OPTIMIZATION OF ADVANCED CEMENTITIOUS MATERIAL OVERLAYS AND UPGRADES, INCLUDING SHOTCRETE

Quarterly Progress Report
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Submitted by:
Graduate Student- Morgan Dickinson, PE
Graduate Student-Muhammad Faheem Afzal

PI- Islam Mantawy, Ph.D., PE

Affiliation: Department of Civil and Environmental Engineering
Florida International University
Miami, Florida

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

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ABC-UTC
Florida International University
Miami, FL

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1. Background and Introduction

Ultra-High strength concrete (UHPC) applications have been studied as one of the many strategies in Accelerated Bridge Construction (ABC). Bridge maintenance procedures can be accelerated with the application of UHPC in specific situations. Deck overlays have been placed over deteriorated and damaged bridge decks for many years in order to extend the deck service life. Application of UHPC has the potential to reduce lane closure time during the repair process if sufficient strength is obtained in a few hours. Typically, a concrete strength of 3,000 to 4,000 psi is required to open a lane to traffic. UHPC also provides a higher strength for the composite bridge deck section and mitigates additional corrosion by inhibiting penetration of additional chloride ions. Commercial UHPC mixes, with a lower slump, have been developed that have been shown to hold cross slopes up to 10% by adding admixtures.

Recent developments in UHPC mixes have been applied with pneumatic spray application. Such repair method may be applicable to horizontal, vertical, inclined, and overhead surfaces.

Significant research has been performed on UHPC and their applications as an overlay and upgrading material. However, as outlined later in this report, there are still a number of important questions and concerns that should be addressed and remain to be studied, in addition to the use of new techniques such as pneumatic spray application to eliminate the use of formwork.

This research project addresses the design considerations required for successful application of UHPC as an alternative material for deck overlay and other deck repairs and upgrades including the underside of bridge decks and flexural members such as superstructure girders. This research project will include a comprehensive literature review on bridge deck overlays and other upgrade applications; performing material level testing; performing large scale level testing for UHPC bridge deck overlays and upgrading flexural members, and conducting numerical modeling to optimize design parameters.

2. Problem Statement

Deterioration of bridge deck and flexural members is a major issue for bridge owners. The primary causes of deck deterioration include vehicle traffic, environmental effects (i.e. freeze-thaw, salt spray), and maintenance practices (snowplows, de-icing chemical treatments). Deterioration is featured by delamination, cracking, corrosion of reinforcing steel, abrasion, scaling, and other mechanisms. Deterioration of the top deck surface is common, but in coastal areas subjected to salt spray, the underside of the deck and superstructure girders, may also deteriorate.

One of the recent advances in UHPC application is the development of UHPC applied with pneumatic spray methods. Spraying UHPC to the underside of a bridge deck will save the time and effort of building formwork while providing the strength and corrosion mitigation technique discussed above.

While significant research has been conducted on UHPC and their applications as an overlay and repair material, there are still a number of questions and concerns that should be addressed which include:

1. Overlays are often placed in climates where de-icing salts are applied which cause deterioration of the top surface of the bridge deck. Deterioration may also occur on the bottom of the deck, particularly in coastal areas where salt-spray occurs. Repair techniques should be developed for the deteriorated bottom face of bridge deck and may include UHPC pneumatically sprayed are typically considered for the top surface of the deck, especially in northern applications. What changes to the UHPC mix designs will be required to successfully apply the material with spray methods?
2. Are the recently developed ABC-UTC non-proprietary UHPC mixtures suitable for bridge deck overlay and underside upgrade of bridge desks using pneumatic repair application?
3. UHPC mix designs typically contain 2% steel fibers, but some applications have been documented with different percentages. Synthetic fibers have been applied in some spray applications. What is the effect of the type and quantity of steel/synthetic fiber content? What modifications should be made to the mix based on the type and quantity of fibers?
4. What is the maximum achievable thickness of UHPC in pneumatic spray application, for different conditions such as horizontal versus vertical surfaces? Unpublished European practice reports on pneumatic spray application indicate a 3-inch thickness is achievable.
5. The durability of bridge elements, repaired, upgraded or protected using pneumatic spray application with steel and synthetic fibers should be investigated.
6. How can material rebound during the pneumatic spray application for different surfaces be minimized? This includes vertical surfaces (bridge columns and web of bridge girders), overhead surfaces (bottom of bridge decks and girders), and inclined surfaces (abutment wing walls).
7. What mix and material properties influence the pumpability of UHPC for pneumatic spray applications?
8. Hydro-blasting/Sandblasting and other methods of removing deteriorated concrete and surface preparation may result in varying thickness of overlay to attain design grades. What is the effect of such variation on the overlay performance?
9. Bonding of the UHPC to the adjacent normal strength concrete is an important factor. Bonding can be evaluated with Graybeal’s pull off test. Surficial friction can be measured with the push down tests or slant shear tests. How does the roughness of the interfacial surface between UHPC and normal strength concrete impact moment capacity? What is the optimum interfacial surface roughness?

10. Fatigue or cyclic loading research is lacking. More data is needed for the cyclic loading behavior on UHPC overlays.
11. Will higher tensile capacity of the UHPC allow the material to be placed over expansion joints on single span or as a link slab at intermediate supports? Covering the joints will reduce the level of maintenance needed for the joint. The advantages of reduced joint maintenance would be beneficial to bridge owners.
12. What are the optimum UHPC design mixes to retain a crowning slope up to 7%?
13. How is the section capacity of the composite section between UHPC deck overlay, deck normal strength concrete, and bridge girder altered?

3. Objectives and Research Approach

The objective of this study is to investigate the various parameters involved in optimizing the design of UHPC overlays and upgrades using pneumatic spray application and to develop design guidelines for UHPC overlays and upgrades. The activities listed below will be directed to this objective.

4. Description of Research Project Tasks

Following are description of tasks as described in the research proposal. Figure 1 shows the proposed flowchart for the project tasks for pneumatic UHPC application.

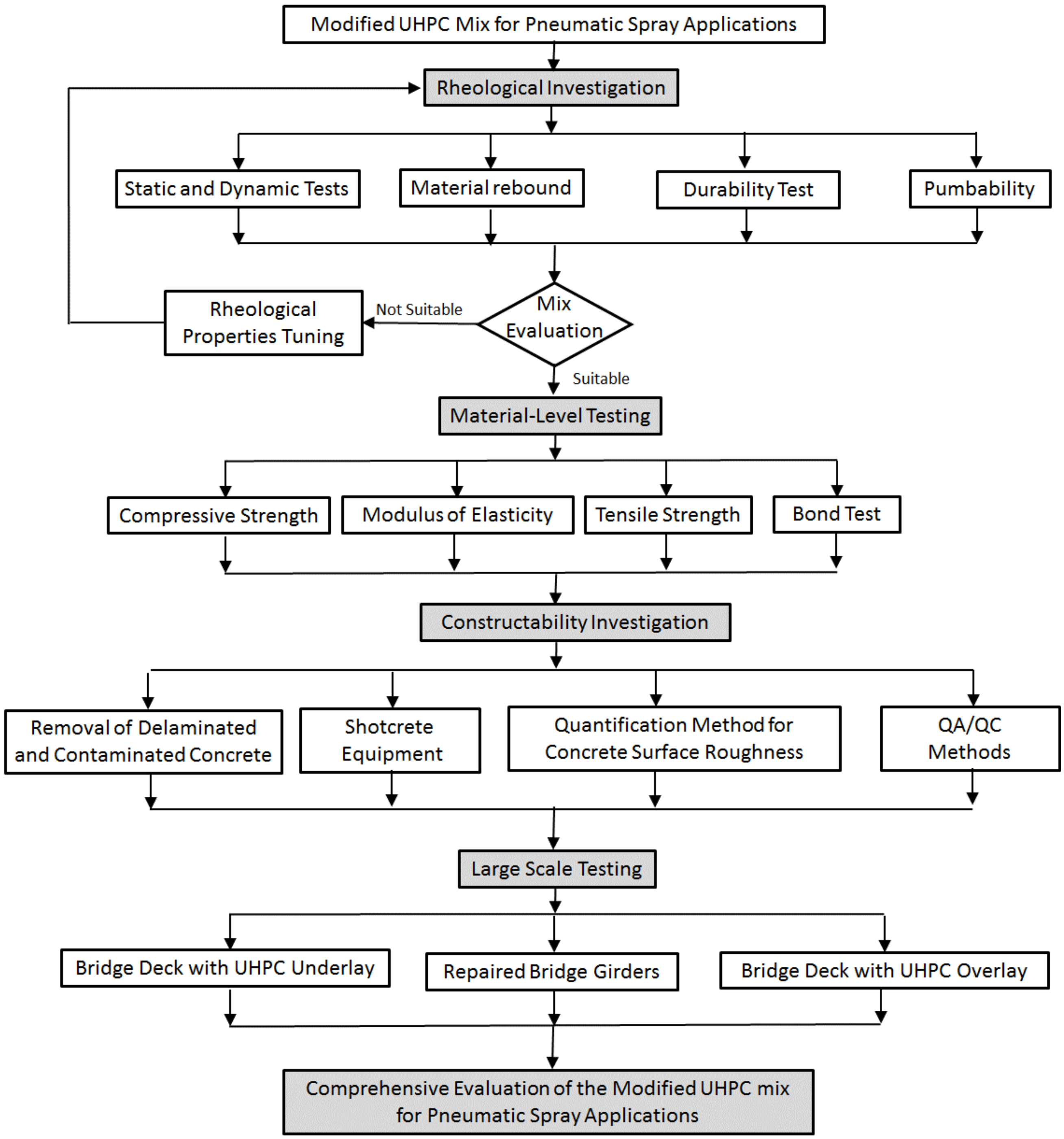


Figure 1. Flowchart of research tasks.

5. Rheology, Material, and Constructability Investigations for UHPC for Pneumatic Application

5.1 Literature Review

In this task, a comprehensive literature review is being conducted. The researchers will continue the review of the development of UHPC deck overlays and upgrades for better understanding of design challenges and issues. The literature review includes the following subject areas:

1. The current design practice of concrete overlays,
2. Material properties of UHPC,
3. Composite action of UHPC and Normal strength concrete, and
4. Pneumatic Spray Application.

The need for cost-effective and durable rehabilitation methods have been documented by many researchers [1-3]. Concrete overlays are classified as bonded or unbonded. Fowler and Trevino [1] point out the primary purpose of an overlay is to extend the life of bridge decks, and that bonded concrete overlays (BCO) have been applied since 1909. Bonded overlays can also improve the frictional surface and increase the durability of the wearing surface. Fowler and Trevino provide a simplified flowchart for developing an overlay in Figure 2.

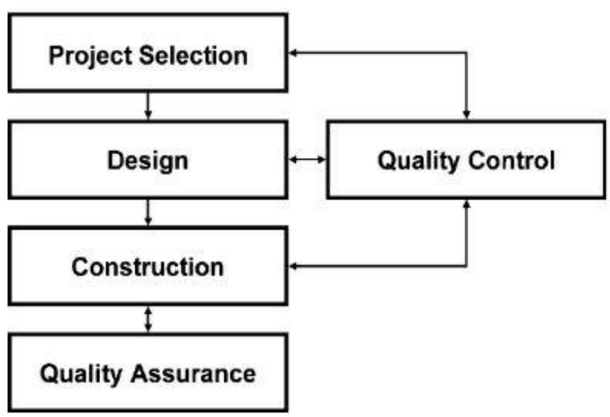


Figure 2. Simplified Flowchart to Develop Overlay (Fowler and Trevino [1])

Bridge overlays are typically placed after concrete removal, to limit the increase in dead load which will reduce the live load capacity. Trevino and Fowler also [1] state, “Compatibility between the overlay and original pavement concrete is important, and the coefficient of thermal expansion and modulus of elasticity should be lower than the original concrete if possible.” This statement makes sense if overlay and original bridge deck consist of conventional concrete. UHPC is significantly stronger and stiffer than conventional concrete and must be designed with different aspects.

Wibowo and Sritharan [4] presented a study in which an existing bridge was overlaid with UHPC. They noted that bridge deterioration typically begins with cracking in the deck, which then progresses as water and chlorides have an infiltration path, eventually leading to reinforcing steel corrosion. This corrosion can initiate within 4 to 8 years. One of the issues faced by Wibowo and Sritharan was maintaining the cross slope of the UHPC overlay. LafargeHolcim provided a lower slump mix design that held a 2% cross slope in a full-scale bridge application in addition to admixtures which may hold slopes up to 10%. The mix was also placed with a conventional vibratory screed. Wibowo and Sritharan also conducted limited flexural testing on large scale specimens consisting of normal strength concrete with UHPC overlay. Increases in stiffness and ductility were observed, however, the increase in stiffness was attributed to the overall increase in depth. They did not look at a replacement depth of UHPC that would maintain the existing deck thickness. Also, no cyclic testing was performed for this study.

Graybeal, et al., [2] and Haber, et al., [5] studied overlays on existing bridges, with a focus on the tensile strength of the bond between the UHPC and the normal strength concrete. The overlay was placed with a proprietary UHPC mix that had thixotropic properties. Haber [6] indicates that the primary differences between typical UHPC formulations and UHPC mixes that have been formulated for overlay applications are the rheological properties. The overlay formualtions are thixotropic in which the UHPC remains solid-like and will flow when agitated or sheared. Typical UHPC formulations will flow freely under gravity.

Caltrans [7] provides design guidance for concrete overlays. This memorandum does not address UHPC, but the general guidelines discuss depth, bonding, live loads, and surface preparation. The memorandum also states that tapering sections should be avoided as they deteriorate quickly.

Several researchers have studied the basic properties of UHPC mixes, including compressive strength, tensile strength, creep, durability among others. Haber et al., [5] presented a table of typical UHPC properties, as shown in Table 1. Farzad et al., [8] presented UHPC mix proportions and material properties from research conducted at FIU. These are presented in Tables 2 and 3. The UHPC is Ductal pre-mix, delivered in 50-lb. bags. The mixes for this study will be based on the Ductal pre-mix formulas and a non-proprietary ABC-UTC UHPC mix design.

Table 1. Typical Properties of Field Cast UHPC Concrete adapted from Haber et al., [5]

Material Characteristic	Average Result
Density	155 lb/ft^3
Compressive Strength (ASTM C39, 28-day strength)	24 ksi
Modulus of Elasticity (ASTM C469, 28-day modulus)	7,000 ksi
Direct Tension cracking strength (uniaxial tension with multiple cracking)	1.2 ksi
Split cylinder cracking strength (ASTM C496)	1.3 ksi
Prism flexural cracking strength (ASTM C1018; 12 in span)	1.3 ksi
Tensile strain capacity before crack localization and fiber debonding	>0.003
Long term creep coefficient (ASTM C512; 11.2 ksi load)	0.78
Long term shrinkage (ASTM C157; initial reading after set)	555 microstrain
Total shrinkage (embedded vibrating wire gage)	790 microstrain
Coefficient of thermal expansion (AASHTO TP60-00)	8.2 x 10^{-6} in/in/^{0}F
Chloride Ion penetrability (ASTM C1202; 28-day test)	360 coulombs
Chloride Ion penetrability (AASHTO T259; 0.5-in depth)	<0.10 lb/yd^3
Scaling resistance (ASTM C672)	No scaling
Abrasion resistance (ASTM C944 2x weight; ground surface)	0.026 oz. lost
Freeze-thaw resistance (ASTM 666A; 600 cycles)	RDM = 99%
Alkali-silica (ASTM C1260; 28-day test)	Innocuous

RDM = Relative dynamic modulus of elasticity; ASTM = American Society of Testing and Materials; AASHTO = American Association of State highway and Transportation Officials.

Table 2. Mix proportions used to mix 1 m^3 of UHPC, from Farzad, et. al., [8].

Constituent	Proportion (lbs)
Ductal Premix	4684.8
Ice (water)	256.3
HRWR (Superplasticizer)	64.0
Steel Fiber	333.4 (2%) and 666.7 (4%)

Table 3. Mechanical Properties of UHPC, from Farzad, et al., [8]

UHPC	Age (days)	Compressive Strength (ASTM C-39) (ksi)	Standard Deviation	Flexural Toughness (ASTM C-1018) (ksi)
2% steel fiber	3	10.0	0.50	
	7	10.9	0.20	
	14	16.1	0.15	
	28	25.2	0.30	3.2
	60	28.0	0.50	
4% steel fiber	3	11.5	0.40	
	7	11.7	0.30	
	14	17.5	0.70	
	28	26.0	1.00	3.6
	60	28.0	0.45	

UHPC overlays are gaining in popularity as a rehabilitation material due to the material properties. These properties include high compressive strength and tensile capacity compared to normal strength concrete, along with lower permeability and low shrinkage. UHPC also has a high early strength that allows for reduced lane closure and construction time. Haber, et al., [6 presented strengths of about 9,000 psi at 2-day.

Current research has shown that UHPC bonds well to normal strength concrete, both in direct tension testing [2, 6] and shear testing [4]. Shrinkage stresses do not appear to be a significant design concern either [3]. UHPC has also been shown to mitigate corrosion activity [9]. Graybeal [2] presented a direct tension test methodology, illustrated in Figure 3.

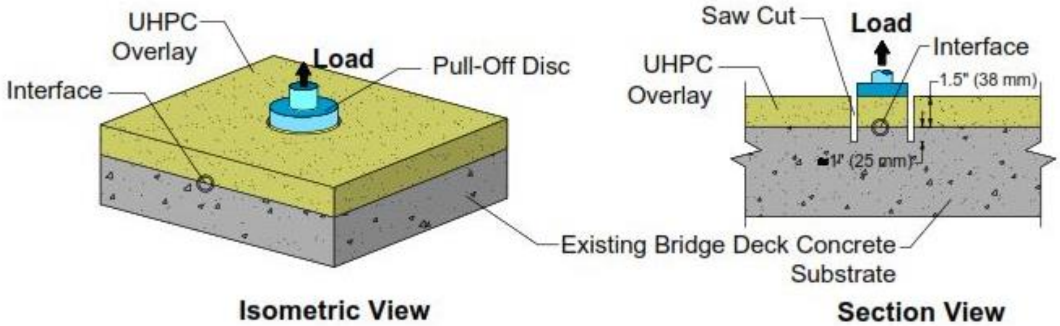


Figure 3. Illustration. Direct tension pull-off bond test based on ASTM C1583 [2].

Bruwiler [10] indicated UHPC exhibits both a tension hardening and a tension softening behavior. This is shown in Figure 4. Elastic behavior extends from point O to point A, followed by hardening from point A to point B. Softening behavior is exhibited as the stress reduces with an increase in the macro crack width. This softening behavior results from pulling the steel fibers out of the cement matrix.

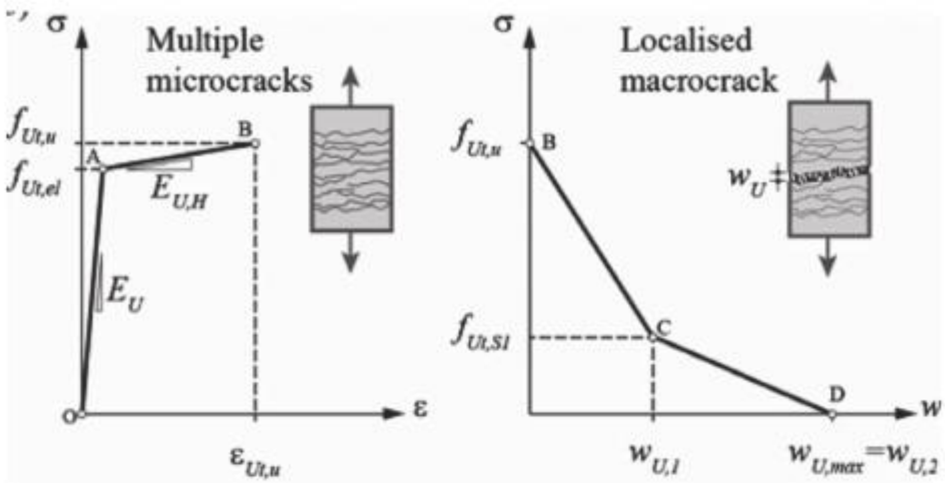


Figure 4. UHPC Tensile Behavior [10].

Al-Basha, et al., [11] performed as series of tension, slant shear and other testing to look at variations in roughness at the bond interface. Some of their results are presented in Table 4. They concluded acceptable bond strengths which can be obtained between UHPC and NSC, but this strength is dependent on the surface roughness.

Table 4. Average direct tensile strengths for different textures [11].

Texture (average texture depth)	**Rough (0.11 in)**	**Horizontal Grooves (0.03 in)**	**Chipped (0.04 in)**
Average Tensile Strength (psi)	139.2	63.8	153.7

Concrete surface roughness and surface moisture conditions need to be quantified in the field to achieve quality finished products. Sandblasting has shown to be effective in creating a strong bond between conventionally applied UHPC to a normal strength concrete substrate [12]. Different applications may require different concrete surface roughness. Repair applications require a roughened surface with exposed aggregate to obtain a sufficient bond between the older existing concrete and newly applied repair material.

Only two studies have been identified to date that included cyclic loading [6, 10]. It appears there is a need for more cyclic load data with regard to UHPC overlay and upgrades.

Ginouse and Jolin [13] pointed out that the placement process controls the rebound and in-place properties of the spray applied product. Although they studied typical shotcrete applications, the principals will be applicable to UHPC spray application, as it is essentially the same process. Their study investigated the spatial distribution of the sprayed concrete, with a static nozzle location. They stated, "As intuitively expected, the distribution obtained confirms that more material is transported closer to the nozzle axis". In other words, the flow of sprayed material is much denser on the nozzle axis and becomes more dilute toward the spray edges".

The spray pattern is dependent on a variety of factors including the configuration of the nozzle, pressure and fluid properties [14]. Shotcrete nozzles have a standard configuration that has been successful for many years.

"Shootability" and "pumpability" of the mix are the two primary concepts to be considered with any spray application [15]. Pumpability is related to the plastic viscosity (torque viscosity) of the mix. Pumpability improves with decreasing viscosity. Shootability is related to yield (or flow resistance). Shootability increases as yield increases.

For pneumatic spray application, Kyong-Ku Yun et al. [16] shows that air entraining admixture AEA and silica fume are beneficial for both shootability and pumpability and in turn, pumping efficiency, built-up thickness and rebound mitigation. Polymer and viscosity modifying agent (VMA) were found to have negative effects on pumpability because they significantly increased the torque viscosity of wet mix shotcrete (WMS) mixtures. There was no clear relationship between flow resistance and final pump piston pressure. The rebound rate had an almost inverse relationship with the built-up thickness.

For UHPC flowability, Zemei Wu et al. [17] shows that the flowability of UHPC with 1%, 2% and 3% straight fibers, the flowability decreased by 14.9%, 25.6% and 38.1% as compared to the one without fiber. Steel fiber content had little effect on first crack strength and first crack deflection of flexural load-deflection curve of UHPC, but considerable effect on the peak load. When 2% straight, hooked end and corrugated fibers were added, the peak load increased by 46.3%, 81.1% and 61.4% and the peak deflection increased by 76.7%, 153.3% and 123.3%.

Rui Wang et al. [18] show that the addition of steel fiber decreased the flowability and entrapped air content of fresh UHPC mixtures. To prepare flowable UHPC, a very high dosage for superplasticizer reducing the water to binder ratio will have an adverse effect on strength gain. Adding 1% steel fiber causes little increases in flexural strength however adding 2-3% steel fiber provided a remarkable increase in flexural strength.

Zhang and Morgan [19] state the initial set time for shotcrete should be less than 10 minutes and the final set time should be less than 45 minutes. The most important factor affecting the set time is the type and quantity of accelerator. Aluminum Sulphate, with a dosage of 4 to 6 % by mass, typically provide the required set time.

Kyong-Ku Yun et al. [20] states that upon addition of air entraining admixture (AEA), both the torque viscosity and flow resistance tended to decrease in a balanced manner. A superplasticizer had a more pronounced effect on the flow resistance rather than torque viscosity.

One of the researchers leading this project, has spoken with “Shotcrete applicators” and attended typical shotcrete applications. In these discussions, the applicators suggest adding fly ash to the mix design to enhance the flow of the material through the hoses. Application may be possible with a smaller diameter hose, as the UHPC has little aggregate, reducing the amount of waste typically associated with spray applications. These discussions are still preliminary, as is the initial research into how the material should be applied. Ductal provided an Identity Card of Material, which summarized several material properties of spray applied UHPC, but it does not include details on the mix design or constituents.

5.2 Rheological investigation

Rheological investigations for this project, started on various UHPC mixes to assist in evaluating pneumatic application of UHPC. Critical parameters for ‘shotcrete” are the “pumpability” and “shootability” of the mix.

The pumpability requirements have been described in terms of slump for normal strength concrete. The slump value ranging from 1 ½ to 3 in. is considered desirable for shotcrete sprayed onto vertical or over-head surfaces [21]. For self-compacting high-performance concrete such as UHPC, a static and dynamic flow test is prescribed by ASTM C1437. The minimum value desired for pumping a high-performance concrete such as UHPC is considered to be 9 in resulted from dynamic test of flowability [16].

Shootability of the mix is a quantitative measure of how well the material stays in place after application and includes the concept of material rebound. The existence of a yield stress value seems to provide a good explanation as to why “shotcrete” is shootable [15]. The higher the yield stress, the greater the thickness that can be built up without sloughing. This results in better "shootability".

5.2.1 Effects of Mix Composition and Admixtures on Concrete Rheology

W/C Ratio - The water-cement ratio (W/C) is the most important parameter with respect to properties of fresh and hardened concrete. An increase in the W/C ratio reduces the plastic viscosity and flow resistance, increasing pumpability. For low W/C ratios, high range water reducer (HRWR) should be used to produce workable or pumpable concrete. A higher W/C ratio generally lowers compressive strengths which is not desirable in most cases.

HWRW (Superplasticizer) - The effect of superplasticizer is to produce large reduction of flow resistance and small reduction of plastic viscosity. They are mainly used for low W/C concretes such as UHPC. its effect is much greater as compared to other admixtures.

Air Entraining Agents - Air Entraining agents such as wood resin, salts of fatty acids, and lignosulphonates cause a rapid decrease in flow resistance and plastic viscosity. It has been observed by other researchers that flow resistance can be significantly reduced for an air content of up to 10% for normal strength concrete. However, the plastic viscosity only reduces significantly up to 5% air content [19].

Researchers have found that an increase in air content of the "shotcrete" mix will improve pumpability. During the shooting process much of the excess air is expelled, in turn leading to an increase in "shootability".

So, it will be fair to say that in order to reduce the flow resistance and plastic viscosity, an air content from 5-10% should be tested in trial mixes. The strength reduction can be compensated by having lower W/C ratio. Even though UHPC durability can be impacted by air entraining agents, the shotcrete process could help expelling the air content at impact which is advantageous.

Steel Fibers - Steel fiber content increases both flow resistance and plastic viscosity. If longer fibers are added, only the flow resistance increases. Therefore, increasing the fiber content will reduce the workability of the mix.

5.2.2 Rheological Testing on Mix Designs

Initial rheological investigations have been performed on the Ductal UHPC premix (JS1000) and Fast Set UHPC from Ductal (JS-1212). Additional testing is planned for the ABC-UTC non-proprietary UHPC mix. Steel fibers have been incorporated into the initial testing. Synthetic/flexible fibers and air content variations will be studied in subsequent testing. The following tests have been performed to date to assist in this evaluation:

1. Static flow tests were conducted in accordance with ASTM C1437. Dynamic flow testing was not performed as the static flow results were high, and the dynamic flow would have exceeded 10 inches for the mixes tested. Flowability of the pneumatically applied mixes are very critical and is a key indicator of pumpability of the UHPC. This test was performed on various mixes in order to evaluate the best mix for pumping.
2. Compressive strength testing was performed on 2 inch by 2 inch by 2 inch cubes. The cubes were tested in accordance with ASTM C-109.

Additional rheological testing to be performed will include initial and final setting time. These tests will be recorded in accordance with the AASHTO T197 test method for penetration resistance. This will be performed on each mix to evaluate how quickly each mix will set.

The mix designs listed in Tables 5 and 6 were prepared for the initial rheological investigation.

Table 5. Ductal JS1212 Fast Set Mix Designs

Quantity of Ingredients								
	Premix (lb)	**Water (lb)**	**Premia 150 (lb)**	**Optima 100 (lb)**	**Turbocast 650a (lb)**	**Steel Fiber (lb)**	**Total Weight (lb)**	**Volume (ft^3)**
Mix 1	6.250	0.365	0.051	0.034	0.066	0.444	7.21	0.05
Mix 2	6.337	0.370	0.052	0.035	0.066	0.349	7.21	0.05
Mix 3	6.133	0.358	0.050	0.033	0.064	0.571	7.21	0.05
Mix 4	6.217	0.401	0.051	0.034	0.065	0.442	7.21	0.05
Mix 5	6.183	0.437	0.051	0.034	0.065	0.439	7.21	0.05
Mix 6	6.237	0.364	0.056	0.038	0.072	0.443	7.21	0.05
Mix 7	6.224	0.363	0.062	0.041	0.079	0.442	7.21	0.05
Mix 11	21.232	1.238	0.174	0.116	0.223	0	22.98	0.15

Note: Premia, Optima and Turbocast are HRWR additives

Table 6. Ductal JS1000 Mix Designs

Quantity of Ingredients						
	Premix (lb)	**Water (lb)**	**HRWR (lb)**	**Steel Fiber (lb)**	**Weight (lb)**	**Volume (ft^3)**
Mix 12	6.250	0.341	0.086	0.444	7.12	0.05
Mix 13	6.332	0.346	0.087	0.351	7.11	0.05
Mix 14	6.145	0.336	0.084	0.552	7.12	0.05
Mix 15	6.216	0.378	0.085	0.441	7.12	0.05
Mix 16	6.183	0.413	0.085	0.439	7.12	0.05
Mix 17	6.237	0.341	0.100	0.443	7.12	0.05
Mix 18	6.225	0.340	0.114	0.442	7.12	0.05

Mix 22	21.246	1.160	0.291	0.000	22.70	0.15

5.3 Material Investigation

Testing Program. In addition to the rheological testing; the following material testing will be performed on the mixes:

1- Compressive strength,
2- Tensile strength,
3- Modulus of elasticity
4- Bond test between UHPC and normal concrete

The results of the initial rheological tests and material tests have been considered in order to finalize the mixes which will be used for the initial pneumatic applications. Application has been made with Ductal mixes, and application with ABC-UTC mixes are planned.

UHPC cores which will be obtained from test panels constructed from pneumatic spray application will be obtained. The UHPC cores will also be tested for compressive strength, tensile strength and modulus of elasticity.

Bond strength between the concrete substrate and the modified UHPC mix using pneumatic spray applications will be evaluated through either bi-surface shear or direct tension pull-off bond tests with different concrete surface roughness and UHPC layer thickness. Sandblasting will be one of most important surface preparation methods since the application of upgrading the underside of the existing bridge deck and superstructure elements will require either sandblasting or water-jetting.

5.3.1 Rheological Test Results with Ductal mixes.

To date, compressive strength testing has been performed on cubes cast with two Ductal mixes during the initial round of rheological testing. The results are summarized in Table 7.

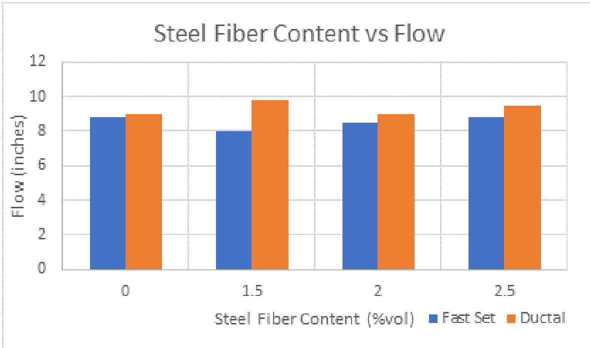
Table 7. Results of Initial Rheological Testing

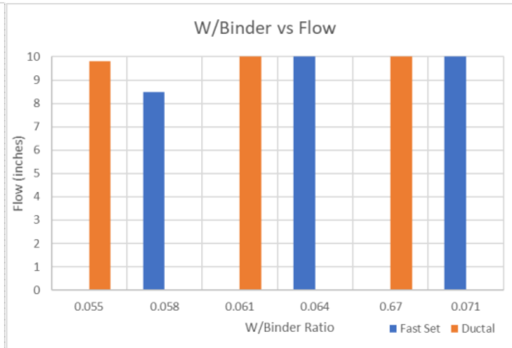
Mix Designation	Basic Mix	W/Binder Ratio by Weight	HRWR % by Weight	Steel Fibers % by Weight	Steel Fibers % by Vol	Flow Test Value (avg) (inches)	Compressive Strength (ksi)	
							7 days	28 days
Mix # 1	JS1212 Fast Set	0.058	0.021	6.2	2	8.5	13.18	19.30
Mix # 2	JS1212 Fast Set t	0.058	0.021	5	1.5	8.0	14.21	17.60

Mix Designation	Basic Mix	W/Binder Ratio by Weight	HRWR % by Weight	Steel Fibers % by Weight	Steel Fibers % by Vol	Flow Test Value (avg) (inches)	Compressive Strength (ksi)	
							7 days	28 days
Mix # 3	JS1212 Fast Set	0.058	0.021	7.5	2.5	8.8	14.91	19.68
Mix # 4	JS1212 Fast Set	0.064	0.021	6.2	2	>10	12.91	19.31
Mix # 5	JS1212 Fast Set	0.071	0.021	6.2	2	>10	11.92	19.70
Mix # 6	JS1212 Fast Set	0.058	0.023	6.2	2	9.8	14.29	17.23
Mix # 7	JS1212 Fast Set	0.058	0.025	6.2	2	7.8	7.90	18.64
Mix # 11	JS1212 Fast Set	0.058	0.022	0	0	8.8	16.90	17.70
Mix # 12	JS1000	0.055	0.012	6.2	2	9.0	15.98	18.85
Mix # 13	JS1000	0.055	0.012	5.0	1.5	9.8	14.77	16.99
Mix # 14	JS1000	0.055	0.012	7.5	2.5	9.5	12.06	16.69
Mix # 15	JS1000	0.061	0.012	6.2	2	>10	15.02	21.84
Mix # 16	JS1000	0.067	0.012	6.2	2	>10	12.90	19.84
Mix # 17	JS1000	0.055	0.014	6.2	2	9.8	10.18	11.92
Mix # 18	JS1000	0.055	0.016	6.2	2	9.3	13.05	17.38
Mix # 22	JS1000	0.055	0.013	0	0	9.0	15.00	18.00

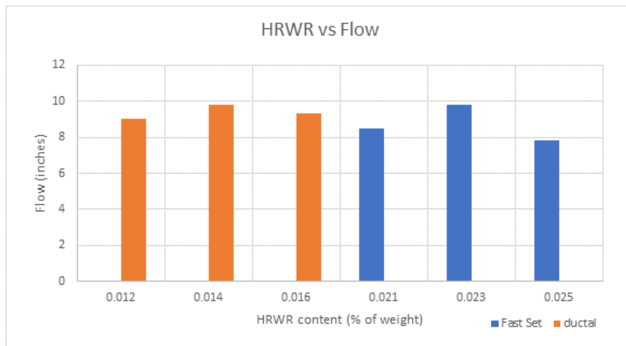
W/Binder is measured as weight of water/weight of premix.

Steel Fiber Content and Flowability -The first set of tests compared variations in steel fiber content to flow. Results are shown in Figure 5a. The regular Ductal JS1000 mix showed a higher flow than the J1212 Fast Set mix for all steel fiber contents tested. For both mixes the relative differences in flow were small. The JS1212 Fast Set mix flow was between 8 and 9 inches. The JS1000 mix flow was between 9 and 10 inches. Note that measurements greater than 10 inches cannot be made, as the diameter of the plate is 10 inches. Figure 6 shows the flowability of JS1212 for Mix 6 and Mix 7.



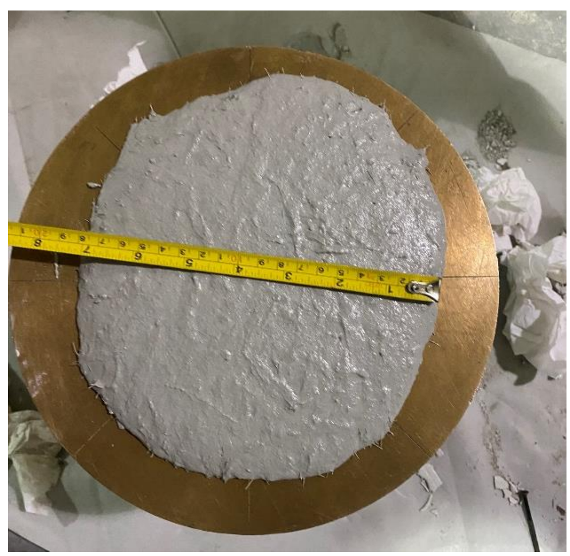


(a) (b)



(c)

Figure 5. Flowability Test Results



(a) (b)

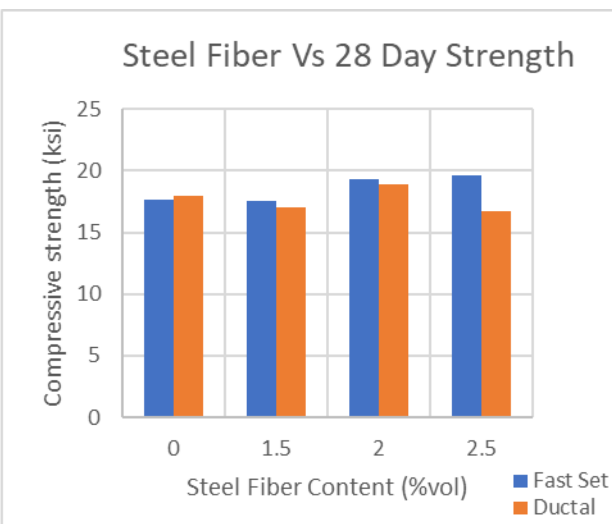
Figure 6. Flowability Testing

W/Binder Ratio and Flowability -Variations in the W/Binder ratio were also tested for flowability. Results are shown in Figure 5b. Note that the W/Binder ratio is presented as the weight of water to the total weight of premix. The initial samples were prepared with the manufacturer's recommended W/Binder ratio. As expected, the increase in W/Binder ratio increased the flow. However, the maximum flow values of 10-inches were surpassed for W/Binder ratio of 0.06.

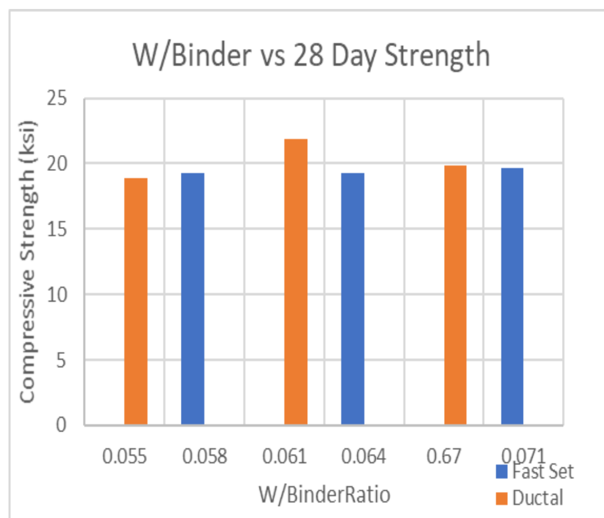
HRWR and Flowability– The manufacturer's recommendation for HRWR was greater for the JS1212 Fast Set mix than the JS1000 mix. The manufacturer's recommendations were followed for the initial mixes. Subsequent mixes had increasing amounts of the HRWR. While the differences are small, it appears an optimum flow is obtained, and then the flow values decrease with additional HRWR for both types of UHPC. Test results are shown in Figure 5c.

Strength Testing - Compressive strength testing was performed on cubes obtained from each mix except for the mixes with no steel fiber. Compressive strength cylinders were cast for these mixes. The results are presented below in Figure 7.

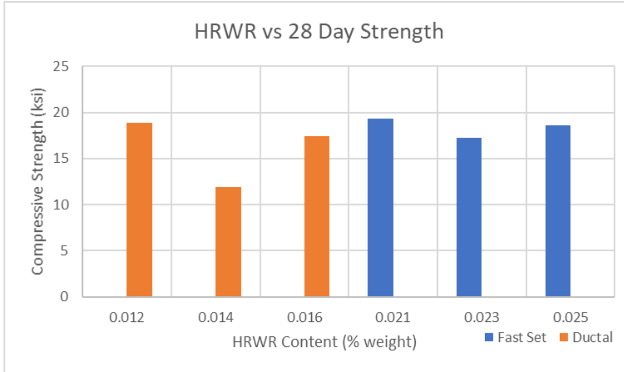
Steel Fiber Content and Strength - The JS1212 fast set mix showed increased strength with additional fibers, with a relatively small gain recorded when fiber was increased from 2 to 2.5%. The compressive strength of all samples ranged from 16.7 to 21.8 ksi. This is consistent with the finding by other researchers that adding 1% steel fiber causes little increase in compressive strength, however, the addition of 2 to 3% steel fiber provided a remarkable increase in compressive strength [17]. The JS1212 Fast Set mixes showed higher strength than the JS1000 mixes.



(a)



(b)



(c)

Figure 7. Compressive Strength Test Results

W/Binder Ratio and Strength - The JS1000 mixes increased in strength when the W/Binder increased by 0.5%, and then decreased with additional water. The fast set mixes exhibited little change in strength over the range in W/Binder ratio tested.

HRWR and Strength - The strength decreased with an increase in HRWR, for both UHPC types, although the variation in strength was less for the fast set mix. One set of samples appeared to be an outlier, with a 28-day strength of 11.92 ksi, significantly less than strengths measured for all of the mixes tested.

Based on the initial test results presented above, and observations during the testing, the initial spray application will be made with the JS1212 Fast Set mix, at a 2% steel fiber content, W/Binder ratio of 0.058 and HRWR content of 0.168 lbs/bag.

5.3.2 Rheological Test Results with ABC-UTC mixes.

Rheological testing has been performed on a number of non-proprietary mix designs developed under the ABC-UTC program at FIU. The test results have not been published. In reviewing the test results, one of the ABC-UTC mixes was selected for supplemental testing and to study the effect of steel fibers, synthetic fibers and a blend of steel and synthetic fibers. The effect of variations in the quantity of HRWR will also be studied. The testing program is outlined below in Table 8. Test results are pending evaluation.

Table 8. Rheological Testing on ABC-UTC Mixes

Mix Designation	Basic Mix	W/Binder Ratio by Weight	HRWR Ratio by weight	Steel Fibers % by Vol	Synthetic Fibers % by Vol
ABC-UTC Mix #1	ABC-UTC	0.19	0.01	2	0
ABC-UTC Mix #2	ABC-UTC	0.19	0.009	2	0

ABC-UTC Mix #3	ABC-UTC	0.19	0.01	2	0
ABC-UTC Mix #4	ABC-UTC	0.19	0.012	2	0
ABC-UTC Mix #5	ABC-UTC	0.19	0.014	2	0
ABC-UTC Mix #6	ABC-UTC	0.19	0.016	2	0
ABC-UTC Mix #7	ABC-UTC	0.19	0.01	2	0
ABC-UTC Mix #8	ABC-UTC	0.19	0.01	2	0
ABC-UTC Mix #9	ABC-UTC	0.19	0.009	2	0
ABC-UTC Mix #10	ABC-UTC	0.19	0.007	2	0
ABC-UTC Mix #11	ABC-UTC	0.19	0.01	2	0
ABC-UTC Mix #12	ABC-UTC	0.19	0.01	0	0
ABC-UTC Mix #13	ABC-UTC	0.19	0.01	0	0.5
Mix Designation	**Basic Mix**	**W/Binder Ratio by Weight**	**HRWR Ratio by weight**	**Steel Fibers % by Vol**	**Synthetic Fibers % by Vol**
ABC-UTC Mix #14	ABC-UTC	0.19	0.01	0	1.5
ABC-UTC Mix #15	ABC-UTC	0.19	0.007	0	0.5
ABC-UTC Mix #16	ABC-UTC	0.19	0.007	0	1
ABC-UTC Mix #17	ABC-UTC	0.19	0.007	0	1.5
ABC-UTC Mix #18	ABC-UTC	0.19	0.01	1	0.5
ABC-UTC Mix #19	ABC-UTC	0.19	0.01	0.5	0.5
ABC-UTC Mix #20	ABC-UTC	0.19	0.01	1.5	0.5
ABC-UTC Mix #21	ABC-UTC	0.19	0.01	0	1.0
ABC-UTC Mix #22	ABC-UTC	0.19	0.008	0.5	0.5
ABC-UTC Mix #23	ABC-UTC	0.19	0.008	1.0	0.5
ABC-UTC Mix #24	ABC-UTC	0.19	0.008	1.5	0.5
ABC-UTC Mix #25	ABC-UTC	0.20	0.008	2.0	0
ABC-UTC Mix #26	ABC-UTC	0.20	0.005	0	0
ABC-UTC Mix #27	ABC-UTC	0.20	0.007	2.0	0
ABC-UTC Mix #28	ABC-UTC	0.20	0.007	0	0
ABC-UTC Mix #29	ABC-UTC	0.12	0.031	2.0	0
ABC-UTC Mix #30	ABC-UTC	0.12	0.042	2.0	0
ABC-UTC Mix #31	ABC-UTC	0.12	0.042	0	0.5
ABC-UTC Mix #32	ABC-UTC	0.14	0.042	2.0	0
ABC-UTC Mix #33	ABC-UTC	0.16	0.042	0	0.5
ABC-UTC Mix #34	ABC-UTC	0.20	0.042	0	0.5

ABC-UTC Mix #35	ABC-UTC	0.20	0.042	2.0	0
ABC-UTC Mix #36	ABC-UTC	0.16	0.01	0	0
ABC-UTC Mix #37	ABC-UTC	0.16	0.02	0	0
ABC-UTC Mix #38	ABC-UTC	0.16	0.029	0	0
ABC-UTC Mix #39	ABC-UTC	0.12	0.042	2.0	0
ABC-UTC Mix #40	ABC-UTC	0.20	.009	2.0	0
ABC-UTC Mix #41	ABC-UTC	0.20	.009	0	0
ABC-UTC Mix #42	ABC-UTC	0.18	.009	2	0
ABC-UTC Mix #43	ABC-UTC	0.18	.009	2.0	0
ABC-UTC Mix #44	ABC-UTC	0.18	.009	0	0

Selection of the correct mix design for pneumatic application will involve finding an optimal design that can be pumped (high flow), provide sufficient strength and ductility, and remain in place upon application (higher strength, lower flow). The combination of these parameters will govern the success of the application.

The ABC-UTC mix designs consist of 4 subgroups, based on the aggregate to binder ratios. These subgroups are 60:40, 56:44 and 50:50. A fourth mix design was developed with similar proportions to the proprietary Ductal JS1000 mix. This mix does not contain slag and has an aggregate to binder ratio of 57:43. The Ductal mix proportions, as presented by Graybeal [25] and Shahrokhinasaab [23], are shown in Table 9 below.

The 4 basic mix designs are based on on-going unpublished research conducted at FIU. The basic mixes developed by the researchers have been revised by the addition of steel and/or synthetic fiber. Adjustments were also made to the water to binder ratios and quantities of HRWR added to the mix. The mixes were prepared with local materials, including sand, cement, silica fume and available HRWR.

Table 9. Typical Composition of Ductal, after [25]

Material	lb/yd^3	% by weight
Portland Cement	1,200	28.5
Fine Sand	1,720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
HRWR	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

HRWR and Strength - The strength decreased with an increase in HRWR, for the three ABC-UTC mix designs, although the strength reduction was relatively small. This is shown in

Figure 8. The w/b ratio for the 60-40 and the 56-44 mixes was 0.19. The w/b ratio for the 50-50 mix was 0.2. The steel fiber content was 2% by volume.

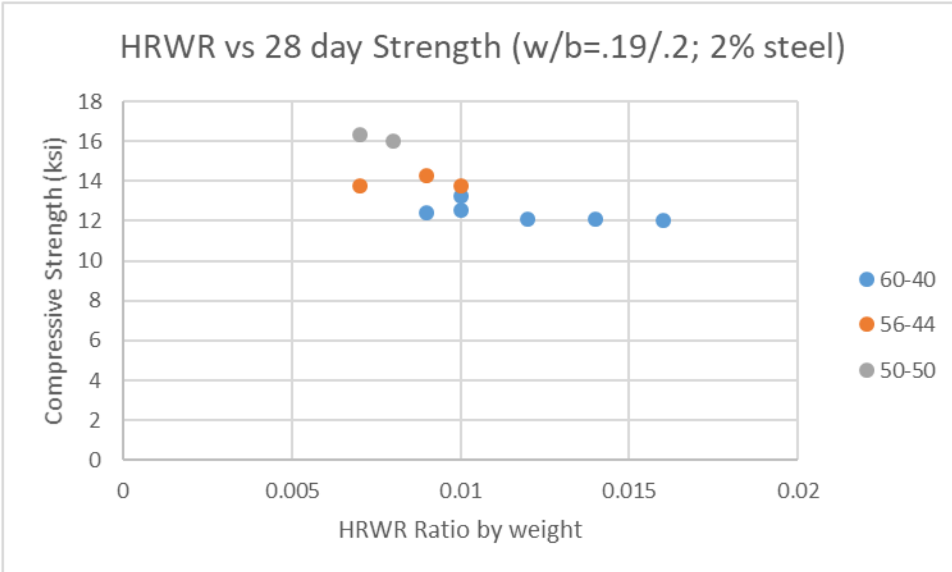


Figure 8. HRWR vs Strength.

Fiber Content and Strength. The effect of fiber content on the 28-day compressive strength is presented in Figure 9 below. The blue and orange data points represent variations in the synthetic fiber content on the strength. There appears to be no benefit to increasing the synthetic fibers beyond 0.5%. The yellow and gray data points show the effect of various steel fiber content with a .5% synthetic fiber content. There appears to be an optimum steel fiber content of about 1% at the HRWR ratio of 0.007. At the higher HRWR ratio of 0.01, the is only a small variation in strength as the steel fiber content increases.

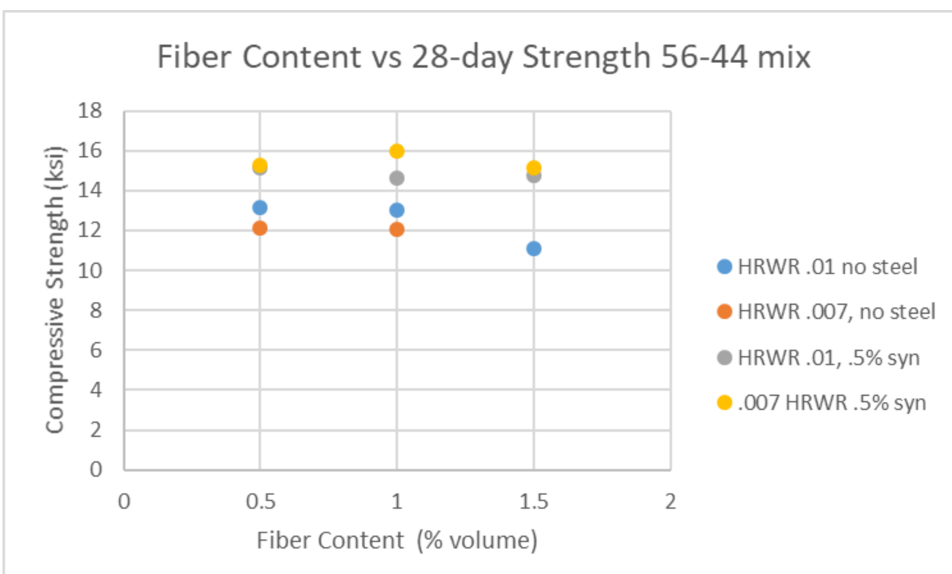


Figure 9. Fiber Content and 28- Strength.

Fiber Content and Flow. The graph below in Figure 10 shows a decrease in flow as the fiber content increases. The effect with the ABC-UTC is more pronounced than the effects as shown with the Ductal mixes.

As with the figure above, the blue and orange data points were generated without steel fibers in the mix, and the synthetic fiber content increased. The maximum flow measured was with 0.5% synthetic fiber content.

The yellow and gray data points were generated with a 0.5% synthetic fiber content, with variations in the steel fiber content. With the HRWR ratio at 0.01%, increased steel fiber content reduces the flow. With the HRWR ratio at 0.007%, the maximum flow was measured at a steel fiber content of 1.0%.

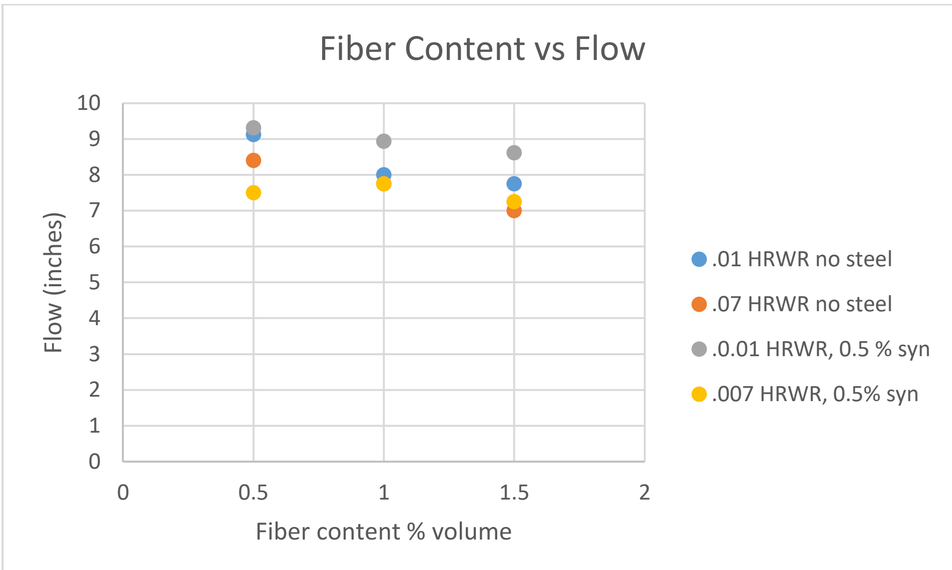


Figure 10. Fiber Content vs Flow.

Water/Binder ratio and Flow. The relationships between the water content (as expressed in the w/b ratio) has the largest impact on the flow. This is expected, as the w/b ratio for UHPC is low, providing just enough water to hydrate the cement and binders. This is shown graphically in the graphs below. Figure 11 shows a large increase with flow as the w/b ratio increases from 0.12 to 0.20.

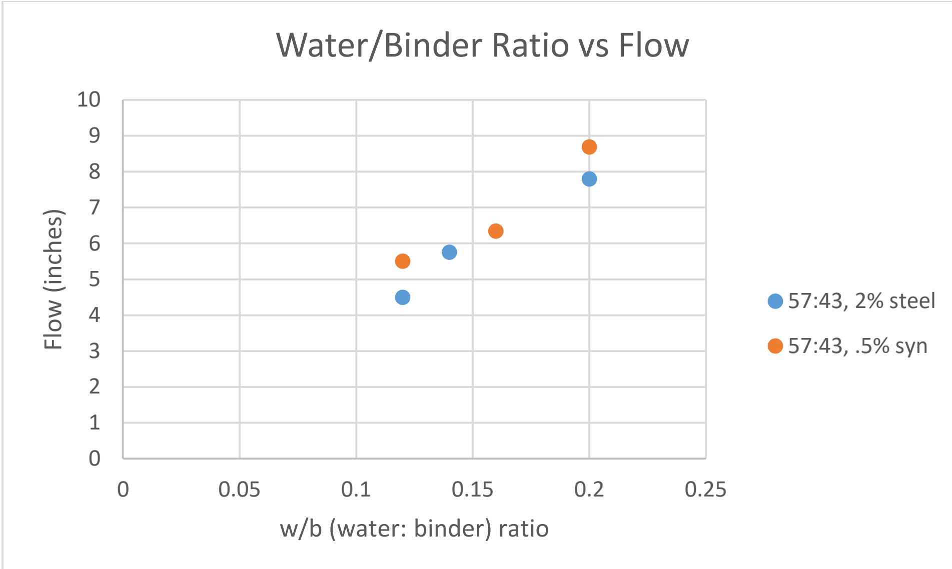


Figure 11. Water to Binder Ratio vs Flow, 57:43 Mix.

As an effort to keep the w/b ratio low, the HRWR ratio was increased for some mixes. Even with very high doses of the HRWR, the measured flow remained low with low water content. This is shown in Figure 12 below.

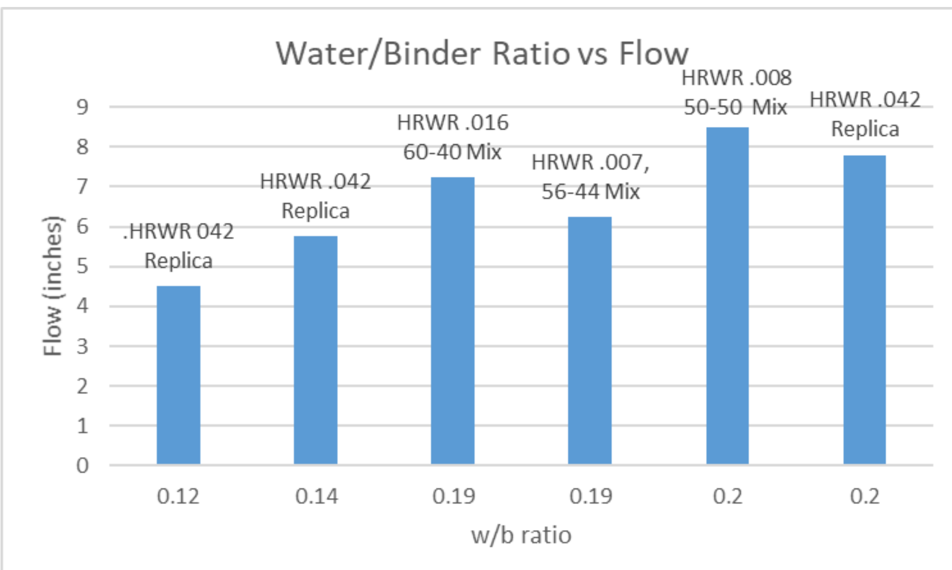


Figure 12. Water to Binder Ratio vs Flow.

5.4 Constructability Investigation:

Pneumatic spray application of UHPC in this project is meant to repair, upgrade or protect bridge elements. Such sub-standard bridge elements usually contain contaminated concrete as well as damaged concrete. When using UHPC, it is not necessary to remove the entire mass of contaminated concrete. Further, there is a need for identifying methods of removing contaminated concrete as well as the effects of various removal methods on properties of finished concrete.

Additionally, there is a need for identifying the equipment needed for pneumatic spray applications using UHPC. It is believed that current spray equipment used for normal strength concrete could be used if flexible synthetic fibers are used.

Based on the discussion provided above, specific objectives related to this category will be as follows:

1- Identifying methods for the removal of contaminated concrete and the effect the removal methods will have on bridge elements, strengthened, upgraded or protected using UHPC in a pneumatic spray application.
2- Identifying the equipment suitable for pneumatic spray application using appropriate UHPC mixtures. The nozzle and hose size should be identified due to the use of fibers. Compressor and pump capacity should be evaluated with respect to the UHPC plastic properties.
3- Establishing methods that could be used in the field to quantify the concrete surface roughness and surface moisture condition to achieve quality finished products. Different applications require different concrete surface roughness. For example, repair application requires rough surfaces with exposed aggregate using sandblasting or water-jetting, However, bridge deck overlay application for new construction requires rough surfaces using puddling techniques in the freshly placed concrete.
4- Identifying quality control and quality assurance methods that can be used to assess the quality of finished products.

Burns [22] performed research on normal shotcrete flow in small diameter lines. One of his findings is that the thickness of the lubrication layer is relatively constant regardless of hose diameter. The layer is made up of cement paste and is approximately 1 mm thick Notably, he found that shotcrete containing steel fibers could not be pumped in hoses smaller than 50 mm (2-inches) in diameter.

A powerpoint presentation published by Ductal [24] indicates that the lines are initially charged with a mix that does not contain fibers. As this mix is pumped through the lines, additional mix with the steel fibers is introduced. It is noted that it takes at least 30 minutes to make additional batches of UHPC. Altering the planned pumping sequence to include two batches will be challenging in future applications.

6. Specimens for Spray-Applied UHPC

6.1 Small Scale Specimens

Testing of composite flexural beams will be performed. The testing will iterate various parameters such as thickness of the UHPC overlay and roughness of the concrete interface between the NSC and UHPC. Flexural strength and Modulus of Rupture of normal strength concrete (NSC) Beams with ½-inch and 1-inch of UHPC overlays will be determined experimentally. UHPC application to the beam specimens will be applied conventionally on some specimens and applied with spray application techniques on other specimens. The flexure beams will be instrumented to obtain load-deflection data.

Fabrication of the composite flexure beams continued this period. In the prior period, Normal Strength Concrete (NSC) was placed in 18 beam molds. Conventionally placed UHPC was placed as overlays on 6 of the beams during this period. UHPC cylinders, 4 in. x 8 in., were cast for elastic modulus and compressive strength testing. The casting process is shown in Figure 13 and Figure 14. Two of the beams are full depth normal strength concrete as reference, to determine flexure strength of the normal strength concrete. Two No. 3 reinforcing bars were placed in each beam mold, with approximately 1-inch cover from the bottom. Testing will be conducted on sets of beams with varying roughness profiles on the interface between the NSC and UHPC. UHPC will either be placed with spray application techniques on the remaining 10 flexure beams.

Figure 13. Beam and Cylinder Molds.

Figure 14. Casting Specimens

The roughness profiles were created on an initial set of reference beams. These beams serve as the molds for roughness profiles. Repeatable roughness profiles were created to allow for meaningful correlations of data. Forms were made by applying an elastomeric roofing compound to the initial reference beams and removing the compound carefully after setting. A series of profile forms, also called skins, were made with this process. The interface roughness will represent:

1. Trowel finish, identified as Profile 1.
2. A trowel finish that was lightly stippled, identified as Profile 2.
3. Puddled surface to represent a typical unformed cold-joint, identified as Profile 3.
4. A puddled surface that was also chipped, identified as Profile 4.

Static load Testing will be conducted on beam sections with various UHPC thickness, interfacial surface roughness coefficients, and mix designs as shown in Table 6. Load-deflection data will be obtained. A set of beams will be tested with the UHPC on the upper face, and another set will be testing with the UHPC overlay on the bottom face.

Normal Strength concrete design mix typical for bridge decks was selected. The design 28-day compressive strength is 4,500 psi. Compressive strength and Modulus of Elasticity tests on NSC and UHPC cylinders will be conducted. Results of the compressive strength tests performed on NSC cylinders is shown Figure 15. Figure 16 shows the cylinder after 7-day compressive strength.

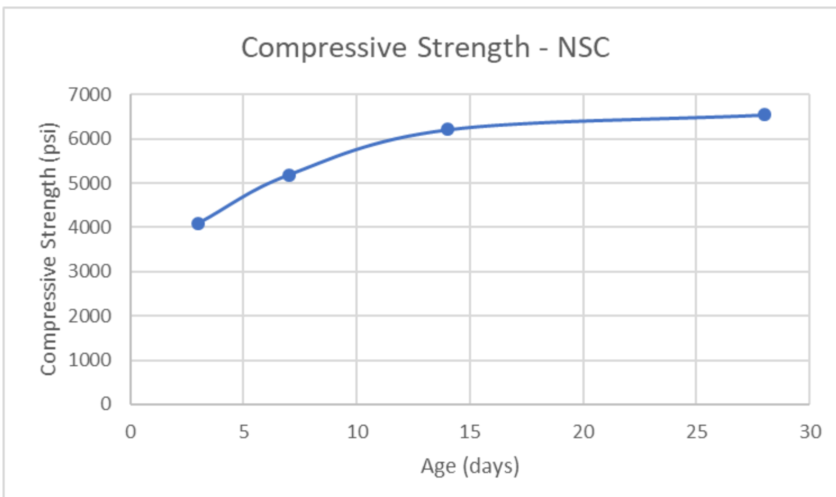
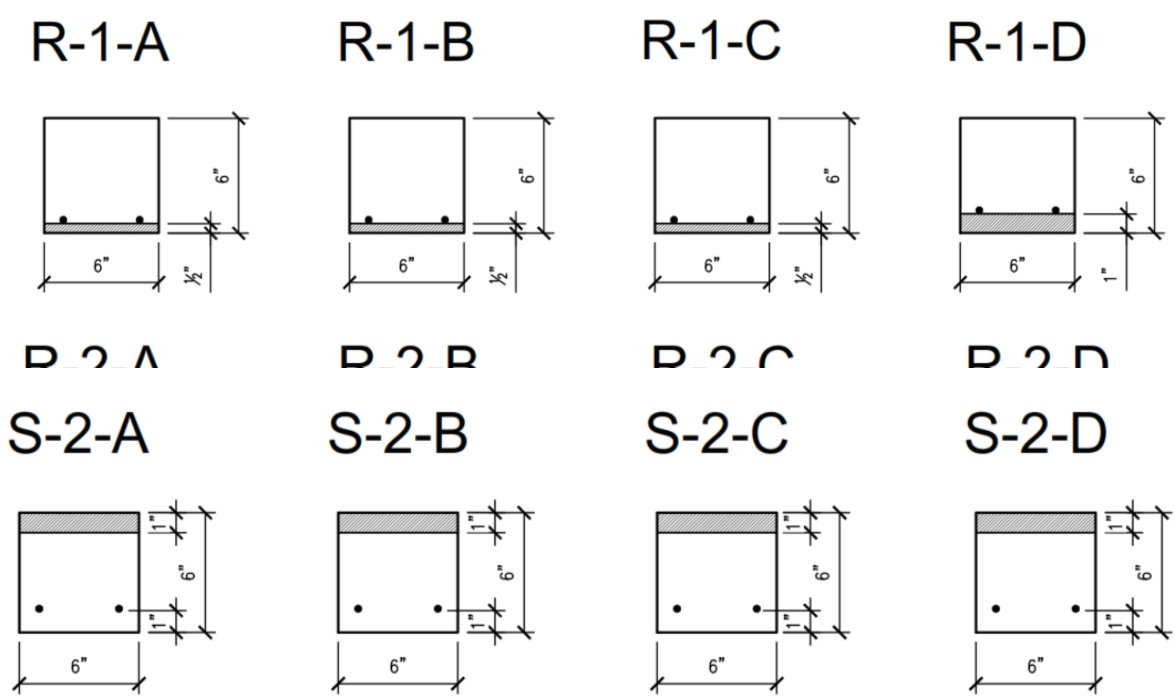


Figure 15. Compressive Strength Test Results, NSC

Figure 16. Compressive Cylinder at 7 days

Figure 17 shows cross sections of the 18 beams. Table 10 summarizes the 'as-built" conditions of the beams and presents the proposed testing program. Figures 18 to Figure 20 shows specimens after removing both roughness skin and molds. When the samples were stripped, sample R-1-C had honeycombs in the concrete. Also, the plywood spacers in the form for sample R-1-B were warped, so that the overlay thickness at the ends of the beam will be about ½ inch but will be about 1 inch at the center.



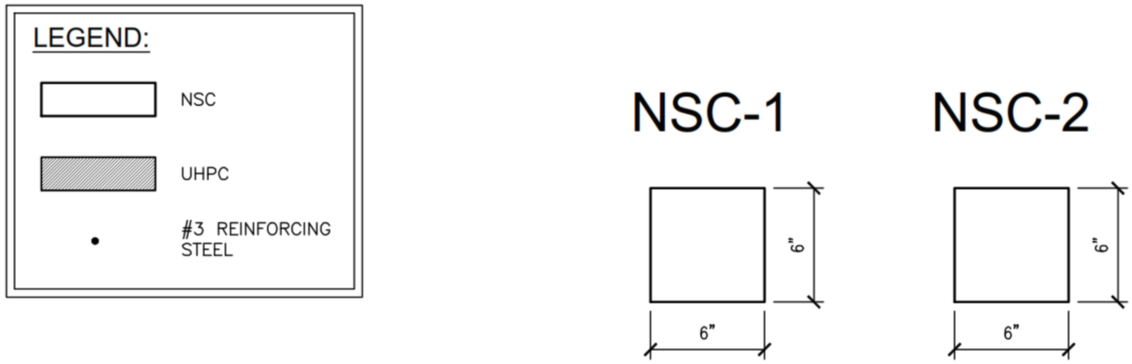


Figure 17 Flexural specimens for material testing.

Table 10. Schedule of Flexure Beam Testing

Beam Designation	Overlay thickness	Roughness profile	Re-bar location	Proposed overlay application and location
R-1-A	1/2	3	adjacent	Spray application on bottom
R-1-B	1/2	3	adjacent	Spray application on bottom
R-1-C	1/2	2	adjacent	Spray application on bottom
R-1-D	1	3	adjacent	Spray application on bottom
R-2-A	1/2	4	opposite	Conventional application on top
R-2-B	1/2	4	opposite	Conventional application on top
R-2-C	1/2	4	opposite	Spray application on top
R-2-D	1/2	4	opposite	Spray application on top
S-1-A	1	1	adjacent	Spray application on bottom
S-1-B	1	1	adjacent	Spray application on bottom
S-1-C	1/2	1	adjacent	Spray application on bottom
S-1-D	1	1	adjacent	Conventional application on bottom
S-2-A	1	2	opposite	Spray application on top
S-2-B	1	2	opposite	Conventional application on top
S-2-C	1	2	opposite	Conventional application on top
S-2-D	1	3	opposite	Conventional application on top

Notes:
Initial placement (NSC) date: 8-7-19
Beam R-1-C had honeycombing in the NSC concrete.
Beam R-1-B had a warped spacer, the thickness of the overlay will vary from ½” at the ends to about 1” in the center.

Figure 18. Flexural beam removed from form; roughness profile skin partially removed.

Figure 19. Flexural beam removed from form; roughness profile skin removed.

Figure 20. Flexural Beam R-1-C honeycombs

Transducers will be instrumented to the beams to measure force-deflection curve. Grids will be drawn on the side of beams for photo documentation before and after testing. Table 11 shows the possible comparison between the test results of the specimens.

Table 11. Anticipated Evaluations of Composite Beam Data

Samples			Comparisons	Common Attributes of Samples
S-1-C	S-1-A	S-1-B	½” vs 1”	Spray applied to bottom; profile 1
S-1-A	S-1-B	S-1-D	Spray vs Normal	Applied to bottom; profile 1; 1” thick
S-2-A	S-2-B	S-2-C	Spray vs Normal	Applied to top; profile 2; 1” thick
S-1-C	R-1-C*	R-1-A R-1-B	Profiles 1, 2, 3	Spay applied to bottom, ½” thick
S-2-B	S-2-C	S-2-D	Profiles2,3	Normal applied to top; 1” thick
R-1-A	R-1-B	R-1-D	½’’ vs 1”	Spray applied to bottom; profile 3
R-2-A	R-2-B	R-2-C R-2-D	Spray vs Normal	Applied to top, ½’ thick profile 4

6.2 Slab Specimen

Full-scale specimens have been cast to validate the models and incorporate parameters discussed above. Large-scale specimens representing bridge deck section with dimensions of 3 ft. wide by 8 ft. long have been cast. The specimens are 9-inch thick and reinforced with two layers (top and bottom) of No. 4 bars on 6-inch centers. The specimen descriptions as follow:

1- Benchmark specimen made of normal strength concrete without any UHPC overlay or bottom application, as shown in Figure 21;
2- Repair specimen with a block-out built in the bottom section. The block-out is 2-in thick, 4 ft. long and 3 ft. in width. The block-out will be filled with UHPC through pneumatic spray application in addition to the outer bottom surfaces, as shown in Figure 22. This specimen represents the repair of the bottom of the deck using pneumatic spray for overhead application.
3- Repair specimen for deck overlay, as shown in Figure 23. The UHPC overlay will be applied by pneumatic spray on flat surface.

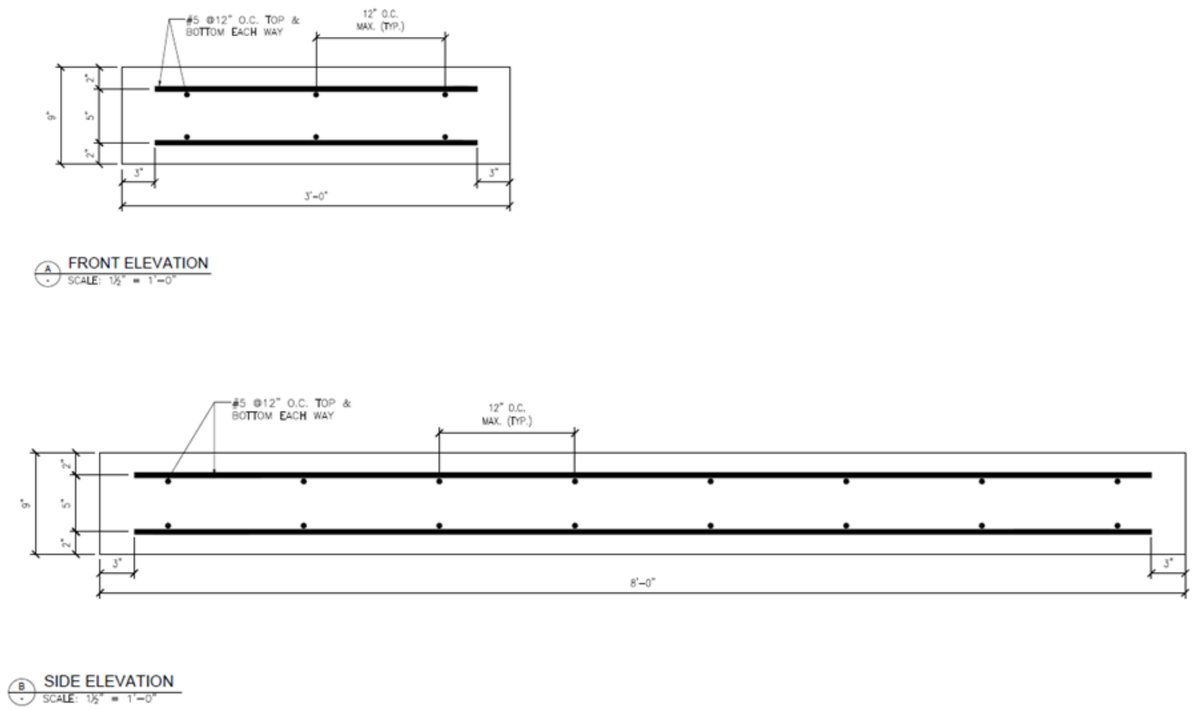


Figure 21. Details of the first specimen (Benchmark)

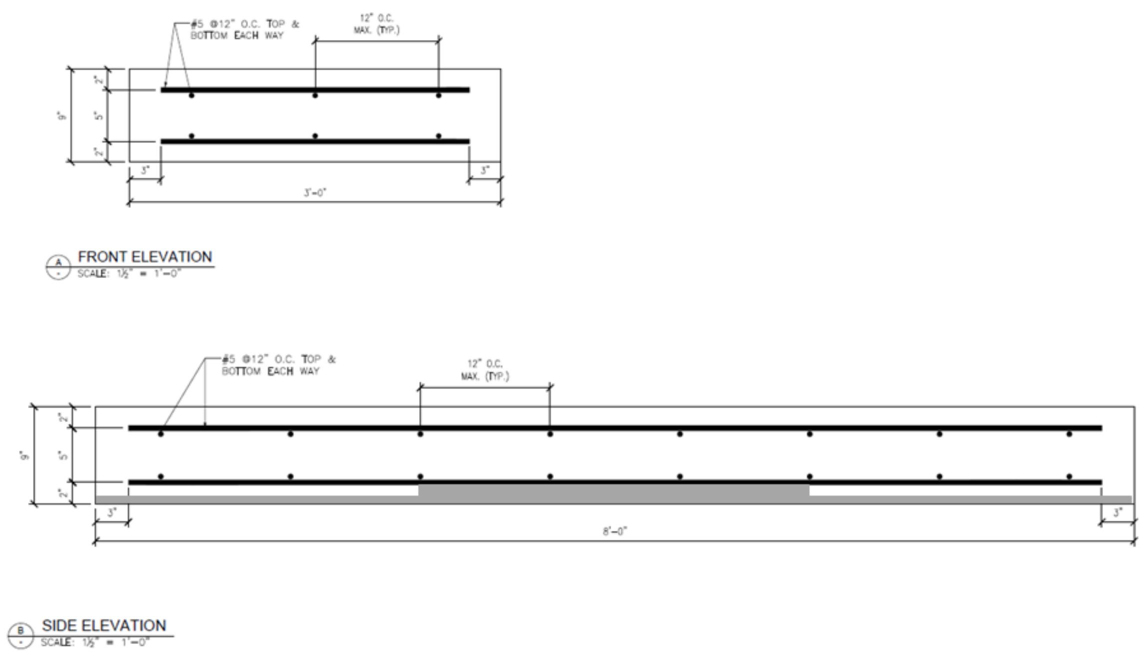


Figure 22. Details of the second specimen (bottom repair)

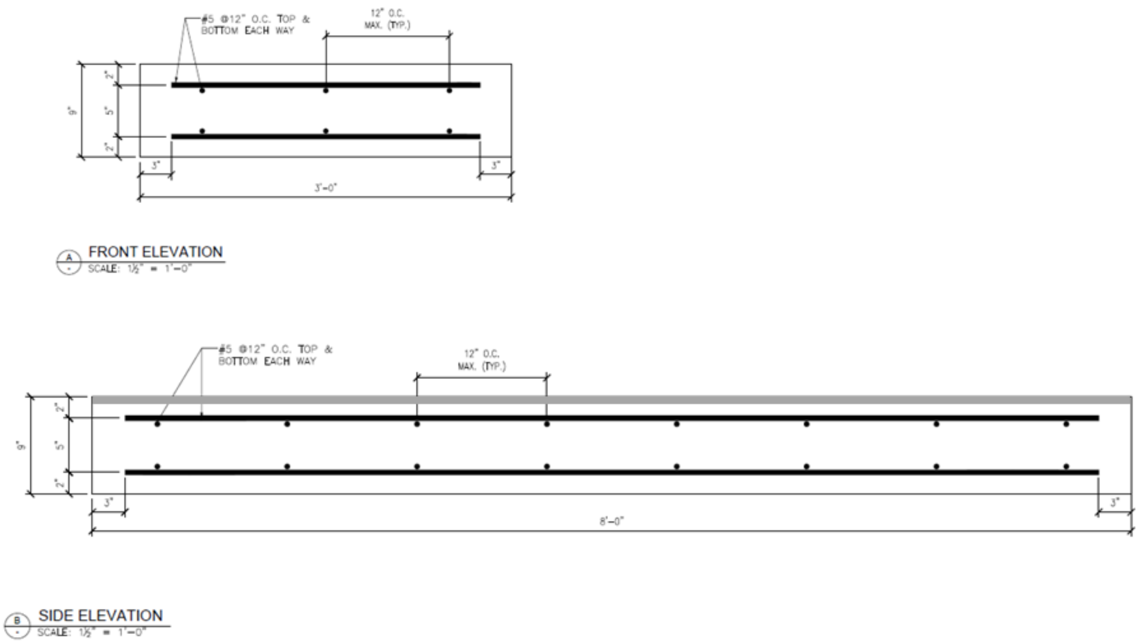


Figure 23. Details of the second specimen (Bridge Overlay)

Large scale specimens are shown in Figure 24. Both the second and third specimens were sandblasted to roughen the concrete surface to enhance the bond between sprayed UHPC and concrete substrate as shown in Figures 25 and 26.

The roughness of the sandblasted surfaces will be measured. The surfaces have been scanned with a three-dimensional laser scanner, FARO Laser scanner Focus 3D X130. The scanner takes fast and accurate measurements with a one million points per second scanning rate. The scanning range is 425 ft. It is equipped with an integrated GPS receiver and 50% noise reduction feature. The data is in the process of being reduced to quantify the roughness in following steps.

- A 3D image has been prepared with Cloud Compare software from the measurements.
- The 3D image of the measured surfaces will then be imported to MATLAB in the form of 3 dimensional coordinates.
- Plotting The peaks and valleys will be plotted, and the optimized smooth plane will be calculated.
- The average surface roughness, Ra will then be calculated.

Figure 24. Large scale slab samples

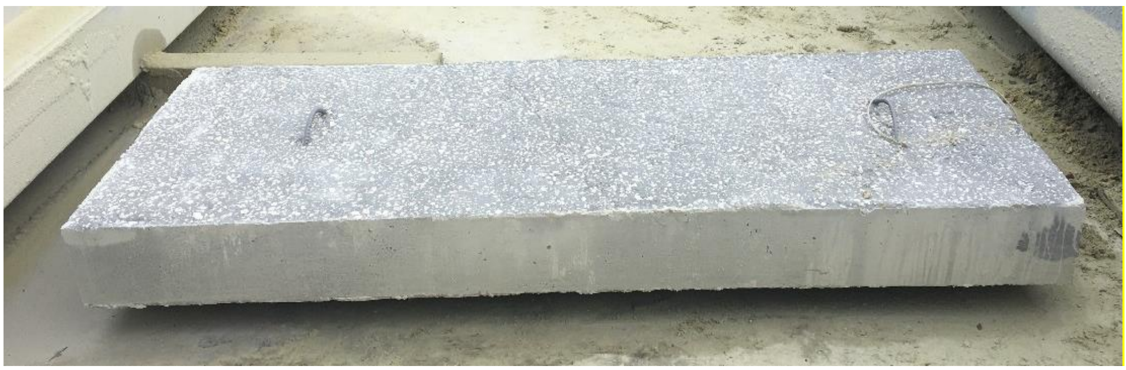


Figure 25. Sand-blasted slab specimen (Top-surface)

Figure 26. Sand-blasted slab specimen (Bottom-surface)

Two additional specimens (Figures 27-28) will also include a surface overlay, 1- inch thick, and bond strength will be performed. These specimens are 3 1/2 -in. thick slabs with single layer of steel reinforcement. They are 2 ft wide and 6 ft long. Rebar hooks have been included for lifting and handling each of these specimens. Surface roughness has been cast one surface of the slabs. Bond strength testing following Graybeal's procedure will be performed on these samples.

One slab has roughness profiles with the profile skins 1 and 2, described above. The second slab has roughness profiles 3 and 4 cast into the surface. Figure 28a shows the skins in the bottom of the form prior to casting. Figure 28b shows the skins on the concrete surface, note that the rightmost skin has been removed. The surfaces have been scanned with a three-dimensional laser scanner, FARO Focus terrestrial laser scanner. The scanner is shown in Figure 29. The data is in the process of being reduced to quantify the roughness as discussed above.

Figure 27. UHPC panel for bond testing and overlay testing of UHPC shotcrete.

(a) (b)

Figure 28. Roughness Profiles Skins

Figure 29. Three-Dimensional Scanner

7. UHPC Shotcrete Application

7.1 Equipment and Set-Up

A small concrete pump was purchased for this research. It was manufactured by Black-Jack pumps and is single cylinder, auto reciprocating pump. The pump discharge is 2-inch diameter, connected to a 2-inch hose. The shotcrete nozzle is also 2 -inch diameter. Wet spray nozzles are available commercially in 1 ½ -inch and 2-inch diameters. Figures 30 through 33 show the equipment.

FIU’s UHPC mixer will only batch about 2,5 cubic feet per batch. This dictated the smaller pump and nozzle selection. The smaller batches also well suited to the sample sizes prepared for this research program.

Figure 30. Black-Jack Pump, reducer and hose.

Figure 31. Black-Jack pump showing hopper and discharge.

Figure 32. Nozzle and hose assembly

Figure 33 Nozzle with Air and Concrete lines connected.

The air compressor is rated at 100-125 cfm at 110 psig. It is diesel powered and is shown in Figure 34.

Figure 34. Air compressor.

7.2 Small Scale Specimens

An UHPC shotcrete operation was completed with the JS 1000 Ductal mix. The batching operation is shown in Figure 35. The first batch did not have steel fiber and was mixed to the proportions shown as Mix 22 in Table 6. The air compressor had sufficient energy to propel the mix. It sprayed well vertically downward and also horizontally. Two of the flexure beam specimens were sprayed as targets, on vertically down and one horizontally. The mix sprayed horizontally adhered to the wetted concrete surface, but only left a thin layer, about 1/8-inch thick before beginning to run down the sample face.

Figure 35. UHPC batching and mixing operation.

A second batch was then mixed. This batch included steel fibers at 2% by weight. The batch proportions are shown as Mix 12 in Table 6. This mix was also sprayed on Flexural Beam samples. The initial 2 samples sprayed with non-steel fiber were sprayed again. Six (6) additional samples were also sprayed. Three (3) were sprayed vertically down and 3 were sprayed horizontally. These additional samples were not wetted prior to spraying, the spray was applied to the dry concrete surface. Figures 36 through 41 show the spraying operations and samples.

Figure 36. Application vertically down on flexure beam samples

Figure 37. Pneumatic application horizontally.

The steel fiber mix was observed to adhere to the samples. A thicker layer was achieved before the material began to slowly run down the sample face. Application of subsequent layers resulted in a thicker coat of UHPC. An increase in thickness was also observed with the vertically down application. A summary of the flexure beam UHPC application is presented in Table 12.

Table 12. Summary of Flexure Beam overlay application

Beam Designation	Proposed thickness	Roughness profile	Re-bar location	Application method, location,	Date applied
R-1-A	1/2	3	adjacent	Spray application on bottom, horiz	10/30/20
R-1-B	1/2	3	adjacent	Spray application on bottom	10/30/20
R-1-C	1/2	2	adjacent	Spray application on bottom	damaged
R-1-D	1	3	adjacent	Spray application on bottom, horiz	10/30/20
R-2-A	1/2	4	opposite	Conventional application on top	10/11/19
R-2-B	1/2	4	opposite	Conventional application on top	10/11/19
R-2-C	1/2	4	opposite	Spray application on top	10/30/20
R-2-D	1/2	4	opposite	Spray application on top	10/30/20
S-1-A	1	1	adjacent	Spray application on bottom, down	10/30/20
S-1-B	1	1	adjacent	Spray application on bottom	10/30/20
S-1-C	1/2	1	adjacent	Spray application on bottom	10/30/20
S-1-D	1	1	adjacent	Conventional app on bottom	10/11/19
S-2-A	1	2	opposite	Spray application on top	10/30/20
S-2-B	1	2	opposite	Conventional application on top	10/11/19
S-2-C	1	2	opposite	Conventional application on top	10/11/19
S-2-D	1	3	opposite	Conventional application on top	10/11/19

Figure 38. Vertically down application on flexure beams.

Figure 39. Horizontal application on flexural beam samples

Figure 40. Horizontal Spray

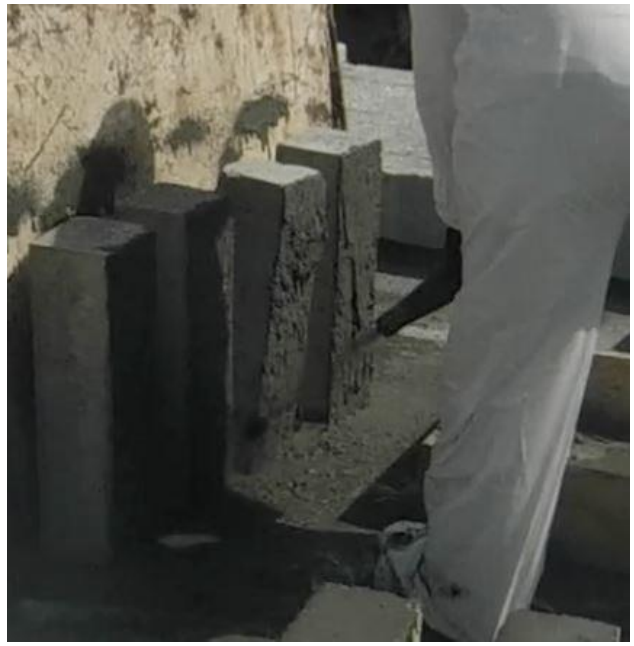


Figure 41. Horizontal Spray, note rebound.

UHPC was placed conventionally (not pneumatically) on Beams R-2-A, R-2-B, S-1-D, S-2-B, S-2-C, and S-2-D on October 11, 2019. The mix was Ductal JS 1000, corresponding to Mix 12 on Table 6.

7.3 Large Scale Specimens

Another shoot was performed on November 22, 2021. The UHPC mix had a W/C ratio of 0.18, and a viscosity modifier agent (VMA) was added to the mix. This material was sprayed onto a large panel that had been prepared with the roughness profiles 3 and 4. This is shown on Figures 42 and 43, The UHPC was sprayed in layers, with a 3 to 5 minutes wait to spray a subsequent layer. Three layers were applied. Some running and dripping was still observed, the material was made to spray from top to bottom instead of bottom to top.

Figure 42. Ppneumatic application of UHPC, third layer.

Figure 43 UHPC sprayed on roughened surface, the white are roughness profiles skins that had not been removed.

8. Expected Results and Specific Deliverables

It is anticipated that UHPC will be investigated for use as overlay material, applied with traditional methods and with spray applications. The high strength of the UHPC provides a stronger bridge sections and culvert with higher corrosion resistance. Factors such as the required interfacial surface roughness, variable thickness and selection of a mix design will be addressed with guidelines for selection of these variables. The procedure will be presented in the form of a selection matrix or flow chart to guide the design and construction practice.

9. Schedule

Duration of this project was anticipated to be about 18 months. Timeline for various tasks is shown in Figure 44 up to the date of the sixth quarter report. The COVID19 pandemic resulted in pushing the anticipated schedule out, as FIU closed the laboratories in the nationwide effort to contain the virus. As of this writing, they have been re-opened with limited access and COVID related requirements. The closure impact to the schedule is shown below. The progress in this quarter included conducting pneumatic application of shotcrete to small samples (material level testing Task 2)

Item	**% Completed**
Percentage of Completion of this project to Date	70%

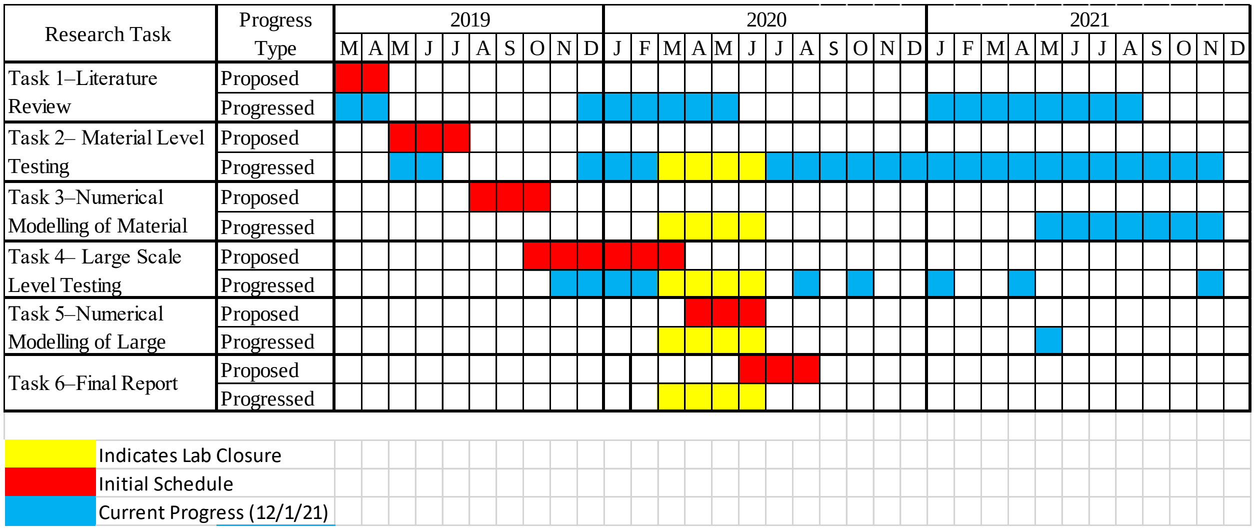


Figure 44. Project Progress.

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