EXPLORING FIBER-REINFORCED POLYMER CONCRETE FOR ACCELERATED BRIDGE CONSTRUCTION APPLICATIONS

Quarterly Progress Report
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Submitted by:
PI: Travis Thonstad
Research Assistant: Carolyn Donohoe

Affiliation: Department of Civil and Environmental Engineering
University of Washington

ABC UTC
ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

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ABC-UTC
Florida International University
Miami, FL

1. Background and Introduction

The use of precast concrete superstructure elements is a popular strategy for accelerated bridge construction (ABC) and rehabilitation projects. The major advantage is that precast concrete elements can be fabricated before, or in parallel with, on-site activities, thus expediting project delivery. To complete the superstructure, closure joints between adjacent precast superstructure elements are filled with a field-cast material, creating continuity between the concrete elements and splicing steel reinforcement that protrudes from the precast members into the joints. The geometry of the closure joints, the speed at which the connections can be completed, how long before the bridge can be opened to traffic, and the cost of the system are all dependent on the material that is used to fill the gaps between precast elements. The closure joint material must possess strength and durability equal to or better than the adjacent concrete and must be capable of transferring the tensile forces between reinforcement from adjacent elements.

2. Problem Statement

The tension and bond strengths of ultra-high performance concrete (UHPC) make it an excellent closure joint material. However, the time at which UHPC achieves its design strength is directly proportional to the rate of hydration of the cementitious binder. While UHPC may provide the best solution in many instances, alternative joint materials that utilize polymer binders, instead of cementitious ones, may be more suitable if rapid strength gain is needed. This project explores a potential alternative closure joint material, fiber-reinforced polymer concrete (FRPC), which displays levels of the two critical characteristics (bond and tension strength) that are comparable to, or potentially better than, those of UHPC. FRPC has the advantage of requiring shorter closure windows (approximately 4 hours versus 72 hours of UHPC) due to the very rapid strength gain of the polymer, which could be ideal for overnight construction or rehabilitation projects, and provides an additional option to the engineer and contractor when choosing a closure joint material for a particular circumstance.

3. Objectives and Research Approach

The objectives of the proposed research are to review the most promising FRPC materials, assess the temperature dependent properties of FRPC behavior, characterize the mechanical properties (tensile, flexural, and compressive strength) of cast FRPC, and characterize the splice performance of deformed bars embedded in FRPC materials. Based on the results of this experimental investigation, recommendations for the use of FRPC in ABC applications will be developed to maximize the benefit of this relatively new material for different ABC project applications.

4. Description of Research Project Tasks

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

Task 1 – Literature Review

This task is complete. Previous research on fiber reinforced polymer concrete has been compiled and separated into areas of interest pertinent to bridge construction applications. A summary of the compiled research can be found in the September 2021 Progress Report.

Task 2 – FRPC Material Characterization

This task is in nearly complete. The objective of this task is to characterize the mechanical properties of a commercially available FRPC material (compressive strength, modulus of elasticity, flexural toughness, and tension strength) at several test temperatures and ages using standard test methods that would be part of a typical quality control program. The use of commercially available chemistries is preferred so that the results of the research are scalable. A summary of progress-to-date is given below.

Polymer concrete has been used in a variety of commercial uses such as floor drains, utility drains, etc. since the 1970s (ACI 2019) with its first uses in the United States in 1958 as building cladding (Fowler 1999). A variety of commercially produced PC products are available throughout the US and are typically provided in prepackaged bags and pails. While some data on the mechanical properties of different FRPC mixtures exists in the literature or is available through product data sheets, the wide variability in formulations makes generalization between different products difficult.

A commercially available FRPC material has been identified, Kwik Bond Polymers Hybrid Composite Synthetic Concrete (HCSC). HCSC comprises a hybrid co-polymer resin binder, graded aggregates, and pre-blended basalt fibers. A high molecular weight methacrylate (HMWM) primer is used in conjunction with the binder for bonding HCSC to concrete and steel substrates. Kwik Bond Polymers has donated the required HCSC materials for this project. Representatives from the company have worked with the research team to develop procedures for proportioning, mixing, and molding HCSC in the lab and were on site for initial trial mixtures.

Fig. 1. Laboratory mixing process for HCSC (1) addition of initiator and accelerator to binder resin, (2) addition of binder to mixer, (3) addition of aggregates and fibers to mixer, (4) mixing

Fig. 1 shows the laboratory mixing process for HCSC. One of the perceived advantages of HCSC and other commercially available polymer concretes in comparison to UHPC is the simplicity for the end user (i.e., the contractor). In the laboratory, HCSC resin was first mixed with the desired ratios of methyl ethyl ketone peroxide (MEKP) intiator and accelerator using a standard squirrel cage mixer (a dosage of 3% accelerator by volume initiator was selected for this project after initial trial batches). The resin, along with bags of pre-packaged aggregate blend, were then added to a standard drum mixer and mixed for roughly two minutes. The mixture was then ready to be discharged and placed. In a field application, mixing would typically be completed using a volumetric mix truck to accommodate the required quantity of material.

Fig. 2 shows the experimental setups and HCSC test specimens for Task 2 testing. The development of mechanical properties over time and influence of temperature on the mechanical properties of cured HCSC were investigated by experimentally testing beam and cylinder specimens under monotonic loads to failure.

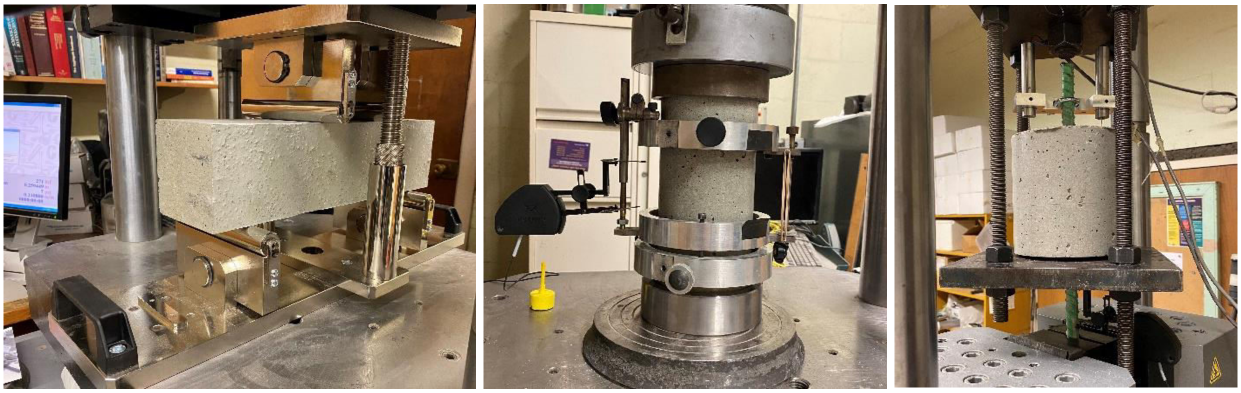

(a) (b) (c)

Fig. 2. FRPC Material Characterization Tests (a) Modulus of Rupture (b) Modulus of Elasticity and Compressive Strength (c) Bond Pullout Strength

To elucidate the influence of temperature on the mechanical properties of HCSC, test specimens (cylinders, beams, bar pulls) were cast and allowed to cure under ambient conditions (roughly 75 °F and 45% RH) for 7 days. The specimens were then conditioned to the target test temperatures (0 °F, 32 °F, 120 °F) using temperature-controlled cabinets. The specimens were kept in the temperature-controlled cabinets for at least 16 hours prior to testing to achieve the desired internal temperature, monitored by embedded thermocouples in select specimens. The specimens were then removed, one-by-one, from the cabinets and tested promptly. The surface temperature of the specimens was recorded before and after each test. Three specimens per temperature were tested. A set of specimens were also tested under ambient conditions at 7 days for reference.

Fig. 3 shows the influence of testing temperature on the mechanical properties of the test samples. The normalized strength was calculated by dividing the strength data by the corresponding average ambient temperature value, was used here to enable comparison between the three strengths (compression, flexure, and bond), and was plotted in Fig. 3 against the surface temperature at the time of testing. Deviation from the target temperature was evident in the data, due to changes in specimen temperature during handling and setup. Several observations can be made:

- The variation in mechanical properties with temperature was consistent between the three sets of tests.
- The material strengths were higher at cooler temperatures and lower at elevated temperatures when compared to strengths measured at room temperature.
- The relationship between strength and temperature was roughly linear, although the lines had a slight negative curvature.
- A temperature change of 40 °F resulted in a roughly 25% change in material strength, a significant variation that must be accounted for in design.

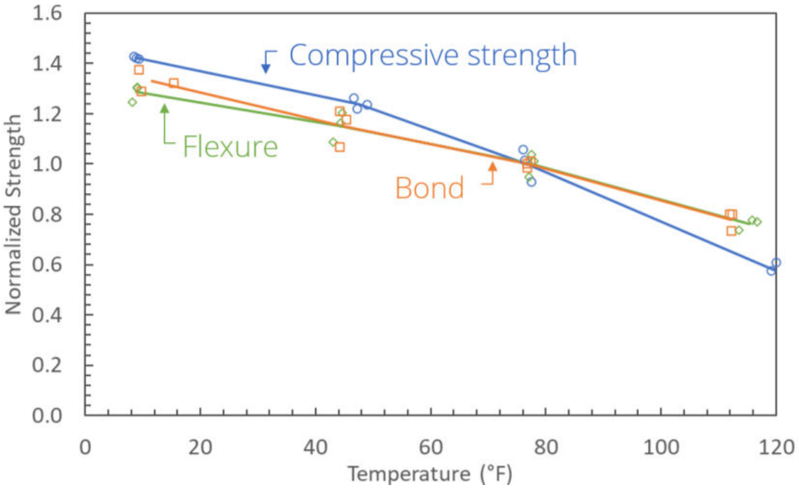


Fig. 3. Normalized strength (compression, flexture, and bond) as a function of test temperature

To quantify the evolution of mechanical properties over time, especially the strength gain over the first few hours after mixing, test specimens (cylinders, beams, bar pulls) were cast and allowed to cure under ambient conditions (roughly 75 °F and 45% RH). Starting at the earliest feasible time (determined to be 2 hours after mixing), specimens were removed from their molds and tested to failure at least every hour, until 8 hours after mixing. The remaining specimens were tested at convenient intervals, and three specimens were reserved for testing at 7 days.

Figure 4 shows the development of the normalized strength as a function of time after mixing. Both compressive and flexural strengths are shown; the remaining bond test series is scheduled for early December 2021. The normalized strengths were calculated by dividing the compressive or flexural strength data by the corresponding 7-day values (i.e., the normalized strength at 7 days is exactly 1.0). Several observations can be made:

- Both curves asymptotically approached the 7-day value, as expected.
- The development of flexural strength occurred sooner than the development of the compressive strength. This is consistent with observations made by others for cementitious concretes (e.g., Peruchini et al., 2021) although the behavior is seen here on a scale of hours rather than days.
- By 4 hours after mixing, the compressive and flexural strengths were 70% and 80% of their 7-day values, respectively. This would likely be sufficient to allow reopening.

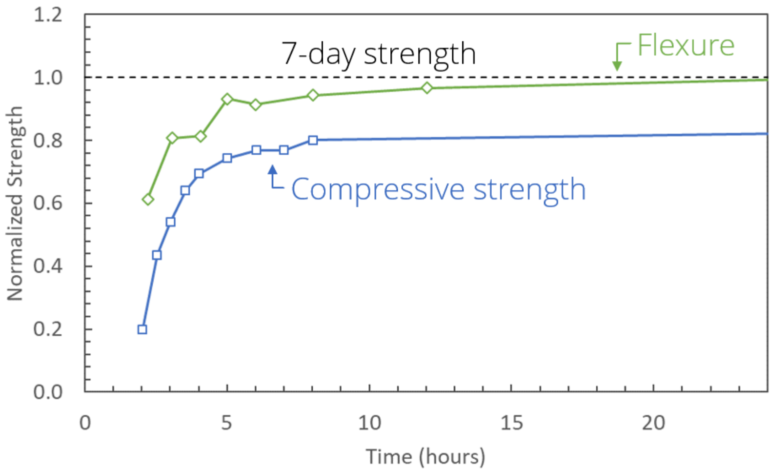


Fig. 4. Normalized strength (compression, flexture) as a function time after mixing

Figure 5 shows the normalized compressive strength, as a function of time after mixing, for three levels of accelerator, measured as a volume ratio to the initiator. The volume of the accelerator can be adjusted to achieve a range of working and curing times or to accommodate particular site conditions (cold/hot weather). The normalized strengths were calculated by dividing the compressive strength data by the corresponding 7-day values (i.e., the normalized strength at 7 days is exactly 1.0). Two test series were performed at the start of the project to determine the appropriate level of accelerator to use for the remainder of the project and, therefore, have fewer data points. The strength gain over time for a non-proprietary UHPC is also shown for reference (Peruchini et al., 2021). The figure clearly shows the tradeoff between working time and the development in strength. If shorter working times can be tolerated, significant strength (70% of the 7-day value) can be achieved 2 hours after mixing.

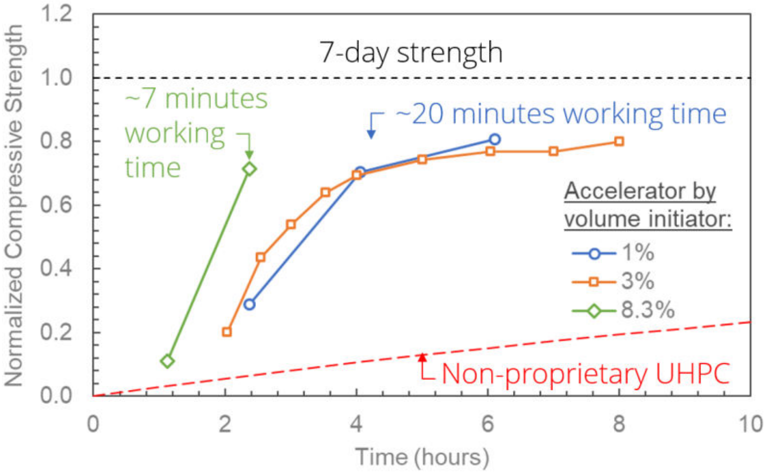
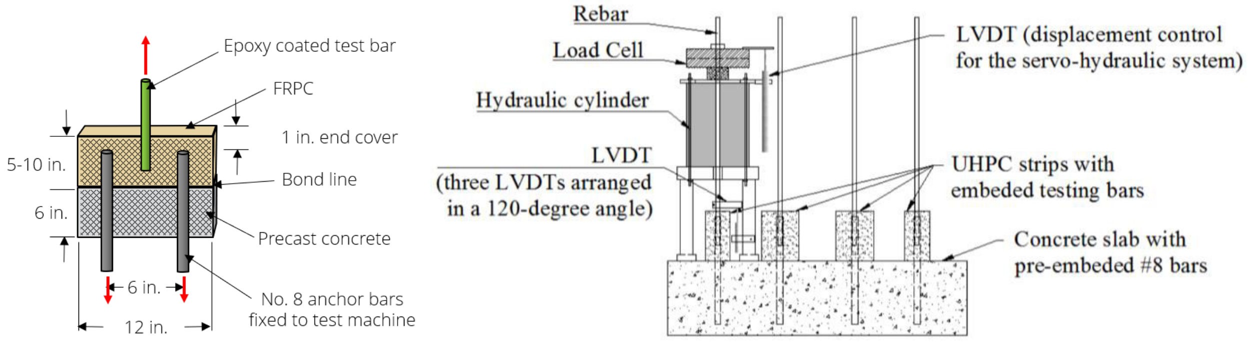


Fig. 5. Normalized compressive strength as a function time after mixing for three levels of accelerator by volume initiator.

Task 3 – Testing of Splice Specimens

Planning for this task is underway. The objective of this task is to characterize the non-contact splice performance of epoxy coated deformed bars embedded in FRPC materials. The tests will focus on a simplified, non-contact splice configuration that isolates the behavior of reinforcement in a closure joint to a specimen size that can be conditioned to different temperatures using conventional laboratory equipment and tested using a universal testing machine under precise displacement control. The variables that will be investigated include the temperature at time of testing, overlap length between bars, side cover, and bar size.

Fig 6 shows the simplified non-contact splice configuration that will be used in this project and the setup used by Yuan and Graybeal (2014) at FHWA to investigate the non-contact lap-splice performance of reinforcement in UHPC, for reference. The use of a precast slab, similar to the FHWA tests, would have increased the test complexity and cost and has not been shown to significantly influence the performance of non-contact splice specimens in previous studies (e.g. Yuan and Graybeal, 2014; Haber and Graybeal, 2018); neither concrete damage in the precast slabs nor tension failure between the UHPC strip and the precast concrete were reported during testing. Therefore, steel fixtures will be used to anchor the reinforcement instead of a slab. The addition of a precast concrete "strip" between anchor bars, roughly equal in size to the FRPC strip and below the splice, acts to stiffen the specimen. A roughened surface will be provided on the precast concrete strip, the surface will be primed using HMWM, and HCSC will be cast against it in the horizontal position, mimicking the field orientation of the joint. The non-contact splice specimens will be conditioned using temperature control cabinets and identical procedures to those used for the Task 2 specimens.



(a) (b)

Fig. 6. Pullout test loading setup (a) this study (b) FHWA study (Yuan and Graybeal, 2014).

Table 1 shows the preliminary test plan for Task 3. The experimental plan for this test series was constructed to be a rotatable central composite design (CCD) (Box et al., 2005) in test temperature, T; splice length, ℓ_s; side cover, c_b; and bar diameter, d_b. This design includes an embedded factorial design, repeated center points to quantify batch-to-batch uncertainty, and additional axial points that allow for the estimation of curvature in the region of interest. The experimental design was centered around the point (T =75 °F, ℓ_s = 3.75 in, c_b = 2.5 in, and d_b = 0.63 in) in the parameter space.The tests will be conducted in three sets, or "blocks", comprising 10 specimens apiece. Each block of specimens will be made from the same batch of HCSC.

Table 1. Task 3 Experimental Matrix

	Run	***Temperature T (°F)***	***Splice length ℓ_s (in)***	***Cover C_b (in)***	***Bar diameter d_b (in)***	***Point Description***
Block / Batch 1	1-1	45	5.00	1.88	0.50	Factorial
	1-2	45	2.50	3.13	0.50	Factorial
	1-3	115	2.50	1.88	0.50	Factorial
	1-4	115	5.00	3.13	0.50	Factorial
	1-5	45	2.50	1.88	0.75	Factorial
	1-6	45	5.00	3.13	0.75	Factorial
	1-7	115	5.00	1.88	0.75	Factorial
	1-8	115	2.50	3.13	0.75	Factorial
	1-9	80	3.75	2.50	0.63	Center
	1-10	80	3.75	2.50	0.63	Center
Block / Batch 2	2-1	45	2.50	1.88	0.50	Factorial
	2-2	45	5.00	3.13	0.50	Factorial
	2-3	115	5.00	1.88	0.50	Factorial
	2-4	115	2.50	3.13	0.50	Factorial
	2-5	45	5.00	1.88	0.75	Factorial
	2-6	45	2.50	3.13	0.75	Factorial
	2-7	115	2.50	1.88	0.75	Factorial
	2-8	115	5.00	3.13	0.75	Factorial
	2-9	80	3.75	2.50	0.63	Center
	2-10	80	3.75	2.50	0.63	Center
Block / Batch 3	3-1	80	3.75	2.50	***0.38***	Axial
	3-2	80	3.75	2.50	***0.88***	Axial
	3-3	***10***	3.75	2.50	0.63	Axial
	3-4	***150***	3.75	2.50	0.63	Axial
	3-5	80	3.75	***1.25***	0.63	Axial
	3-6	80	3.75	***3.75***	0.63	Axial
	3-7	80	***1.25***	2.50	0.63	Axial
	3-8	80	***6.25***	2.50	0.63	Axial
	3-9	80	3.75	2.50	0.63	Center
	3-10	80	3.75	2.50	0.63	Center

Modifications to the preliminary plan are now being finalized based on input from the advisory panel and the results of Task 2. The testing is expected to be completed in Q1 2022.

Task 4 – Development of Design Recommendations

No progress has yet been made on this task. The results of the non-contact lap-splice tests and the measured mechanical properties will be used to develop design recommendations for precast concrete closure joints using FRPC. These design recommendations will be used to develop example joint configurations for connecting common precast concrete superstructure elements, such as decked girders or precast deck panels.

Task 5 – Interim and Final Reporting

This task in ongoing. The research team will submit timely quarterly reports, present annually at the Research Days meeting, and complete final report summarizing findings reached during the project.

5. Expected Results and Specific Deliverables

The successful completion of the research project will directly impact the design/construction industry, by providing a better understanding of the properties of FRPC and its potential for use in closure joints between precast members, such as decked bulb tees, PCI NEXT beams, or precast deck panels. The main deliverable will be a report that summarizes:

- Recommendations for the selection of FRPC as a closure joint material in ABC applications,
- Design equations for the required development length of epoxy coated reinforcement embedded in FRPC, and
- Example closure joint geometry utilizing FRPC.

In addition, the results of the project will be summarized in a 5-min demonstration video and a journal publication.

6. Schedule

Progress on tasks in this project is shown in the tables below.

Item	% Completed
Percentage of Completion of this project to Date	50%

Research Tasks	2021											2022					
	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Task 1 – Literature Review	▨	▨	▨	▨	▨	▨											
Task 2 – FRPC Material Characterization				▨	▨	▨	▨	▨	▨	▨	■						
Task 3 – Testing of Splice Specimens											■	■	■	■			
Task 4 – Development of Design Recommendations															■	■	■
Task 5 – Interim and Final Reporting				▨			▨			▨			■			■	■

Work performed ←|→ Work to be performed

7. References

ACI. (2019). *Polymer Concrete: Guidelines for Structural Applications (ACI 548.6R-19).* Committee 548, American Concrete Institute, Farmington Hills, MI, USA.

Box, G.E.P., Hunter, W.G., and Hunter, J.S. (2005). Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building. 2nd edition. John Wiley & Sons, New York.

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Haber, Z.B. and Graybeal, B.A. (2018) “Lap-Spliced Rebar Connections with UHPC Closures” J. Bridge Eng, 04018028

Peruchini, T.J., Stanton, J., and Calvi, P. (2021) “Longitudinal Joints between Deck Bulb Tee Girders Made with Nonproprietary Ultra-High-Performance Concrete” J Bridge Eng, 26 (12): 04021092

Yuan, J. and Graybeal, B. (2014) “Bond Behavior of Reinforcing Steel in Ultra-High Performance Concrete.” Report No. FHWA-HRT-14-90, USDOT FHWA, Washington, DC.