

**EXPLORING FIBER-REINFORCED POLYMER CONCRETE FOR
ACCELERATED BRIDGE CONSTRUCTION APPLICATIONS**

**Quarterly Progress Report
For the period ending August 31, 2021**

Submitted by:
PI: Travis Thonstad
Research Assistant: Carolyn Donohoe

**Affiliation: Department of Civil and Environmental Engineering
University of Washington**



**ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER**

Submitted to:
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 chapter of the final report, summarizing the findings of this research, is currently being developed.

The behavior of polymer concrete is highly dependent on the chemistry of the binder. Other important factors include the proportioning of binder and aggregates in the mixture and the aggregate composition and type. Of the potential binder chemistries, epoxy, methacrylate, and polyester have been extensively studied for polymer concrete. Fig. 1 compares the compressive stress-strain behavior of several polymer concretes available in the literature. The stress-strain behavior for conventional concrete and ultra-high-performance concrete are also included for reference. Compressive behavior is shown here because it is the most widely reported; however, similar plots could be constructed for flexural or tensile strengths with similar observations made.

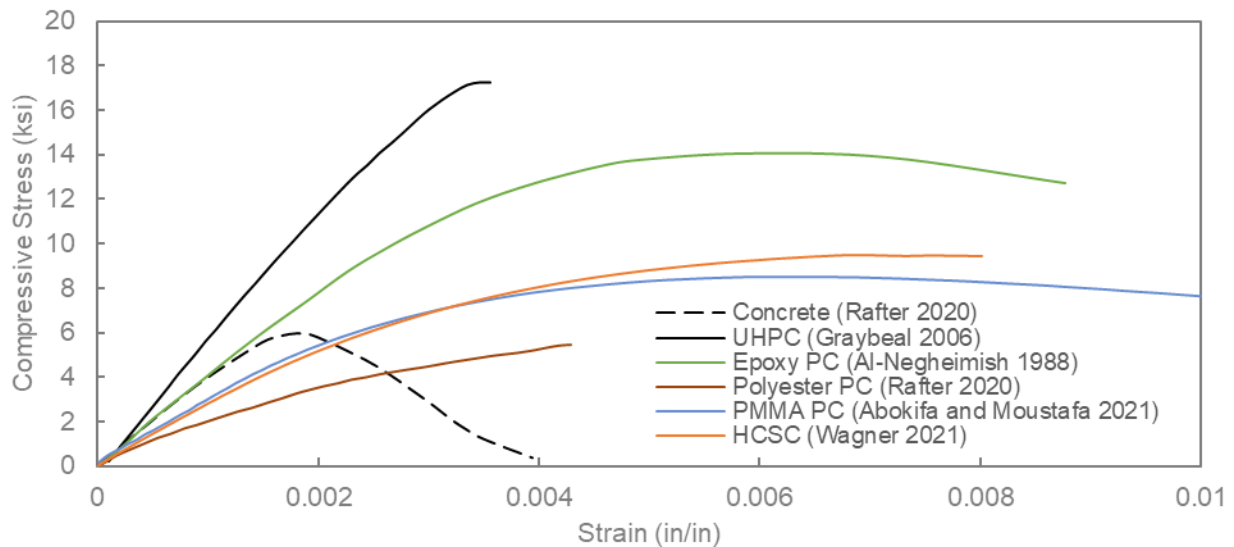


Fig. 1. Compressive stress-strain behavior of polymer concretes at room temperature

In general, polymer concretes can be designed with comparable or higher compressive strengths than conventional cementitious concrete at room temperature. These strengths are achieved at a much larger strain, and therefore polymer concretes tend to exhibit lower elastic moduli when compared with conventional cementitious concrete. Additionally, the mechanical properties of polymer concretes vary considerably with temperature, strain rate, and load duration.

The influence of temperature on the properties of polymer concretes is of particular interest for ABC applications. Table 1 summarizes previous experimental campaigns that have considered the influence of temperature on the mechanical properties of polymer concretes. Researchers have investigated the influence of temperature at several different stages: during curing or hardening of the polymer binder, freeze/thaw cycling, exposure to extreme temperatures prior to testing at ambient conditions, and during the testing itself. The studies in Table 1 are separated by these different test regimes.

Fig. 2 shows the influence of testing temperature on the compressive strength of several polymer concretes. Compressive behavior is shown here because it is the most widely reported; however, similar plots could be constructed for flexural or tensile strengths with similar observations made.

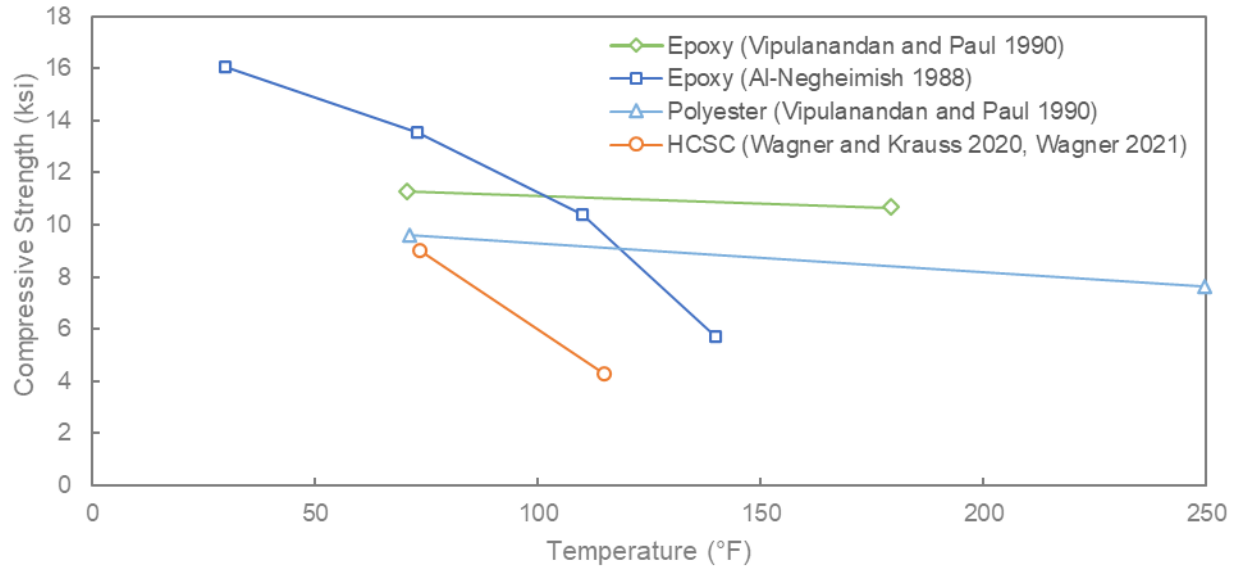


Fig. 2. Influence of temperature on compressive strength of polymer concretes

In general, the strength of polymer concretes varies inversely with temperature. At lower temperatures, polymer concretes have higher strengths and elastic moduli and lower strain capacities when compared to the properties at room temperature. The reverse is true at higher temperatures. While this trend holds for all polymer concretes, the variation in mechanical properties as a function of temperature depends significantly on the binder chemistry. Understanding the variation in mechanical properties with temperature for commercially available polymer concretes is critical for determining design recommendations for ABC closure joint applications.

As an additional tool for the modification of polymer concrete behavior, fibers can be added to the mixture of binder and aggregate. Fibers have been shown to increase the splitting tensile strength and ductility of the mixture and decrease the coefficient of thermal expansion, which is typically higher than that of conventional concrete and steel. Possible fiber materials include steel, glass, basalt, and other recycled materials. Various studies using epoxy and polyester PC with glass, carbon, or steel fibers have been conducted and are summarized in Table 2.

Table 1. Summary of research investigating the influence of temperature on polymer concretes

Author	Temperature varied	Resin	Reinforcement/ Fibers	Key conclusions
Hong 2017	Curing temperature	Epoxy	None	<p>Rapid strength gain in the first 24 hours of curing, with 27% of the compressive strength after 6 hours and 70% after 24 hours</p> <p>Flexural strength decreased with an increase in curing temperature. Slow decreases in the strength up to 20C then rapid decrease</p> <p>The bond strength exceeded the ACI recommendation of 1.7 MPa up to a curing temperature of 60 C</p> <p>Flexural strengths were highest at -10C and decreased with an increase in curing temperature. Specimens above 40C were insufficient per ACI recommendations</p> <p>There is a strong correlation coefficient between compressive strength and bond and flexural strength, indicating that the bond and flexural strength can be used to draw general conclusion from only compression strength data.</p>
Ribeiro et al. 2003b	Curing temperature	Epoxy, polyester	None	<p>Curing cycle does not influence the final mechanical properties, but the time required varies with temperatures. Seven days cure at room temperature was shown to be equivalent to three hours cur at 80C.</p> <p>Epoxy resin results in higher strengths with foundry sand and polyester resin results in higher strengths with clean sand</p>
Vipulanandan and Paul 1990	Curing temperature, test temperature	Epoxy, polyester	None	<p>Splitting tensile strength of epoxy PC is almost unchanged but increases with curing temperature for polyester PC.</p> <p>Gap-graded aggregates had the highest strength and modulus.</p> <p>The compressive strength increases with increases in temperature.</p>
Aboutaha et al. 2005	Test temperature	Epoxy (Transpo T48A, Flexolith, Redeck, Strongwell)	Varies with proprietary blend	<p>Compressive strength and modulus of PC is higher at low temperatures and lower at high temperatures compared to room temperature.</p> <p>The flexural modulus of PC increases at low temperatures and decreases at high temperatures.</p>

Al-Negheimish 1988	Test temperature	Epoxy	Gr 60 uncoated rebar for flexural tests	<p>The compressive strength of PC decreases with increases in temperature. The trend is linear between 30F and 110F with sharper decreases after 140F</p> <p>The modulus of elasticity decreases with increases in temperature</p> <p>At higher temperatures the stress-strain curve become nonlinear at lower percentages of ultimate strength</p>
Krauss and Lawler 2018	Test temperature	Polyester Polymer Concrete (PPC)	Gr 60 epoxy coated rebar, Gr 120 uncoated rebar	<p>For #6 bar, bar yield or breakage occurred for embedment of 4.5 and 7.5 inches (6*db or greater) at room temperature. For elevated temperatures (110F) the reinforcement pulled out before yielding was achieved. At an embedment of 7.5db and 3in side cover, the reinforcement had an average stress of 67700 psi at the time of pullout failure.</p> <p>As embedment length increases the bar stress at failure increased.</p> <p>No significant difference in failure stress of the PC was noted for specimens with epoxy coated versus uncoated reinforcement</p>
Wagner and Krauss 2020	Test temperature	Hybrid Composite Synthetic Concrete (HCSC)	Gr 60 epoxy coated rebar	<p>NYSDOT pull-out tests at elevated temperatures were sufficient to develop yield stress for the tested bars and embedment length</p> <p>The compressive strength of HCSC at elevated temperatures is less than the strength at room temperature.</p>
Oussama et al. 2012	Exposure temperature	Epoxy	None	<p>Optimum polymer content for highest mechanical performance and lowest cost is around 13%</p> <p>After being exposed to temperatures greater than 150C, the epoxy polymer displays loss of strength, primarily due to thermo-oxidative degradation and debonding between the binder and aggregate.</p> <p>After high temperature exposure, there is significant reductions in compressive strength, up to 50% loss after an exposure to 250C.</p> <p>Increases in flexural strength were report until 150C, then a reduction in strength was found. The behavior of the samples became more brittle with high temperature exposure</p>

Ribeiro et al. 2003a	Thermal expansion thermal cycle	Epoxy, polyester	Glass fibers (1% by weight), carbon fibers (2% by weight)	<p>At higher temperatures the coefficient of thermal expansion is higher. And at temperatures above 10C, the increase rate for epoxy PC is higher than polyester PC</p> <p>The addition of glass fibers had no significant influence of the coefficient of thermal expansion, while carbon fibers had a strong reducing effect.</p> <p>The coefficient of thermal expansion varies via a polynomial law and therefore vary continuously between -15C and 60C</p>
Heidari-Rarani et al. 2014	Freeze-thaw cycles, thermal fatigue cycles	Epoxy	E-glass fibers (0.5% by weight)	<p>Freeze/thaw cycles did not change the failure mode type</p> <p>Heat to cool thermal cycles increased the durability and load bearing capacity where the cool to heat thermal cycles increased the risk for brittle tensile fracture</p> <p>Fracture toughness was more sensitive to higher mean temperature cycles, where tensile strength was more influenced by lower mean temperature cycles</p>
Reis and Ferreira 2006	Freeze-thaw cycles, thermal fatigue cycles	Epoxy	Glass fibers (1% by weight), carbon fibers (2% by weight)	<p>With increases in peak temperature, the flexural elasticity decreases, and failure is more ductile, resulting in a higher fracture toughness.</p> <p>The high peak temperature also results in a loss of mechanical strength, due to degradation of the cohesion between polymeric chains.</p>
Ribeiro et al. 2004	Test temperature, Freeze-thaw cycles, Exposure temperature	Epoxy, polyester	None	<p>Freeze/thaw cycles between -10C and 10C resulted in little damage, potentially due to the reduced degree of water adsorption and water content</p> <p>Flexural properties are highly dependent on temperature, with epoxy being more sensitive than polyester</p> <p>Temporary changes in temperature have no significant influence on the flexural strength as long the specimen is returned to the original temperature.</p>

Table 2. Summary of research incorporating fiber-reinforced polymer concrete

Author	Resin	Reinforcement/ Fibers	Aggregate and microfillers	Key Conclusions
Heidari-Rarani et al. 2014	Epoxy	E-glass fibers (0.5% by weight)	Coarse mineral aggregate, foundry sand	Freeze/thaw cycles did not change the failure mode type Heat to cool thermal cycles increased the durability and load bearing capacity where the cool to heat thermal cycles increased the risk for brittle tensile fracture Fracture toughness was more sensitive to higher mean temperature cycles, where tensile strength was more influenced by lower mean temperature cycles
Reis 2005	Epoxy (Silicem eposil 551)	Glass fibers (1% by weight), carbon fibers (2% by weight)	Siliceous foundry sand	The addition of fibers increases the compressive strength compared to unreinforced PC. Glass fibers resulted in an increase of 27.5-45.4% and 36.1-55.1% for carbon fibers. Fibers also result in a slightly more ductile failure; unreinforced PC displays a brittle failure
Reis and Ferreira 2006	Epoxy	Glass fibers (1% by weight), carbon fibers (2% by weight)	Siliceous foundry sand	With increases in peak temperature, failure is more ductile, resulting in a higher fracture toughness. High peak temperature results in a loss of mechanical strength, due to degradation of the cohesion between polymeric chains.
Ribeiro et al. 2003	Epoxy, polyester	Glass fibers (1% by weight), carbon fibers (2% by weight)	Siliceous foundry sand	At higher temperatures the coefficient of thermal expansion is higher. And at temperatures above 10C, the increase rate for epoxy PC is higher than polyester PC The addition of glass fibers had no significant influence of the coefficient of thermal expansion, while carbon fibers had a strong reducing effect. The coefficient of thermal expansion varies via a polynomial law and therefore vary continuously between -15C and 60C
Mebarkia and Vipulanandan 1992	Polyester	Glass fibers, (6% by weight)	Blasting sand (well-graded)	An increase of fibers result in a reduction of the compressive modulus and an increase in compressive strength of 33% over unreinforced PC Glass fibers increased the failure strain and toughness

Sett and Vipulanandan 2004	Polyester	Glass fibers, carbon fibers, 0-6% by weight	Blasting sand (well-graded)	<p>Optimum polymer content is 14% when unreinforced. With 6% glass fibers, 18% polymer is optimal for strength and workability. For 6% carbon fibers, 20% polymer is optimal for workability and tensile strength.</p> <p>Tensile strength of PC is improved by 85% and 60% from the additional of 6% fibers, glass and carbon, respectively.</p> <p>Glass fibers improved the compressive strength of PC, but carbon fibers did not have a significant difference</p>
Vipulanandan and Mebarkia 1996	Polyester	Glass fibers, 0-6% by weight	Blasting sand (well-graded)	<p>The addition of 6% glass fibers with 18% polymer content resulted in an 80% increase in flexural strength compared to unreinforced PC.</p> <p>Silane treated aggregates and fibers doubled the flexural strength for a mix including 6% glass fibers and 18% polymer content.</p>

Task 2 – FRPC Material Characterization

While some data on the mechanical properties of FRPC already exists in the literature, the wide variability in properties makes generalizations difficult between different commercially available products. The use of commercially available chemistries is preferred so that the results of the research are scalable. 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.

This task is in progress. A commercially available FRPC material has been identified, Kwik Bond Polymers Hybrid Composite Synthetic Concrete (HCSC), and materials have been donated by Kwik Bond Polymers for use in 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.

The experimental plan for Task 2 was discussed at a meeting with the advisory panel on July 19, 2021. In addition to testing samples cured at ambient temperatures and conditioned to several test temperatures, two additional batches will be cast and cured at the test temperatures and the amount of accelerator will be adjusted to maintain a reasonable working time. Additional considerations discussed in this meeting included evaluating non-destructive testing techniques for assisting with decision making on-site.

Fig. 3 shows the experimental setups and HCSC test specimens. Task 2 is currently underway. Strengths at 7 days are consistent with previously tested specimens by others and the product data sheets.

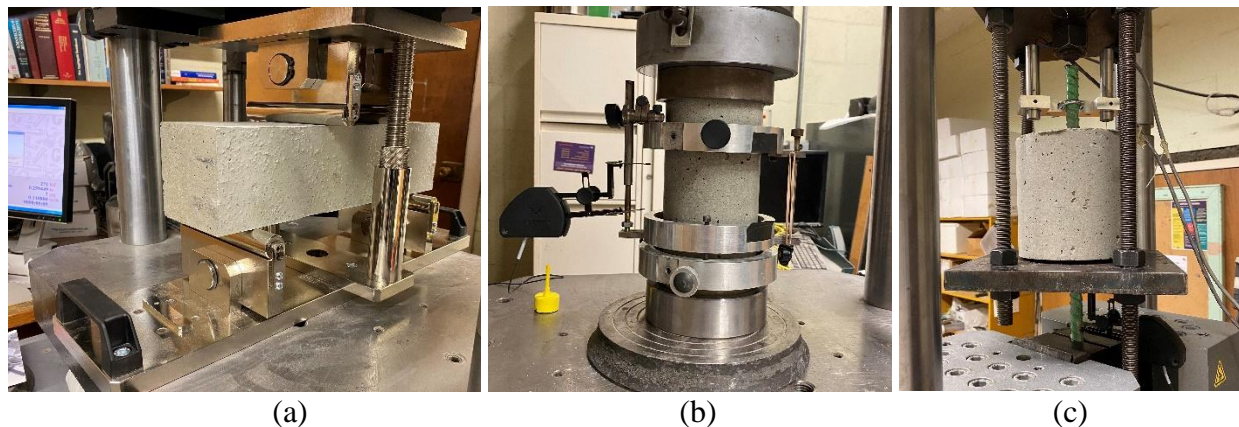


Fig. 3. FRPC Material Characterization Tests (a) Modulus of Rupture (b) Modulus of Elasticity and Compressive Strength (c) Bond Pullout Strength

Task 3 – Testing of Splice Specimens

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, embedded length of the bar, overlap length between bars, side cover, and bar size.

Planning for this task is underway. A preliminary test plan was developed and discussed with the advisory panel. Modifications to the preliminary plan are now being based on their input and the preliminary results of Task 2. Fabrication of the testing fixtures will commence as soon as the procedure is finalized and is expected to be completed over Summer 2021.

Task 4 – Development of Design Recommendations

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.

No progress has yet been made on this task.

Task 5 – Interim and Final Reporting

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.

This task is ongoing.

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	30%

Research Tasks	2021												2022		
	F	M	A	M	J	J	A	S	O	N	D	J	F	M	
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

- Abokifa, M., and Moustafa, M. A. (2021). “Experimental behavior of poly methyl methacrylate polymer concrete for bridge deck bulb tee girders longitudinal field joints.” *Construction and Building Materials*, 270, 121840.
- Aboutaha, R. S., Lui, E. M., Martin, G., Petrina, P., Phoenix, L., and Giannelis, E. (2005). *Investigation of Durability of Wearing Surfaces for FRP Bridge Decks*. Syracuse University, Cornell University, 397.
- ACI. (2019). *Polymer Concrete: Guidelines for Structural Applications (ACI 548.6R-19)*. Committee 548, American Concrete Institute, Farmington Hills, MI, USA.
- Al-Negheimish, A. I. (1988). “Bond strength, long term performance and temperature induced stresses in polymer concrete-portland cement concrete composite members.” The University of Texas of Austin, Austin, Texas.
- Graybeal, B. A. (2006). Material Property Characterization of Ultra-High Performance Concrete. 188.
- Heidari-Rarani, M., Aliha, M. R. M., Shokrieh, M. M., and Ayatollahi, M. R. (2014). “Mechanical durability of an optimized polymer concrete under various thermal cyclic loadings – An experimental study.” *Construction and Building Materials*, 64, 308–315.
- Hong, S. (2017). “Influence of Curing Conditions on the Strength Properties of Polysulfide Polymer Concrete.” *Applied Sciences*, 7(8), 833.
- Krauss, P. D., and Lawler, J. S. (2018). *Bond Behavior of Reinforcing Steel in Kwik Bond Polyester Polymer Concrete*. Final Report for Kwik Bond Polymers WJE No. 2006.4138.6.
- Mahdi, F., Abbas, H., and Khan, A. A. (2013). “Flexural, shear and bond strength of polymer concrete utilizing recycled resin obtained from post consumer PET bottles.” *Construction and Building Materials*, 44, 798–811.
- Mebarkia, S., and Vipulanandan, C. (1992). “Compressive Behavior of Glass-Fiber Reinforced Polymer Concrete.” *Journal of Materials in Civil Engineering*, 4(1), 91–105.
- Oussama, E., Elhem, G., Mignot, V., and Mongi, B. O. (2012). “Mechanical and physical properties of epoxy polymer concrete after exposure to temperatures up to 250°C.” *Construction and Building Materials*, 27(1), 415–424.

- Rafter, C. (2020). "Hybrid Composite Synthetic Concrete (HCSC)." *Presentation to WSDOT*, September 2020.
- Reis, J. M. L. dos. (2005). "Mechanical characterization of fiber reinforced Polymer Concrete." *Materials Research*, 8(3), 357–360.
- Reis, J. M. L., and Ferreira, A. J. M. (2006). "Freeze–thaw and thermal degradation influence on the fracture properties of carbon and glass fiber reinforced polymer concrete." *Construction and Building Materials*, 20(10), 888–892.
- Ribeiro, M. C. S., Nóvoa, P. R., Ferreira, A. J. M., and Marques, A. T. (2004). "Flexural performance of polyester and epoxy polymer mortars under severe thermal conditions." *Cement and Concrete Composites*, 26(7), 803–809.
- Ribeiro, M. C. S., Reis, J. M. L., Ferreira, A. J. M., and Marques, A. T. (2003a). "Thermal expansion of epoxy and polyester polymer mortars—plain mortars and fibre-reinforced mortars." *Polymer Testing*, 22(8), 849–857.
- Ribeiro, M. C. S., Tavares, C. M. L., Figueiredo, M., Ferreira, A. J. M., and Fernandes, A. A. (2003b). "Bending characteristics of resin concretes." *Materials Research*, 6(2), 247–254.
- Sett, K., and Vipulanandan, C. (2004). "Properties of Polyester Polymer Concrete with Glass and Carbon Fibers." *ACI Materials Journal*, 101(1).
- Vipulanandan, C., and Mebarkia, S. (1996). "Flexural and Facture Properties of Glass Fiber Reinforced Polyester Polymer Concrete." *ACI Symposium Publication*, 166.
- Vipulanandan, C., and Paul, E. (1990). "Performance of Epoxy and Polyester Polymer Concrete." *ACI Materials Journal*, 87(3).
- Wagner, E. (2021). *Kwik Bond Hybrid Composite Synthetic Concrete (HCSC) Material Characterization*. Final Report for Kwik Bond Polymers WJE No. 2006.4138.9.
- Wagner, E. I., and Krauss, P. D. (2020). *Bond Behavior of Reinforcing Steel in Kwik Bond HCSC Material*. Final Report for Kwik Bond Polymers WJE No. 2006.4138.8.