cast concrete has also helped to facilitate the design of simpler connection details. The enhanced properties of UHPC can allow for precast bridge deck closure pours of 6 in. or less, allowing them to be effectively designed as narrow shear keys. Previous research involving full-scale structural testing has shown that field-cast UHPC deck connections can perform equally as well or better than a monolithically cast bridge decks. This research also showed that reinforcement in both transverse and longitudinal UHPC-filled connections does not debond from UHPC, even under severe loading conditions. The results of these studies are particularly useful for the proposed application of non-proprietary UHPC by the MDT Bridge Bureau.

**References Cited**

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

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

Dr. Terry Wipf, P. E. D. S. S. A. A.-H., P.E.; Brent Phares, P.E.; and Dean Bierwagen, P.E. (2011). Iowa's ultra-high performance concrete implementation.

El-Tawil, S. A., M.; Naaman, A.; Hansen, W.; Liu, Z. (2016). *Development, Characterization and Applications of a Non Proprietary Ultra High Performance Concrete for Highway Bridges*. Retrieved from

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

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

Graybeal, B. (2006a). *Material Property Characterization of Ultra-High Performance Concrete*. Retrieved from

Graybeal, B. (2006b). *Structural Behavior of Ultra-High Performance Concrete Prestressed I-Girders*. Retrieved from

Graybeal, B. (2011). *Ultra-High Performance Concrete*. Retrieved from

Graybeal, B. (2012). *Construction of Field-Cast Ultra-High Performance Concrete Connections*. Retrieved from

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

Graybeal, B. A. (2010a). Behavior of field-cast ultra-high performance concrete bridge deck connections under cyclic and static structural loading. Retrieved from http://ntl.bts.gov/lib/35000/35400/35413/FHWA-HRT-11-023.pdf

Graybeal, B. A. (2010b). *Behavior of Field-Cast Ultra-High Performance Concrete Bridge Deck Connections under Cyclic and Static Strutural Loading*. Retrieved from

Graybeal, B. A. (2014). Ultra-high-performance concrete connections for precast concrete bridge decks. *Pci Journal*, 48-62.

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

Jon "Matt" Rouse, T. J. W., Brent Phares, Fouad Fanous, and Owen Berg. (2011). DESIGN, CONSTRUCTION, AND FIELD TESTING OF AN ULTRA-HIGH PERFORMANCE CONCRETE PI-GIRDER BRIDGE.

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

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

Li, V. C. (2003). On Engineered Cementitious Composites (ECC)

A Review of the Material and Its Applications. *Journal of Advanced Concrete Technology, 1*(3), 215-230. doi:10.3151/jact.1.215

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

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

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

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

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

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

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

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

Yuan, J., and Graybeal, B. (2014). *Bond Behavior of Reinforcing Steel in Ultra-High Performance Concrete* (FHWA-HRT-14-090). Retrieved from

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

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

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