OU-2016-2-1- DEVELOPMENT OF NON-PROPRIETARY UHPC MIX

Quarterly Progress Report
For the period ending February 28, 2021

Submitted by:
PI- Royce W. Floyd, P.E., Ph.D.
Co-PI- Jeffery S. Volz, S.E., P.E., Ph.D.
Co-PI- Musharraf Zaman, P.E., Ph.D.
Graduate Student- Yana Dyachkova
Graduate Student- Stephen Roswurm
Graduate Student- Jacob Choate
Graduate Student- Trevor Looney
Graduate Student- Richard Campos
Undergraduate Student- Cole Walker

School of Civil Engineering and Environmental Science
The University of Oklahoma
Norman, OK

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
ABC-UTC
Florida International University
Miami, FL

1. Background and Introduction

Ultra-high performance concrete (UHPC) is a relatively recent advancement in cementitious composite materials with mechanical and durability properties far exceeding those of conventional concrete, which makes it an ideal material for bridge deck joints. The research project's main objective is leverage efforts by all ABC-UTC partner institutions to develop a non-proprietary UHPC mix design that will be labeled as "ABC-UTC Non-Proprietary UHPC Mix". The starting point will be two non-proprietary UHPC mixes developed by partner universities, mainly at OU, and additional research described in this report is currently underway, which will lead to development of the "ABC-UTC Non-Proprietary UHPC Mix". The main focus of the activity at OU is to investigate the effect of different fiber contents on the material properties and bond performance of the "ABC-UTC Non-Proprietary UHPC Mix" and to examine the repeatability of mix designs developed in different parts of the country. The OU team is coordinating the overall effort of researchers at the five ABC-UTC partner institutions to investigate material properties, bond strength, shear strength, and full-scale structural performance of the "ABC-UTC Non-Proprietary UHPC Mix" developed by the partner institutions working together.

Two mix designs developed by the partner institutions (one at OU and one at ISU) will be shared with the other partner institutions for comparative testing with other well-established UHPC mix designs. Fiber content and fiber type will be considered as primary variables for examining material properties of the mix design. The primary objective is to develop guidance for an "ABC-UTC Non-Proprietary UHPC Mix" made with local materials that can achieve the necessary mechanical properties and durability for use in bridge component connections and other applications, thereby providing an additional option for DOTs. Sharing of information between the partner institutions allows for consideration of repeatability of the proposed mix design and the combined efforts of the partner institutions will lead to more significant results than could be obtained by any of the institutions working individually. Understanding the effect of fiber type and content on material properties, bond, shear, and overall structural performance will be used to identify the optimum fiber content required for the "ABC-UTC Non-Proprietary UHPC Mix" to achieve the properties required for a given application. The study performed by the OU team and primarily described in this report is focused on evaluation of material properties and reinforcement bond behavior of the "ABC-UTC Non-Proprietary Mix" and will synthesize results from the partner institutions to provide a "Guide for ABC-UTC Non-Proprietary UHPC." A technology transfer workshop, with participation of all five partner institutions, is planned at the end of the project to disseminate findings of the proposed study to the ABC-UTC stakeholders. In addition, the OU team will create a short course focused on development and use of non-proprietary UHPC.

2. Problem Statement

Deterioration of bridges can often be related to poor performance of longitudinal connections or transverse deck joints, which can be more frequent when precast panels are used for accelerated bridge construction. Ultra-high performance concrete (UHPC) is a relatively recent advancement in cementitious composite materials with mechanical and durability properties far exceeding those of conventional concrete, which makes it an ideal material for bridge deck joints. It combines a high percentage of steel fibers with an optimized gradation of granular constituents, resulting in a compressive strength in excess of 22 ksi, a high post-cracking tensile strength, and exceptional durability. The short reinforcing bar development lengths and exceptional durability provided by UHPC lead to great potential for use in accelerated bridge construction and as a repair material. All ABC-UTC partner institutions are considering the use of UHPC for bridge deck joints. However, individual institutions are considering a number of other applications for UHPC including: girder end region repairs (OU and ISU), bridge girder continuity connections (OU), link slabs and existing joint retrofit (OU and ISU), UHPC shell retrofits for seismic and non-seismic application and innovative UHPC based solutions (FIU), UHPC elements for resisting seismic forces (UNR), and bridge deck overlays (ISU and FIU).

Many state DOTs have limited experience working with UHPC and do not have specifications for non-proprietary UHPC mix designs. Proprietary UHPC formulations have proven performance but can be very expensive. Guidance for use of UHPC class materials made with local materials is needed to give state DOTs more options for use of this material in construction and repair.

3. Objectives and Research Approach

The proposed study will coordinate the efforts of researchers at the five ABC-UTC partner institutions, with primary focus on mix design, to investigate material properties, bond strength, shear strength, and full-scale structural performance of non-proprietary UHPC developed by the partner institutions. The mix design mainly developed at OU will be shared with the other partner institutions for comparative testing with other well-established UHPC mix designs. Researchers at ISU will also share their mix design to provide additional data point. The final “ABC-UTC Non-Proprietary UHPC Mix” developed in this project will be evaluated at OU and FIU by conducting a series of tests that has been recommended by FHWA for qualifying various mix designs as UHPC. This report outlines the FHWA recommended material tests to be conducted by OU and FIU and progress on conducting those tests up to this point.

The steel fibers used in typical UHPC mix designs are the most expensive component of the mix design, and the high fiber contents typically recommended for UHPC may not be necessary for every application. Fiber content and fiber type will be considered as primary variables for a given mix design including consideration of 0%, 1.0%, 2.0%, 4.0% and 6.0% steel fibers by volume and consideration of synthetic fibers. The primary objective of the project is to develop guidance for an “ABC-UTC Non-Proprietary UHPC Mix” design made with local materials that can achieve the necessary mechanical properties and durability for use in bridge component connections, thereby providing an additional option for DOTs. Sharing of information between the partner institutions will allow for consideration of repeatability of the “ABC-UTC UHPC Mix” and the combined efforts of the partner institutions will lead to more significant results than could be obtained by any of the institutions working individually.

Table 1 summarizes the efforts proposed by each partner institution and Figure 1 shows the overall organization of the project.

Table 1. Research topics to be examined by each partner institution

Institution	**PIs**	**Topic 1**	**Topic 2**
University of Oklahoma (lead)	Royce Floyd, Jeffery Volz, Musharraf Zaman	Development of the final “ABC-UTC Non-Proprietary UHPC Mix” design, conducting FHWA recommended material tests on final mix design, and comparison with other proprietary UHPC mixes without identifying them. Will include examination of material properties with varying fiber content.	Examination of reinforcing bar bond strength in UHPC with different mix designs and fiber contents using pullout and beam splice tests.
University of Washington	John Stanton and Paolo Calvi	Washington shear panel test to investigate shear strength of the “ABC-UTC Non-Proprietary UHPC Mix”, considering different fiber contents	Will test material properties and send local materials to OU and ISU for testing.
Iowa State University	Behrouz Shafei	Durability of the “ABC-UTC Non-Proprietary UHPC Mix”, with different fiber types	Examination of synthetic fibers.
University of Nevada Reno	Mohamed Moustafa	Panel joint testing with the “ABC-UTC Non-Proprietary UHPC Mix”, considering different fiber contents.	Will test material properties and send local materials to OU and ISU for testing.
Florida International University	Atorod Azizinamini	Examination of material properties of “ABC-UTC Non-Proprietary UHPC Mix”, with varying fiber content.	

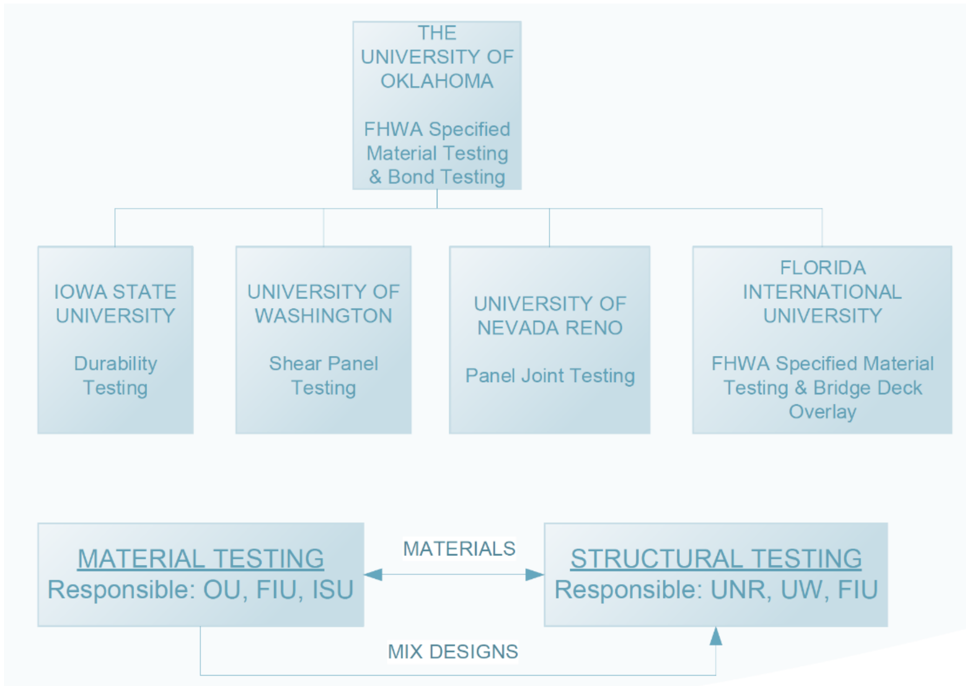


Figure 1. Overall organization of project and information sharing

The UHPC mix design developed at OU is considered the base case for all testing. Researchers from OU and ISU will provide UHPC mix designs developed at those institutions to the team members at UNR, UW, and FIU for use in material and structural testing. OU and ISU will also have the exact cementitious materials, aggregate, and admixtures used for each mixture shipped to UNR, UW, and FIU so that each institution can exactly recreate the mix designs. OU and ISU will provide a sufficient quantity of material for one of the proposed structural tests. For the other tests, researchers at UNR, UW, and FIU will use their own local aggregates and materials. Researchers at UNR, UW, and FIU will provide sufficient quantities of local cementitious materials and admixtures to researchers at OU and ISU such that they can investigate the effects of locally available cementitious materials and admixtures on the "ABC-UTC Non-Proprietary Mix". Researchers at OU and ISU will consider flowability, concrete compressive strength, and modulus of rupture for comparison of the effects of local cementitious materials on mix design performance. They will also conduct at least one set of bond tests (OU) and durability tests (ISU) considering local cementitious variations provided by the other partner universities. In all cases, researchers will obtain the same ½ in. Dramix steel fibers produced by Bekaert for use as the base fiber case. Institutions sharing the exact materials will allow all institutions to begin their work at the same time, without needing to wait for additional mix design development.

Each institution will provide a separate progress and final reports. OU researchers are coordinating the research efforts and will compile a summary connecting the project reports that can be published as the "Guide for ABC-UTC Non-Proprietary UHPC" at the end of the project. Each institution will provide information for the Guide relative to their research along with a short video describing the results of their research. The five institutions are holding bi-monthly virtual meetings (two completed so far) to discuss project coordination, project progress, and to resolve issues with using the different mix designs and obtaining constituent materials. A face to face meeting was held at the Spring 2019 ACI Convention at the same time as the first virtual meeting. Additional face to face meetings will be held at ACI conventions and ASCE SEI congress if possible. A technology transfer workshop will be held during the fourth-quarter of this study as part of the 2019 International Accelerated Bridge Construction Conference sponsored by ABC-UTC in which each partner institution will share its results with the ABC-UTC stakeholders. Materials required for teaching a short course focused on development and use of non-proprietary UHPC will be developed incorporating the results of the project.

4. Description of Research Project Tasks

The following is a description of tasks and worked carried out to date.

Task 1 – Comparison of Local Materials Used in Mix Designs

Effects of UHPC constituent materials locally available to each partner institution and fiber content on behavior of the “ABC-UTC Non-Proprietary UHPC Mix” will be considered using material property tests recommended by FHWA for qualification of UHPC mix designs (Table 2). Mixtures will be tested with 0%, 1.0%, 2.0%, 4.0% and 6.0% fibers by volume

The OU research team has provided the final “ABC-UTC Non-Proprietary UHPC Mix” design to the team members at UNR, UW, and FIU for use in their material property and structural testing. Researchers at OU and FIU will conduct all tests listed in Table 2 for the “ABC-UTC Non-Proprietary UHPC Mix” using locally available cementitious material and aggregates and all fiber contents, while researchers at UNR and UW will perform all tests except for freeze-thaw and creep tests on the final mix design. All material properties will be tested using a series of at least three specimens and the methods listed in Table 2, with modifications necessary for UHPC as specified in ASTM C1856 “Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete.” Creep tests will be conducted on 4 in. x 36 in. cylinders due to capacity limitations of the existing creep frames. Total shrinkage beginning with placement of the fresh concrete will be measured using a 6 in. x 12 in. cylinder with an embedded vibrating wire strain gage (VWSG) in addition to drying shrinkage measured using ASTM C157. Direct tensile strength tests will be conducted based on recommendations made by Graybeal and Baby (2013) and Haber et al. (2018), but exact methods will be dictated by equipment available at each partner university.

The OU team will have a quantity of the exact cementitious materials, aggregates and admixtures used for the mixture constituents shipped to UNR, UW, and FIU so that each institution can exactly recreate the mix designs for one of their proposed structural tests. For the other tests, researchers at UNR, UW, and FIU will use their own local materials. Researchers at UNR, UW, and FIU will provide local cementitious materials and admixtures to researchers at OU, such that the OU team can investigate the effects of locally available cementitious materials and admixtures on the “ABC-UTC Non-Proprietary Mix.” Flowability (ASTM C1437), compressive strength (ASTM C39), and modulus of rupture of concrete (ASTM C78) will be tested by the OU team for comparison of the effects of local cementitious materials on mix design performance. The OU team will also conduct at least one set of bond tests considering variations in local cementitious materials provided by the other partner universities. In all cases, the same ½ in. steel fibers produced by Bekaert will be used for consistency. Institutions sharing the exact materials for large-scale tests will allow all institutions to begin their work at the same time, without needing to do additional mix design development.

Table 2. Material property tests recommended by FHWA to be conducted on the "ABC-UTC Non-Proprietary UHPC Mix"

Property	Test Method	Institution
Flowability	ASTM C1437	All
Compressive Strength	ASTM C39 ASTM C109	All
Modulus of Elasticity and Poisson's Ratio	ASTM C469	All
Splitting Tensile Strength	ASTM C496	All
Flexural Strength	ASTM C78	All
Direct Tensile Strength	Based on FHWA (Graybeal and Baby, 2013, Haber et al., 2018)	All
Total and Drying Shrinkage	Embedded VWSG ASTM C157	All
Compressive Creep	ASTM C512	OU, FIU
Set Time	ASTM C403	All
Freeze-Thaw Resistance	ASTM C666	OU, FIU
Rapid Chloride Ion Permeability	ASTM C1202	All

The base mix design for 2% fibers and the sources of all constituent materials used is included in Table 3. Specimens for flowability, compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, direct tension strength, total and drying shrinkage, and set time have been cast for the OU mix design using materials available in Oklahoma and for all fiber contents (0%, 1%, 2%, 3%, 4%, and 6%). All mixes exhibited adequate flow with minor modifications to the superplasticizer dosage during trial batching, except for the 6% fiber mix. Even with major adjustments to the superplasticizer dosage almost zero flow was measured for this mix. The material was workable in general, however, and could be placed in most specimen forms with some difficulty. Use of a 6% fiber mix for more than laboratory testing would require more extensive mixture modification.

Tests of the material property specimens at 28 days and 56 days have been completed for mixes with Oklahoma materials and all fiber contents. Casting of the material property specimens is shown in Figure 2, example compressive strength specimens (0% mix) are shown in Figure 3, compressive strength results are shown in Figure 4, example splitting tensile strength specimens (0% mix) are shown in Figure 5, and example modulus of rupture specimens (0% mix) are shown in Figure 6.

Direct tension testing was completed. Three different test methods have been considered including the FHWA test method and a dogbone type specimen. Proper alignment of the specimens has been very difficult to achieve with the testing equipment available and several modifications were required. Direct tension tests were conducted on the non-proprietary UHPC using a test setup similar to that developed by Graybeal and Baby (2013) and Haber et al. (2018) for steel fiber contents of 0%, 1%, 2%, 4%, and 6% by volume. Modifications to the test method included using only two LVDTs to measure deformation instead of four, a load controlled rate, and hinged grips at each end of the test specimen. A specimen in the testing machine ready for loading is shown in Figure 7. Specimens with at least 2% steel fibers by volume exhibited some strain hardening behavior, while specimens with no steel fibers or 1% by volume failed immediately after the first crack appeared. A comparison of the direct tension testing results to the splitting tensile strengths and flexural strengths is shown in Figure 8.

Creep specimens have been cast, loaded, and are still being monitored for all fiber contents. An example loaded creep specimen is shown in Figure 9 and creep strain results out to more than one year of age are shown in Figure 10. The 6 x 12 cylinder specimens with embedded vibrating wire strain gages and ASTM C157 shrinkage specimens are being monitored continually. Figure 11 shows shrinkage strain results for the ASTM C157 specimens out to more than one year of age.

Table 3. Baseline non-proprietary UHPC mix design

Material	**Quantity**	**Specific Gravity**	**Supplier**
Type I Cement, lb/yd^3	1179.6	3.15	Ash Grove Chanute, Kansas
Slag, lb/yd^3	589.8	2.97	Holcim, South Chicago
Silica Fume, lb/yd^3	196.6	2.22	Norchem Ohio
w/cm	0.2	NA	NA
Fine Masonry Sand, lb/yd^3	1966	2.63	Metro Materials Norman, OK
Steel Fibers, lb/yd^3	255.2	7.85	Bekaert (Dramix® OL 13/0.2)
Steel Fibers, %	2.0		
Superplasticizer, oz./cwt	18	1.07	BASF (Glenium 7920)

Figure 2. Casting of compression, shrinkage, and modulus of rupture test specimens (left) and creep specimens (right) for the 6% fiber mix

Figure 3. Example tested compressive strength specimens (0% fiber mix)

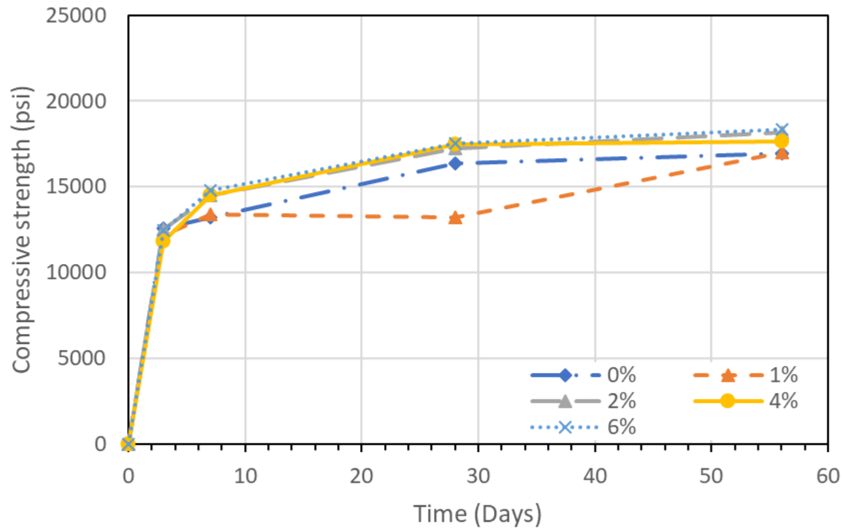


Figure 4. Compressive strength results for cylinder specimens with different fiber contents

Figure 5. Example tested splitting tensile strength specimens (0% fiber mix)

Figure 6. Example tested modulus of rupture beam specimens (0% fiber mix)

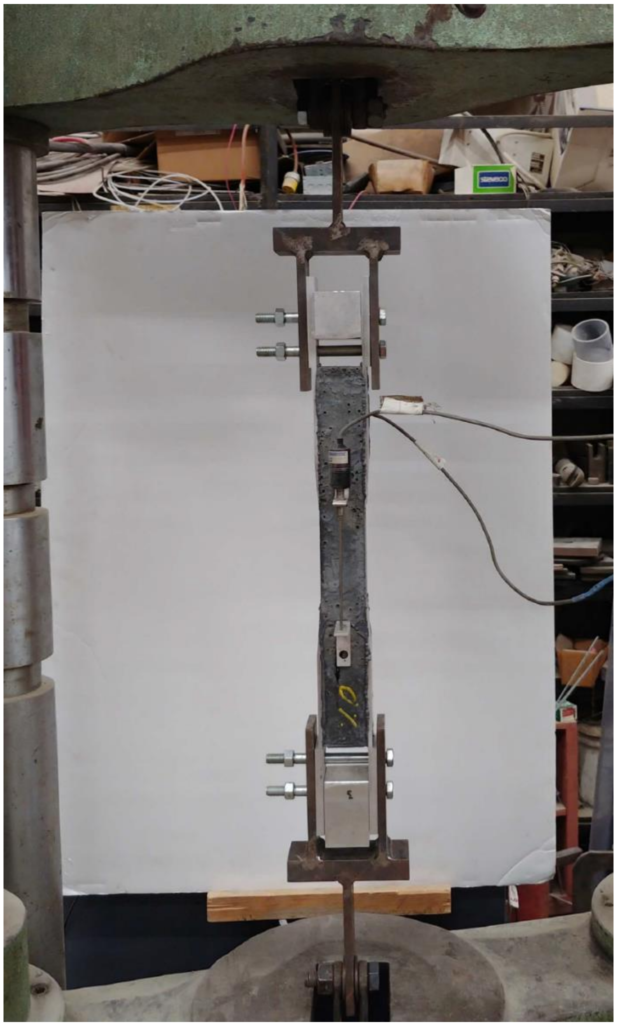


Figure 7. FHWA direct tension test setup

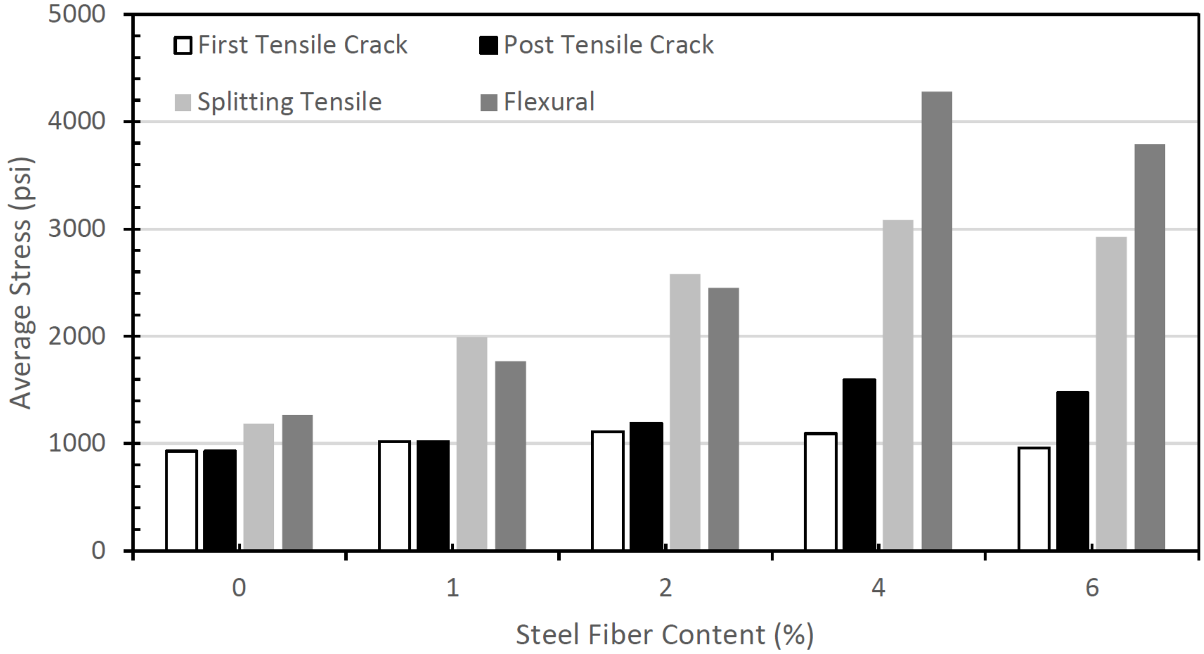


Figure 8. Comparison of FHWA direct tension test results to indirect tension tests

Figure 9. Example creep specimen immediately after loading (0% fiber mix)

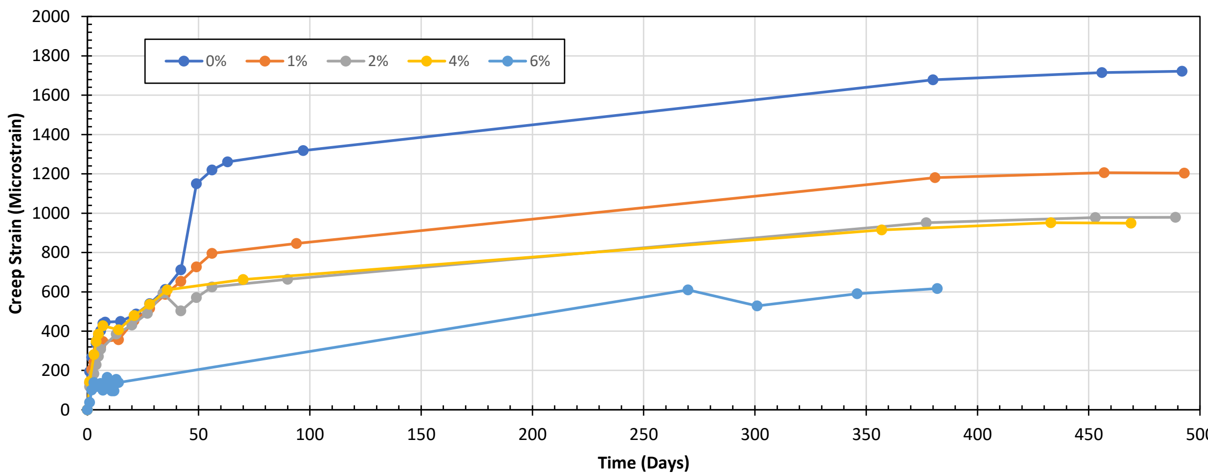


Figure 10. Creep results for baseline mix design with different fiber contents

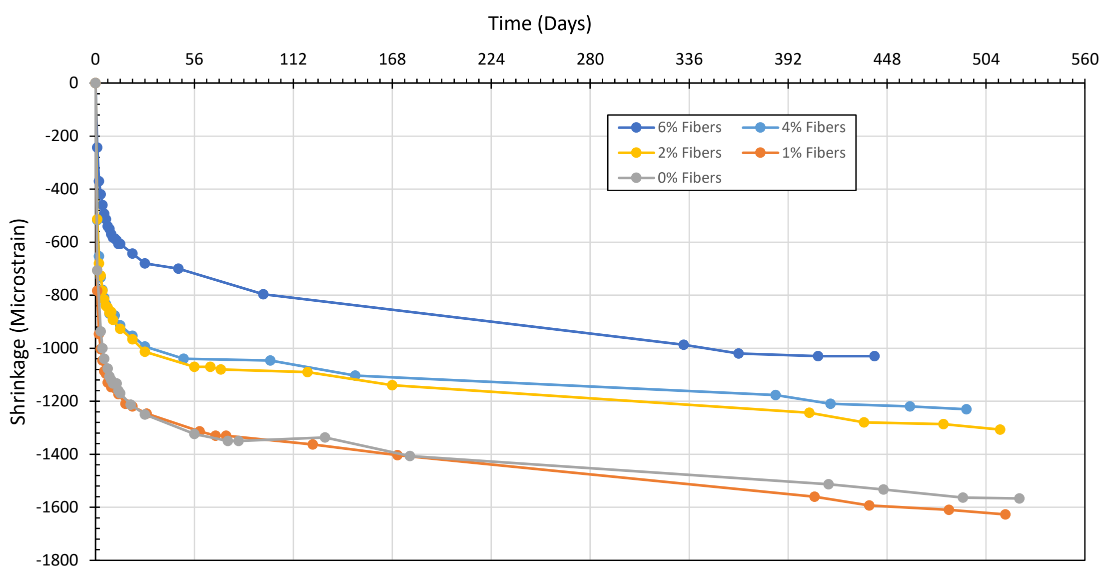


Figure 11. Shrinkage for each fiber content measured using ASTM C157

Set time tests were conducted following ASTM C403 for all mixture variations, but the steel fibers affect the ability of the needle to properly penetrate the UHPC surface. An additional series of set time tests were conducted using no fibers, but including the required adjustments to superplasticizer content to determine if the superplasticizer is the controlling factor for set time rather than fiber content. Figure 12 shows results of the revised set time tests, which indicate that set time does increase with increase in superplasticizer dosage.

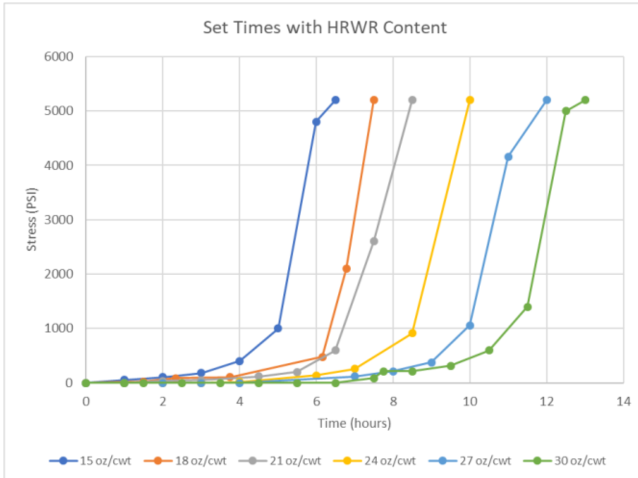
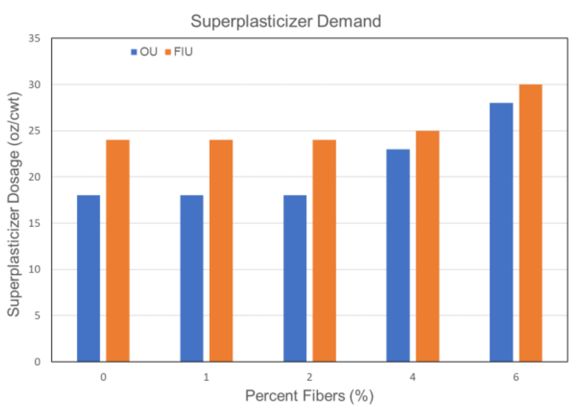


Figure 12. Results of ASTM C403 tests for set time with varying superplasticizer dosage

The FIU research team shipped fine sand, local cement, and slag cement to OU for testing. It was determined that the silica fume and superplasticizer used by both institutions was from the same source. UHPC mixes using constituent materials received from FIU were tested by the OU research team. Trial batches to identify the required high range water reducer dosage were completed first followed by batches for material testing. Flow was tested at time of casting and compressive strength and flexural tension strength tests were conducted at 28 and 56 days of age. A comparison of the superplasticizer demand for the different constituent materials and resulting flow values are shown in Figure 13. The mixes using FIU materials required substantially larger doses of superplasticizer to achieve the same flow. In general, compressive strength and modulus of rupture were similar for mixes using materials from each location, as shown in Figure 14.



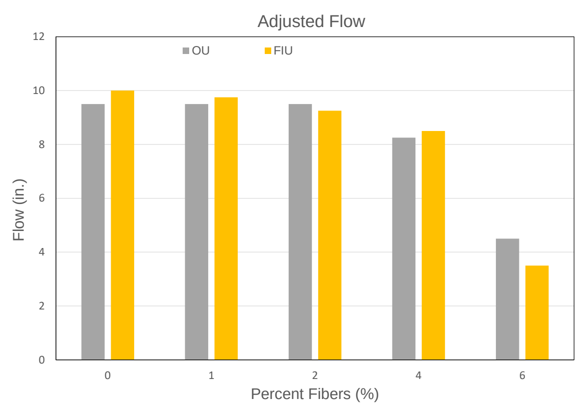


Figure 13. Comparison of superplasticizer dosage (left) and flow values (right) for mixes with FIU and OU constituent materials

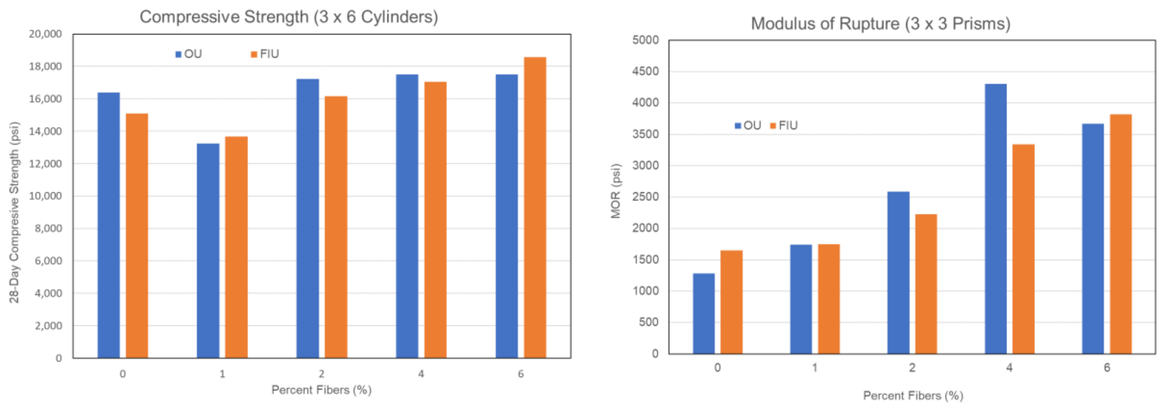


Figure 14. Comparison of compressive strength (left) and modulus of rupture (right) for mixes with FIU and OU constituent materials

Oklahoma constituent materials were shipped to UW for use in shear panel testing, to UNR for comparative testing associated with slab joint testing, and to FIU for use in the workshop at the ABC Conference and for limited comparative testing.

Task 2 – Evaluation of Reinforcing Bar Development Length in UHPC

Pullout bond tests on reinforcing bars and beam splice tests will be conducted to examine the development length of reinforcing bars cast in the "ABC-UTC Non-Proprietary UHPC Mix" using local materials with 1.0%, 2.0%, 4.0% and 6.0% fibers by volume. A proprietary UHPC will also be tested for comparison as part of the matching funds project.

Reinforcing bar development length will be examined using a comparative pullout test to identify the difference between required embedment for No. 3, No. 5, and No. 8 reinforcing bars cast in the "ABC-UTC Non-Proprietary UHPC Mix" with varying fiber contents. Similar specimens will be cast using established proprietary UHPC mix designs as part of the matching funds project. Details for the pullout test specimens and setup used in previous research are shown in Figure 15 (RILEM 1994). Bond between the reinforcing bar and the concrete occurs only in the upper half of the concrete block, through the addition of a PVC or foam tube in the lower portion, significantly reducing the effect of any confinement pressure generated as a result of friction between the specimen and reaction plate. Data recorded during the test will include load and free end slip at each end of the reinforcing bar. Since the pullout test is only useful as a comparative measure, results of the pullout tests will be used to design a flexural beam splice test to evaluate bond performance in a flexural loading configuration. The beam splice test will use No. 5 and No. 8 reinforcing bars. Although there are a variety of bond and development length testing protocols available, the beam splice specimen shown in Figure 16 is generally regarded as the most realistic test method (ACI 408 2003, Ramirez and Russell 2008). The current AASHTO LRFD design provisions for development length and splice length are based primarily on data from this type of test setup (AASHTO 2014). Data recorded during the test will include load, deflection, and strain in the reinforcing steel at each end of the splice.

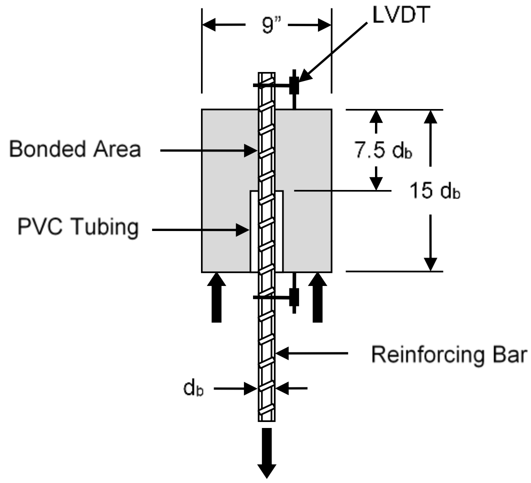


Figure 15. Direct reinforcing bar pullout test setup with preliminary dimensions to be evaluated further

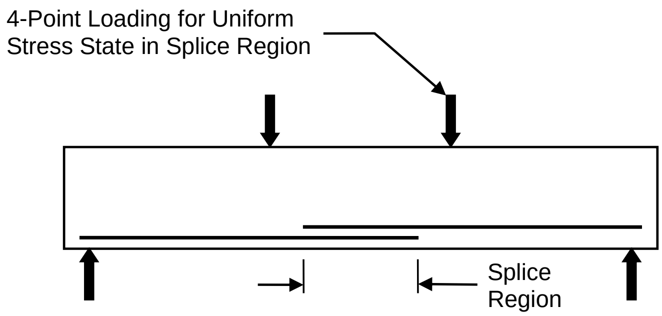


Figure 16. Beam splice test setup with splice region still to be determined.

A trial series of pullout test specimens based on the specimen shown in Figure 15 and using No. 5 bars was cast and tested to evaluate the best embedment to produce a bond failure. The circular specimens had a nominal 8 in. diameter to obtain a minimum cover of $3d_b$ for all bar diameters to be tested. Embedments examined included $2d_b$, $4d_b$, $6d_b$, $8d_b$, and $10d_b$ with a debonded length equal to the embedment length resulting in a specimen height dependent on the embedment. All specimens except the $2d_b$ embedment specimen exhibited signs of reinforcing bar yielding and the $2d_b$ embedment specimen exhibited a splitting failure, as shown in Figure 17. A set of revised specimens were cast having a $2d_b$ embedment but larger overall specimen depth and resulting debonded length in an attempt to prevent splitting failure. The revised specimens had the same 8 in. diameter, but total depths of 2.5 in. ($2d_b$ debonded), 3.5 in. ($3.6d_b$ debonded), and 5 in. ($6d_b$ debonded). Two specimens were cast and tested for each variable combination. All of these tests resulted in pullout failures, so the final dimensions chosen for the pullout test were an 8 in. diameter specimen with $2d_b$ embedment and $4d_b$ debonded length for a total depth of $6d_b$, shown in Figure 18. This resulted in a 3.75 in. thick specimen for the No. 5 bar tests, a 2.25 in. thick specimen for the No. 3 bar tests, and a 6 in. thick specimen for the No. 8 bar tests.

Figure 17. Splitting failure of preliminary pullout specimen with $2d_b$ embedment

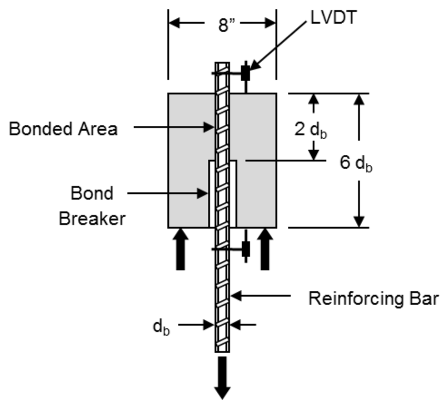


Figure 18. Final dimensions of comparative bond pullout specimens based on preliminary testing

The No. 3, No. 5, and No. 8 bar pullout specimens for 0%, 1%, 2%, 4%, and 6% fiber mixes were cast and tested at 28 days of age. The No. 5 bar specimens with no fibers failed due to splitting of the concrete, but all No. 5 bar specimens containing fibers failed due to pullout of the reinforcing bars. Preliminary pullout test results for the No. 5 bar specimens are shown in Figure 19. The results indicate a significant increase in pullout capacity with the addition of fibers to prevent a splitting failure, but only modest gains in strength as the fiber content is increased beyond 1%.

The results of the No. 8 and No. 3 bar specimen tests are presented in Figures 20 and 21. The results were similar to those observed for the No. 5 bar specimens. The very small embedment length used for the No. 3 bar specimens (0.75 in.) may have contributed to the difference in results obtained for those specimens based only on load since even small variations in the embedded length would have represented a large percentage of the total. The specimens were demolished so that the actual embedment length could be measured for calculation of the bond stress and a more direct comparison with the other bar diameters.

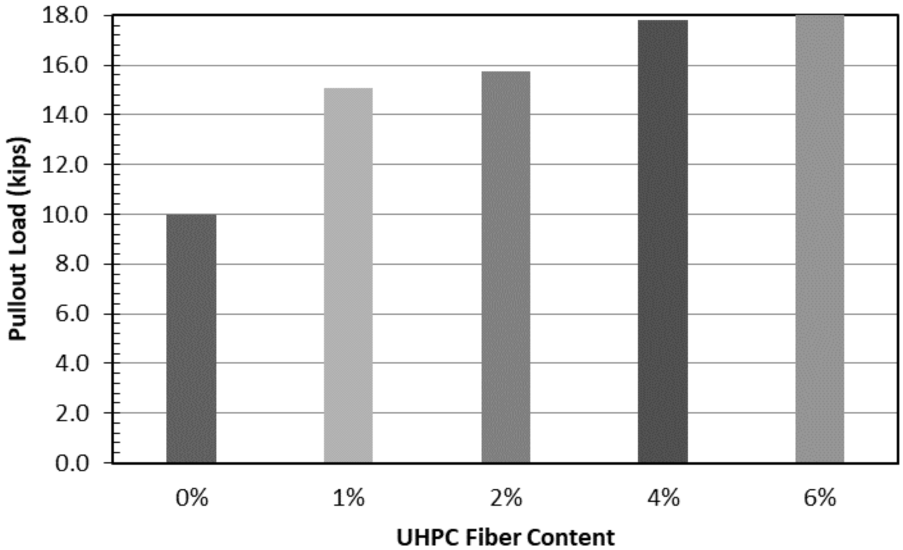


Figure 19. Pullout loads for No. 5 bar specimens with all fiber contents tested

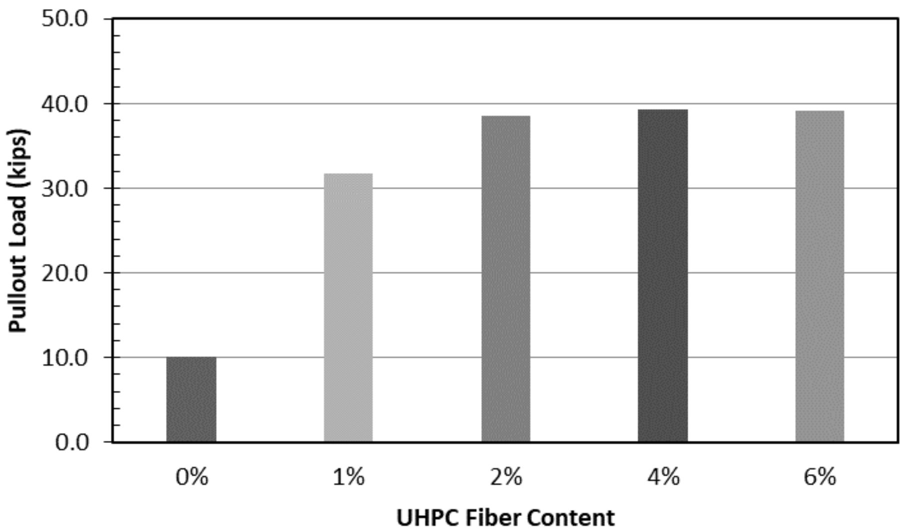


Figure 20. Pullout loads for No. 8 bar specimens with all fiber contents tested

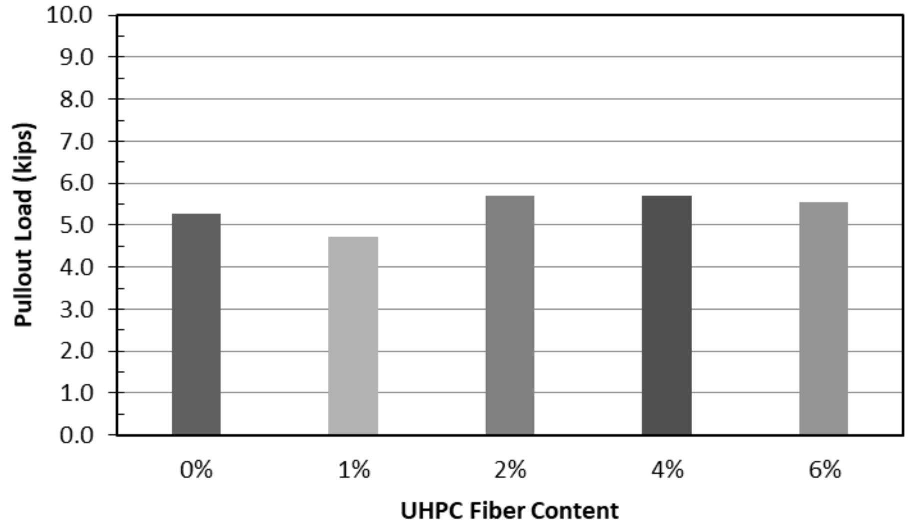


Figure 21. Pullout loads for No. 3 bar specimens with all fiber contents tested

Results of the pull-out tests were used to select the lap splice length used in the beam splice tests. Beam splice test specimen construction was delayed due to difficulty in obtaining additional steel fibers. New fibers were finally shipped and were received in March 2020. However, all research laboratories at OU were shut down due to the COVID-19 pandemic in late March and were closed until late May 2020. A staged reopening was begun in May, but the students working on this task were not allowed back into the lab until July, which further delayed completion of this task. Work began in earnest on these tests in the current quarter.

Splice beams were constructed for No. 5 bars with 1% and 2% steel fiber contents. The beams had dimensions of 7 in. by 7 in., were 10 ft long, and were reinforced with two No. 5 bars with a $2d_b$ splice placed at mid-span. Foil strain gages were placed immediately outside of the splice length to measure strain in the steel at the point of $2d_b$ embedment. The beams were loaded on a 9 ft span with loads placed at the third points as shown in Figure 22. Load was applied in 1 kip increments up until the first flexural crack appeared and in 0.5 kip increments after the first crack was observed. In all specimens the steel reached a strain corresponding to more than half of the specified yield stress, but all beams failed due to bond in the splice region with a single crack propagating through the entire beam depth at the splice location. The beams exhibited distributed flexural cracking throughout the constant moment region, as shown in Figure 23.

Figure 22. Splice beam test setup

Figure 23. Cracking pattern for the non-proprietary UHPC splice beams

A comparison series of pullout tests using a proprietary UHPC material with 2% steel fibers was conducted and the first set of beam splice specimens were cast using the same proprietary material for comparison with the non-proprietary UHPC results. The proprietary UHPC specimens had a higher bond stress, even when normalized by the compressive strength. In most cases the pullout loads for the proprietary UHPC specimens exceeded the specified yield strength of the bars with the $2d_b$ embedment used for the tests. Two splice beam specimens with No. 5 bars and 2% steel fibers were tested for comparison with the non-proprietary UHPC specimens using the same methods. These beams also failed due to bond, but withstood higher loads and exhibited fewer flexural cracks during testing. A photo of the beam crack pattern is shown in Figure 24.

Figure 24. Cracking pattern for the proprietary UHPC splice beams

Figure 25 shows the load deflection curves for each of the six beams that made up the series of splice beams tested with No. 5 reinforcement. Beams labeled D5 indicate proprietary UHPC with No. 5 bars and those labeled J5 non-proprietary UHPC with No. 5 bars.

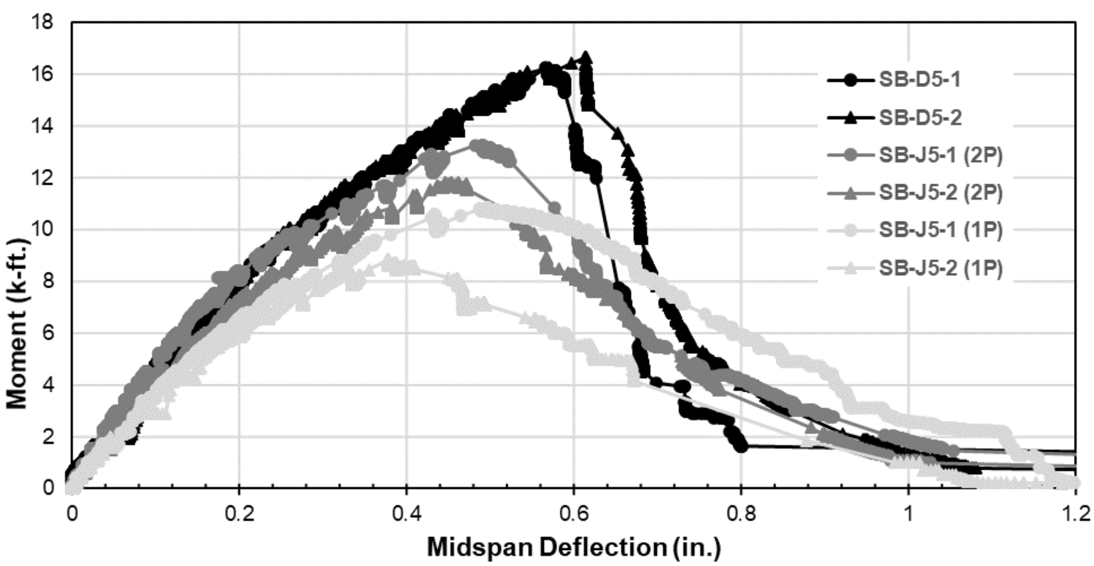


Figure 25. Load-deflection behavior of splice beams

First, it is apparent from Figure 25 that the proprietary UHPC beams reach the highest peak loads, both attaining moments greater than 16 kip-ft. The non-proprietary UHPC beams with 2% fibers reached between 12 and 13 kip-ft, and the non-proprietary UHPC beams with 1% fibers reached the lowest peak moments of between 8 and 11 kip-ft. It is also interesting to note the shape of the ascending curves towards the peak moments; the proprietary UHPC curves are steepest, indicating the stiffest response, while the 2% and 1% non-proprietary UHPC beams are progressively less steep, indicating that they were less stiff, or more compliant to the applied load. Also of interest are the descending branches of the load deflection curves moving away from the peaks. The proprietary UHPC beams shed load quickly after the bond failure at the peak, which indicates an abrupt bond failure, while the non-proprietary UHPC curves roll over more gently after reaching their maximum capacity. This may indicate that the bars in the non-proprietary UHPC splices experienced more of a gradual bond slip instead of a sudden failure. This behavior was noted in the direct pullout testing; whereas the No. 5 bars tended to pull out suddenly from the proprietary and non-proprietary 2% fiber mixes with an audible sound and jolt, the non-proprietary 1% fiber mix resulted in gradual pullout for all three specimens with no audible signs of sudden failure.

Task 3- UHPC Durability Property Testing

In addition to the solid specimens described in Task 1, freeze-thaw testing will be conducted on composite UHPC/conventional concrete specimens with 1.0%, 2.0%, 4.0% and 6.0% fiber by volume. Freeze-thaw testing will be conducted according to ASTM C666 (2015) on a minimum of three rectangular prism specimens for each UHPC fiber content.

As part of the matching funds project, freeze-thaw and permeability testing will be conducted on both the proprietary UHPC and “ABC-UTC Non-Proprietary UHPC Mix” and the results compared to the durability properties of conventional concrete. Freeze-thaw tests will be conducted on each UHPC mix design. Rapid Chloride Ion Permeability (RCIP) tests based on ASTM C1202 (2017) and freeze-thaw tests will also be conducted on each UHPC and conventional ODOT Class AA concrete. A minimum of four RCIP specimens will be tested for each mix design. Specimens will be cut from 4 in. x 8 in. (100 mm x 200 mm) cylinders for testing at 28 and 90 days of age.

Rapid chloride ion permeability tests were conducted on the base mix design with 0% fibers and a commercially available UHPC at 28 and 90 days. The steel fibers impede the testing method and other fiber contents will not be tested. These results indicate similar performance to the commercially available UHPC with both materials in the “Very Low” or “Negligible” range specified in ASTM C1202. Freeze-thaw specimens for all fiber contents of the non-proprietary UHPC mix were tested using ASTM C666 Method A extended to 350 cycles. No degradation of dynamic modulus was observed as shown in Figure 26.

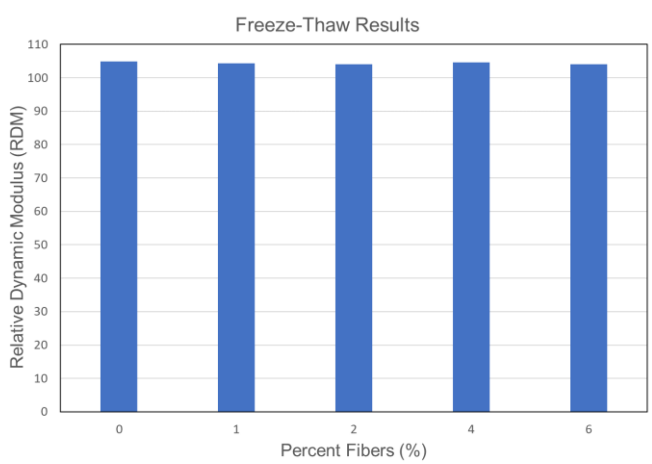


Figure 26. Results of freeze-thaw testing of the non-proprietary UHPC mix

Composite UHPC/conventional concrete specimens were cast for each fiber content and tested using ASTM C666 Method A extended to 350 cycles. Composite specimens were constructed by first casting a conventional concrete half that was giving an exposed aggregate finish using a set retarder and pressure washer, as shown in Figure 27. Non-proprietary UHPC was then cast against the conventional concrete half to create a composite specimen, as shown in Figure 28. Most specimens exhibited significant degradation in dynamic modulus during testing as shown in Figure 28. Only the 4% and 6% fiber specimens would produce frequency results after 200 cycles. However, visual observations indicated that most deterioration occurred in the conventional concrete portion of the specimens, not in the UHPC or at the interface. Cracking was observed in the UHPC portion for only the specimens with no fibers. Cracking in these specimens was a limited number of transverse cracks that went through both halves of the specimens. In all cases except for one of the 0% fiber specimens (specimen 2, Figure 30), the specimens remained intact even after cracking transverse to the length. No indication of separation between the UHPC and conventional concrete was observed for any specimen, even specimen 2 with 0% fibers which cracked transversely and broke into several pieces (Figures 30 and 31). Deterioration of the interface between the conventional concrete and UHPC was observed only after degradation of the base concrete had occurred.

Figure 27. Exposed aggregate surface of base concrete used for composite freeze-thaw specimen

Figure 28. Composite freeze-thaw specimen

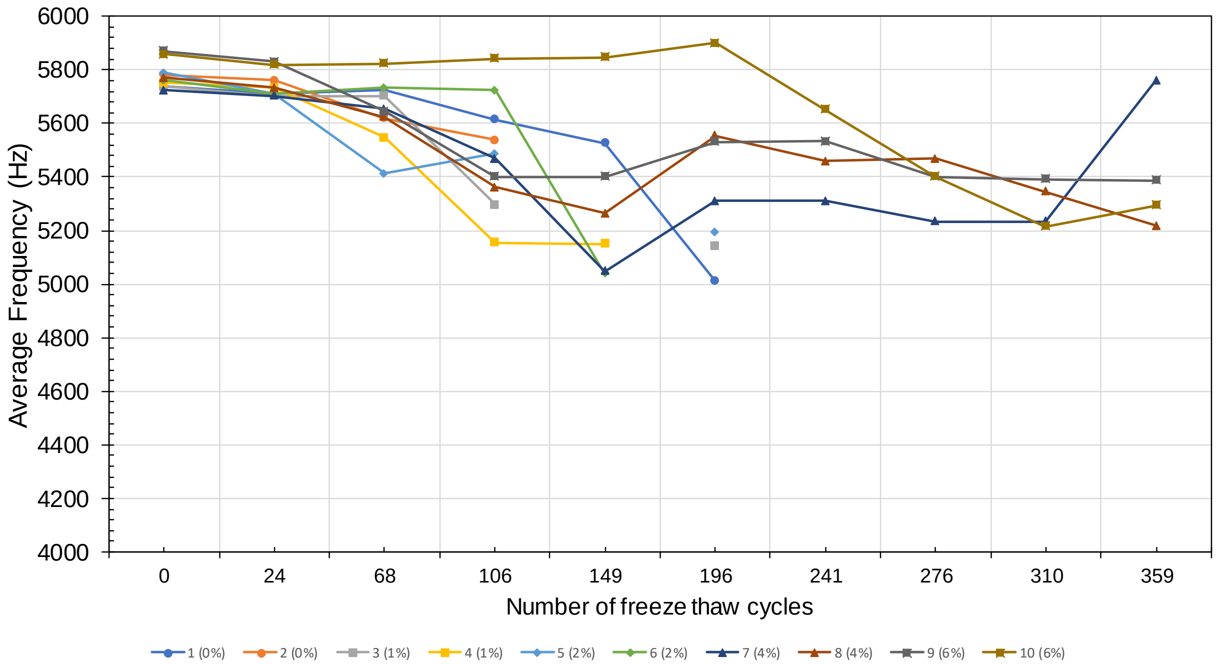


Figure 29. Results of freeze-thaw testing of the conventional concrete-UHPC interface specimens

Figure 30. Splitting failure of composite freeze-thaw specimen with no steel fibers after 150 cycles (top) and after 350 cycles (bottom)

Figure 31. UHPC-conventional concrete interface for failed specimen shown in Figure 24

Task 4- Short Course Development

Materials required for teaching a short course focused on development and use of non-proprietary UHPC will be developed incorporating the results of the project. These materials will include presentation slides, physical models and demonstrations, a plan for limited laboratory testing, and assessment exercises. The PI will teach the course once near the end of the project, but the materials will be designed such that it can be taught for DOTs and other stakeholders after completion of the project as needed. A fee will be charged to participants to fund execution of the short course.

An outline of the course topics was completed in conjunction with the development of the content for the Technology Transfer Workshop described in Task 5. PowerPoint presentations created for the Technology Transfer Workshop will be used to develop the short course. Short course materials are being developed to be used as part of a series of future regional workshops on non-proprietary UHPC presented by ABC-UTC. Input on the proposed outline and topics to be included was solicited from the other project PIs during the project meeting on May 12, 2020 and additional discussion on the short course was held during a project meeting on October 9, 2020. Work has continued on refining the PowerPoint presentations to be used for the short course and on identifying information on non-proprietary UHPC work completed by state DOTs.

Task 5- Technology Transfer Workshop

A technology transfer workshop will be held during the fourth-quarter of this study to share performance of the “ABC-UTC Non-Proprietary UHPC Mix” with the ABC-UTC stakeholders. It will be coordinated by OU, but will involve presentations by each partner institution. Financial support for this workshop is included in the budget.

A two-part Technology Transfer Workshop was conducted at the 2019 International Accelerated Bridge Construction Conference in December 2019. The workshop was split into two, four-hour blocks. The morning session included presentations on the need for non-proprietary UHPC, mix proportioning and material selection, material properties of the “ABC-UTC Non-Proprietary UHPC mix”, durability properties of non-proprietary UHPC, structural performance of non-proprietary UHPC, and effect of local materials on mixture performance.

The morning session presentations were made by representatives from three of the five ABC-UTC partner institutions. Dr. Royce Floyd (OU) and Dr. Jeff Volz (OU) presented on material selection, material properties, durability, and research on non-proprietary UHPC across the country. Dr. Atorod Azizinamini (FIU) presented on UHPC applications and the need for non-proprietary UHPC and Dr. David Garber (FIU) presented on the effects of regional materials on UHPC mix performance. Dr. Mohamed Moustafa (UNR) presented on deck panel joint testing. More than 50 people attended the morning workshop.

The afternoon session included an interactive mixing, testing, and placement demonstration at the FIU materials laboratory where the attendees were able to see the non-proprietary UHPC mixed and tested. Graduate student Trevor Looney (OU) and Dr. Royce Floyd led these sessions with the support of Dr. David Garber, graduate student Esmail Shahrokhinasab (FIU), FIU laboratory staff. A photo of the mixing and placement demonstration is shown in Figure 31. Approximately 30 people attended the afternoon workshop. Attendees provided substantial constructive and helpful feedback throughout the workshop sessions.

A workshop with very similar content is being planned for 2021 as part of an ODOT sponsored project.

Figure 31. Placement of non-proprietary UHPC in demonstration formwork during the mixing and placement demonstration workshop at FIU

Task 6- Assembling Reports and "Guide for ABC-UTC Non-Proprietary UHPC"

Quarterly progress reports and a final report in Microsoft Word and ADA accessible Adobe Acrobat pdf will be provided at the end of the project year. In addition, recommendations and guidance for development and splice length of reinforcing bars cast in UHPC for bridge applications will be provided. A "Guide for ABC-UTC Non-Proprietary UHPC" will be developed incorporating the results of research performed by all partner institutions and described in individual proposals that will be submitted to ABC-UTC and prepared by partner universities. The research team will work with the project Research Advisory Board to identify next steps for implementation of non-proprietary UHPC and the Guide within state DOTs.

This report is the eighth for the project. Work on the final report and Guide is underway. Expected completion for the final report is in March 2021.

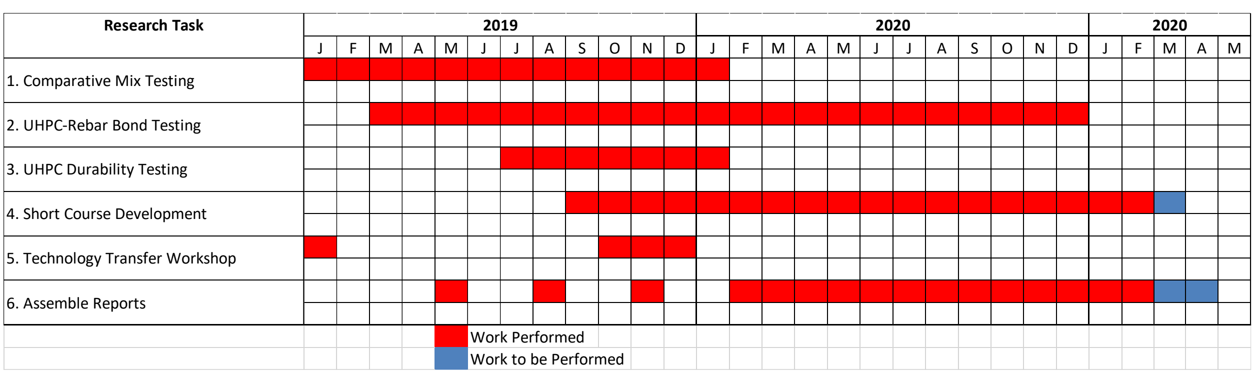
5. Expected Results and Specific Deliverables

Quarterly progress reports and a final report in Microsoft Word and ADA accessible Adobe Acrobat pdf will be provided at the end of the project. In addition, recommendations and guidance for development and splice length of reinforcing bars cast in UHPC for bridge applications will be provided. A synthesized summary of the ABC-UTC collaborative project will be included in the final report and a "Guide for ABC-UTC Non-Proprietary UHPC" will be developed incorporating the results of research performed by all partner institutions. This Guide will include the recommended "ABC-UTC Non-Proprietary UHPC Mix", recommendations for adjusting the Mix for variations in local constituent materials, and recommendations for fiber content necessary for specific applications.

6. Schedule

Progress of tasks in this project is shown in the table below. Restrictions on on-site work at OU due to the COVID-19 pandemic delayed completion of the last few laboratory items required for this project until late 2020, but all lab work has been completed. Similar restrictions delayed work at the other partner institutions. Work is nearing completion at all partner institutions.

Item	% Completed
Percentage of Completion of this project to Date	98%



7. References

1- AASHTO (2014) *AASHTO LRFD Bridge Design Specifications*, 5th edition, Washington, D.C.
2- ACI Committee 408 (2003) "Bond and Development of Straight Reinforcing Bars in Tension (408R-03)," *Technical Documents*, American Concrete Institute, Farmington Hills, MI.
3- ASTM Standard C39 (2016) "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA.
4- ASTM Standard C78 (2015) "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," ASTM International, West Conshohocken, PA.
5- ASTM Standard C109 (2016) "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens," ASTM International, West Conshohocken, PA.
6- ASTM Standard C157 (2014) "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM International, West Conshohocken, PA.
7- ASTM Standard C469 (2014) "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," ASTM International, West Conshohocken, PA.
8- ASTM Standard C496 (2011) 'Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA.
9- ASTM Standard C512 (2015) "Standard Test Method for Creep of Concrete in Compression," ASTM International, West Conshohocken, PA.
10- ASTM Standard C666 (2015) "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," ASTM International, West Conshohocken, PA.
11- ASTM Standard C672 (2012) "Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," ASTM International, West Conshohocken, PA.
12- ASTM Standard C1202 (2017) "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA.
13- ASTM Standard C1437 (2015) "Standard Test Method for Flow of Hydraulic Cement Mortar," ASTM International, West Conshohocken, PA.
14- ASTM Standard C1583 (2013) "Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method), ASTM International, West Conshohocken, PA.
15- ASTM Standard C1856 (2017) "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete," ASTM International, West Conshohocken, PA.
16- Graybeal, B.A. and Baby, F. (2013) "Development of Direct Tension Test Method for Ultra-High Performance Fiber-Reinforced Concrete," *ACI Materials Journal*, 110(2): 117-186.

17- Haber, Z.B., De la Varga, I., Graybeal, B.A., Nakashoji, B., El-Helou, R. (2018) "Properties and Behavior of UHPC-Class Materials," FHWA-HRT-19-036, March 2018, 151 pp.
18- Ramirez, J.A. and Russell, B.W. (2008). *Splice Length for Strand/Reinforcement in High-Strength Concrete*, NCHRP Project 12-60 Report, Transportation Research Board, Washington, D.C.
19- RILEM (1994) "RC5: Bond Test for Reinforcing Steel. 1. Pullout test," *RILEM Technical Recommendations for the Testing and Use of Construction Materials, 7-II-128*, E&FN Spon, London, U.K.……………………..