Task 1 Report – Literature Review

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

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1 Introduction

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) resulted in non-proprietary UHPC mixes made with materials readily available in Montana [1]. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The MDT Bridge Bureau is interested in using UHPC in field-cast joints between precast concrete deck panels. The use of UHPC in this application will reduce development lengths, and subsequently reduce the requisite spacing between the decks and improve the overall performance of the bridge. A second phase of research is being conducted at MSU that will build on the non-proprietary UHPC research already completed, and focus on ensuring the successful application of this material in these field-cast joints. Specifically, this research will investigate several items related to the field batching of these mixes, and the potential variability in performance related to differences in constituent materials. Further, rebar bond strength and the subsequent effect this has on development length will be investigated.

The specific tasks associated with this research are as follows.

Task 1 – Literature Review

Task 2 – Material Sensitivity

Task 3 – Field Batching/Mixing

Task 4 – Bond/Development Length Characterization

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 1 – Literature Review. It should be noted that an extensive literature review focused on UHPC and the development of non-proprietary UHPC mixes was conducted during the Phase I investigation [1]. The literature review conducted in the Phase II research (presented below) is focused on non-proprietary UHPC research conducted since the completion of the Phase I effort, and on the application of UHPC in the desired application (closure pours between precast deck panels).

2 Non-Proprietary UHPC Research

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

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

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

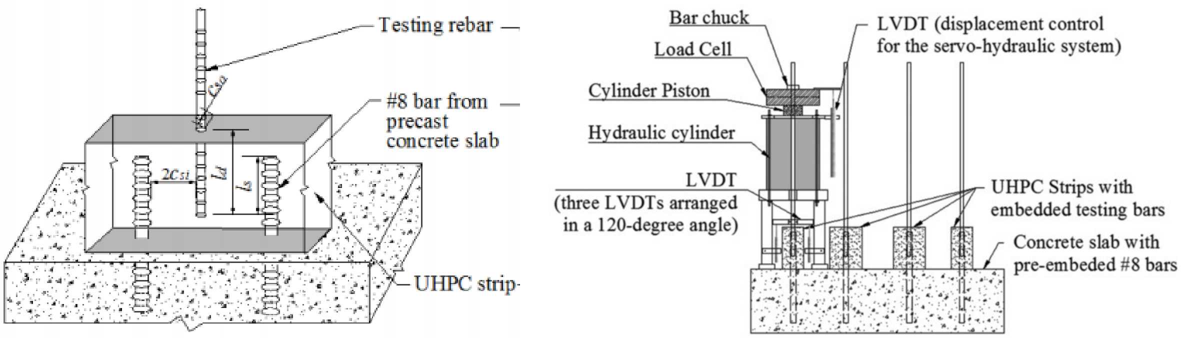
This research determined that a generic UHPC mix can be successful using components from a variety of sources with adequate HRWR dosage. They found that too low of a HRWR dose prevents the mix from turning over, and too high of a dose leads to fiber separation and possible loss of strength. It was determined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

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

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

3 Research Related to Proposed Application – Closure Pours

Previous research on UHPC field-cast joints has shown that UHPC can reduce development lengths of the reinforcing bars in the inter-element connection zone, and thus reduce the spacing and congestion between decks [8-11]. The FHWA investigated bond behavior of reinforcing steel embedded in a proprietary UHPC through a series of bar pullout tests [8, 9]. In these tests, reinforcing bars were embedded into UHPC curbs, which were in turn bonded to a normal strength concrete slab with reinforcing steel. In these tests, the reinforcing steel was loaded in tension until the concrete bond failed or significant yielding of the reinforcing was observed. A typical test specimen and testing configuration are shown in Figure 1. As part of their investigation, they varied side cover (c_{so}), clear cover between bars ($2c_{si}$), bar size, embedment length (l_d), epoxy coating, and yield strength. Based on this research, minimum recommended embedment depths were developed for tensile reinforcement embedded in ultra-high performance fiber reinforced concrete. These recommendations ensure that an embedded reinforcing bar in tension would yield prior to UHPC bond failure. These minimum embedment depths will be discussed further in a later section.



(a) Typical Test Specimen (b) Test Setup

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

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

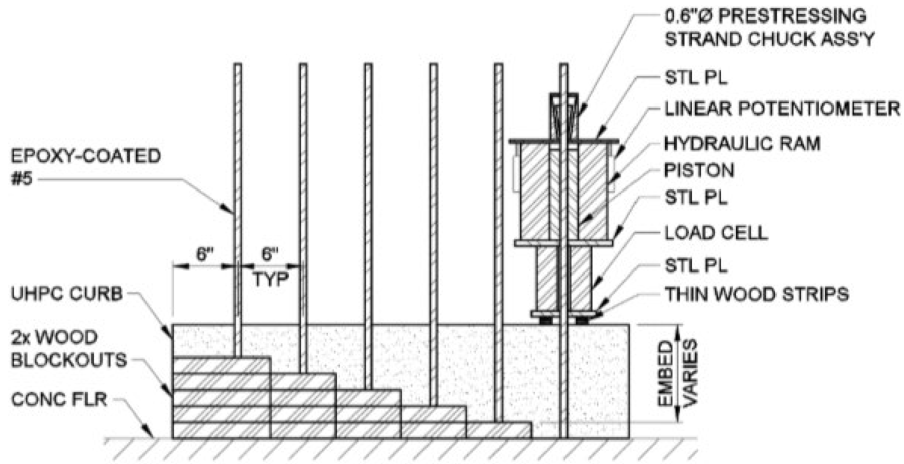


Figure 2: UW Bar Pullout Test Configuration [10]

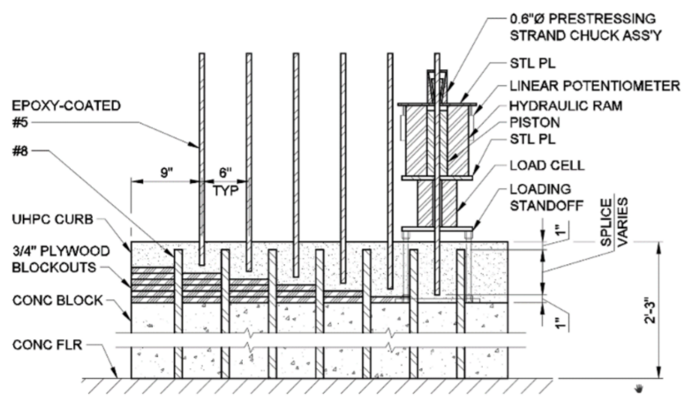


Figure 3: Non-contact Lap Splice Connection Test Configuration [10]

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

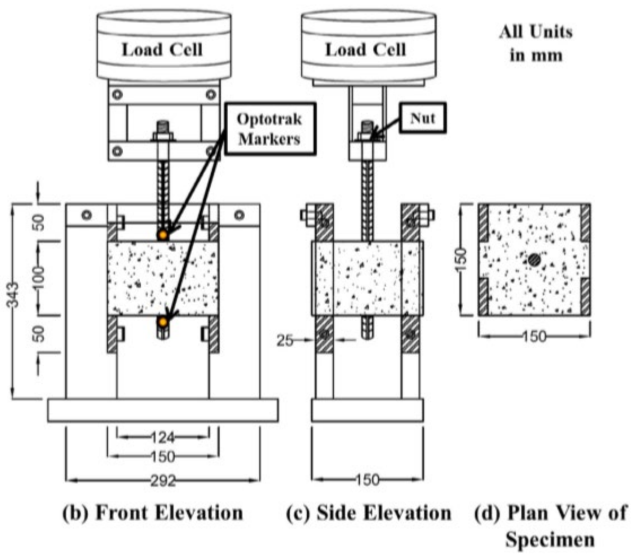


Figure 4. Test configuration of pullout specimen [11]

Yuan [12] performed a study and found that the relationship between bond strength and bonded length is nearly linear. This shows that UHPC has enhanced bond performance when compared to conventional high strength concretes. However, it was determined that neither f'_c nor $f'_c{}^{1/2}$ are effective for predicting the bond strength in UHPC. Deformed mild steel reinforcement embedded in steel fiber reinforced UHPC is capable of achieving the lesser of either the bar yield strength or 75 ksi before bond failure if the following conditions are met:

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

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

A comprehensive study on bond length was performed at the University of Michigan [5] on the UHPC blend that was developed during their research. It was determined that this UHPC blend requires significantly reduced bond length than is required for normal concrete; however, the authors suggest additional research be conducted as their results differ from those reported by Yuan [12] discussed previously. Bond strength models for this UHPC were proposed and used to cast a field joint between two pre-cast bridge deck sections. This joint was tested and it was determined that a 6-inch joint length could be sufficient for load transfer between the two elements.

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. Graybeal [13], Graybeal [14], Graybeal [15] determined that the utilization of UHPC in field-cast connections can mitigate some of these 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.

4 References

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