Use of UHPC in Conjunction with Pneumatic Spray Application and Robotics for Repair and Strengthening of Culverts- Phase I

Quarterly Progress Report
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Submitted by:

Graduate Student-Muhammad Faheem Ud Din Afzal

PI- Atorod Azizinamini, Ph.D. PE

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

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

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1. Background and Introduction

The deterioration of pipes and culverts is a growing problem for transportation agencies. As transportation drainage infrastructures age, the need for repair or rehabilitation often becomes more critical. As a result, the number of pipes and culverts being repaired or rehabilitated is increasing each year. Following charts show the percentage of concrete culverts and also current condition of those culverts.

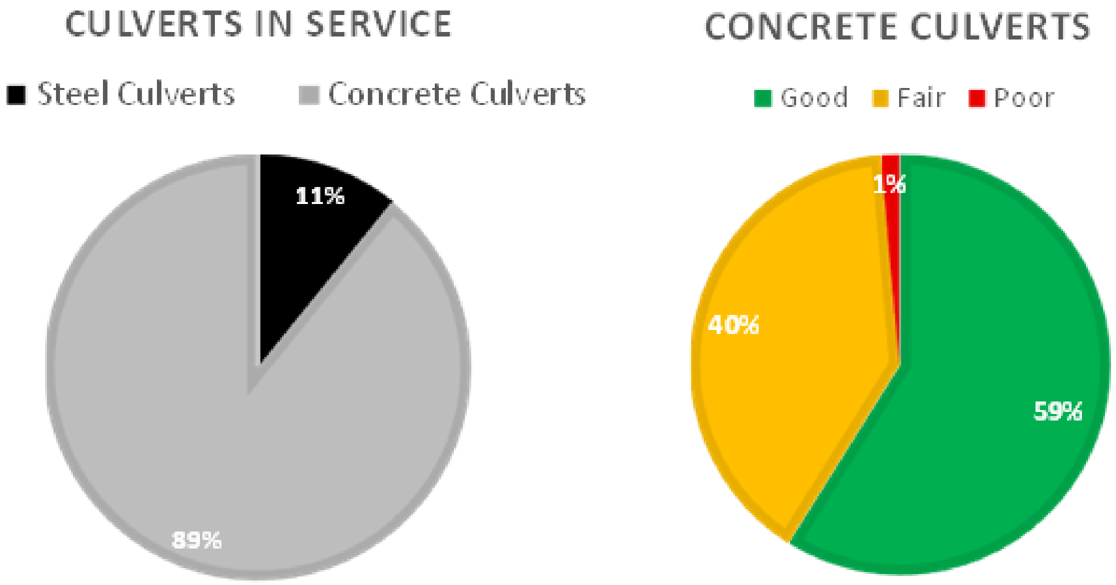


Figure 1: Percentage of concrete culverts (L), Current Condition of Culverts (R)

Many Culverts need repair. Developing an approach for strengthening these structures without interrupting traffic, will greatly assist State DOTs. This project is Phase I of an initiative to develop a method and means for repair and strengthening of existing substandard culverts using UHPC and automation, through robots and utilizing pneumatic spray application to reduce the need for excessive labor and human intervention which will lead to an accelerated repair technique. Phase I is limited to developing information, identifying parameters and factors, needed consideration, and developing the roadmap and paving the way to conduct future phases of the investigation

Ultra-High strength concrete (UHPC) applications have been studied as one of the many strategies in Accelerated Bridge Construction (ABC). Culvert maintenance procedures can be accelerated with the application of UHPC in specific situations. 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 3000 to 4000 psi is required to open a lane to traffic. UHPC also provides a higher strength and mitigates additional corrosion by inhibiting penetration of additional chloride ions. Recent developments in UHPC mixes have been applied with pneumatic spray applications. Such repair methods may be applicable to horizontal, vertical, inclined, and overhead surfaces.

2. Problem Statement

Strengthening and repair of existing substandard culverts is identified as an issue that is common in many states. The main objective of this project is to develop a roadmap for conducting systematic research that could lead to the development of complete design and construction approach for strengthening existing substandard culverts using

a) UHPC
b) Pneumatic Spray Application
c) Automation using robots

One of the recent advances in UHPC application is the development of UHPC applied with pneumatic spray methods. Spraying UHPC on the damaged part of the culvert will save the time and effort of building formwork while providing the strength while no need for traffic mitigation.

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

1. How does the roughness of the interfacial surface between UHPC and normal strength concrete impact moment capacity? What is the optimum interfacial surface roughness?
2. UHPC mix designs typically contain 2% steel fibers, but some applications have been documented with different percentages. What is the effect of iterating steel fiber content? The existing UHPC mixes may need to be modified utilize synthetic and flexible fibers instead of steel fibers in spray applications. What modifications should be made and what effect will they have?
3. Hydro-blasting/Sandblasting and other methods of removing deteriorated concrete and surface preparation may result in varying thickness. How does the roughness of the interfacial surface between UHPC and normal strength concrete impact moment capacity? What is the optimum interfacial surface roughness?

3. Objectives and Research Approach

The scope of this project will be limited to understand the problem in detail and developing a roadmap for conducting systematic research in phases that could ultimately lead to the development of an effective and automated method for strengthening existing substandard culverts. Among the issues to be understood, before undertaking detail research in future phases are

a) Major types of culverts that need to be strengthened. Concrete, steel, and aluminum culverts will be studied in terms of bond between the culvert material and UHPC. The main target for this proposal will be concrete pipe culvert.

b) Identifying properties of UHPC needed for strengthening culverts. This should lead to the development of UHPC more suitable for culvert strengthening application and could reduce the cost
c) Identifying methods and means for field application of UHPC in the field that could involve pneumatic spray application and automation.

Task 1 – Identifying major culvert types needing strengthening

A project advisory panel will be established, consisting of States interested in the problem. This project advisory panel will be used to establish types of culverts that project should concentrate on. Concrete, steel, and aluminum culvert will be studied under this task

Progress: Some information is collected from literature. Please refer to Section 5 for the collected information. Researchers will communicate with RAP for further information collection.

Task 2– Identifying properties of UHPC needed

A series of numerical analyses will be conducted to establish the structural properties of UHPC needed for strengthening the types of existing culverts. This can then be used to modifying the UHPC mix ABC-UTC has developed if it could result in cost saving. One aspect of UHPC that will need some changes is fiber type. The use of flexible synthetic fiber is more user-friendly for pneumatic spray applications along with exploring different UHPC mixtures such as JS1212 to reduce the material rebound.

Progress: Research team is working closely with students in another project related to UHPC for pneumatic spray application "Optimization of Advanced Cementitious Material for Bridge Deck Overlays and Upgrade, Including Shotcrete [ABC-UTC-2016-C2-FIU04]" to identify the most feasible UHPC mixture for shotcrete. Please refer to Sections 4 and 6 for more information collected in collaboration with research team studying UHPC for pneumatic spray application

Task 3– Identifying automated methods for field application

What we are envisioning at this point is a robot that moves along the culvert or pipe along the length of culvert and rotates simultaneously, while pneumatically applying UHPC. Under this task detail of the robots needed will be envisioned.

Progress: We have made progress in terms of the execution of the mix design using pneumatics

Task 4– Developing roadmap

Under this task detail roadmap, in the form of a series of separate buy connected proposals will be developed to be undertaken in the future. These proposals will be proposed in future cycles of ABC-UTC research program.

Progress: The initial design for the robots are in progress

4. Description of Research Project Tasks

Figure 1 shows the proposed flowchart for the project tasks for pneumatic spray application of culverts.

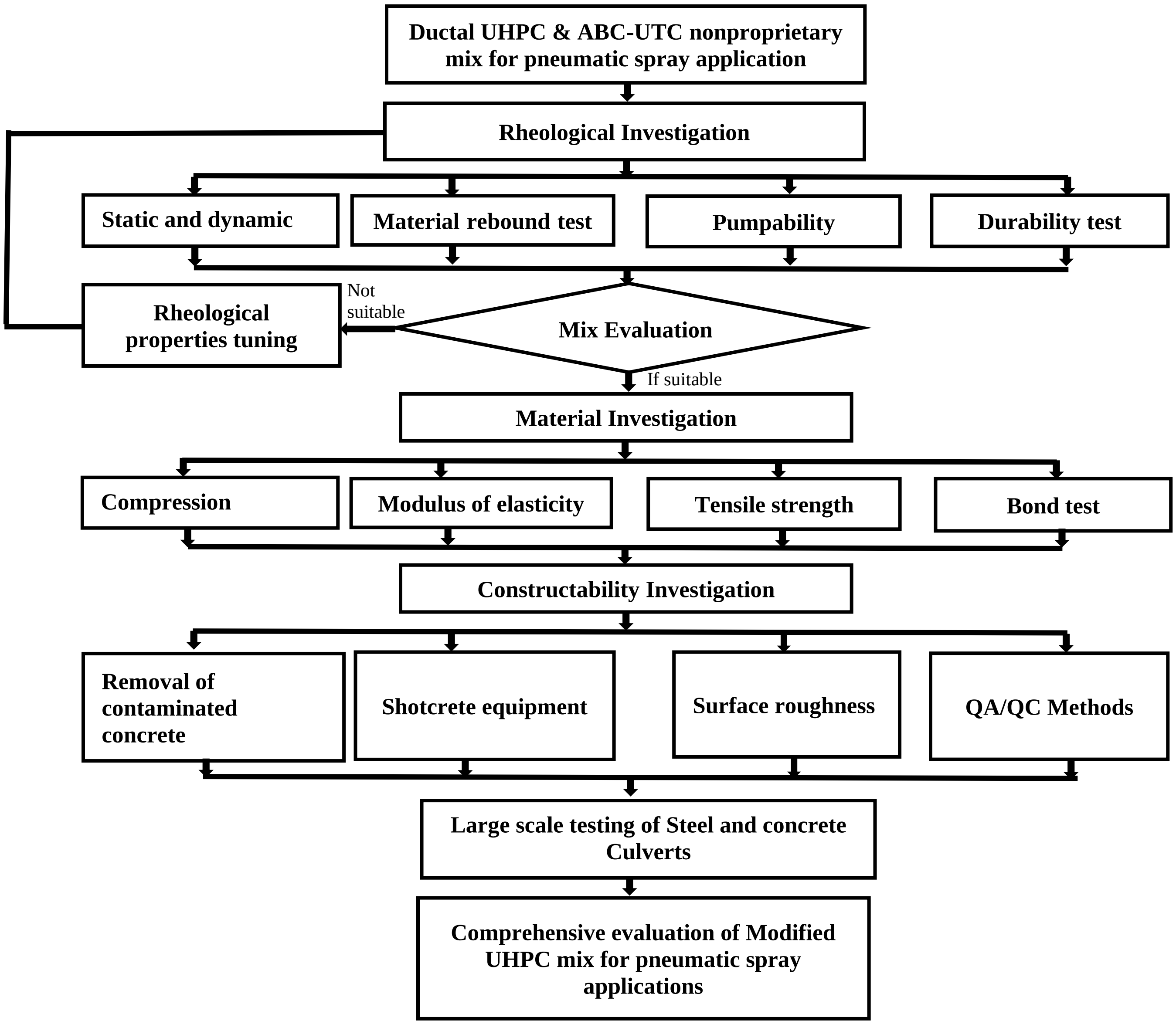


Figure 2. Flowchart of research tasks.

This chart is developed as part of "Optimization of Advanced Cementitious Material for Bridge Deck Overlays and Upgrade, Including Shotcrete [ABC-UTC-2016-C2-FIU04]"

5. Literature on Culvert Damages and Current Repair Methods

5.1 Types of culverts

The most common materials used in culvert conduits are reinforced concrete, corrugated steel, and corrugated high-density polyethylene. Other materials that may be found in culvert conduits are corrugated aluminum, non-reinforced concrete, ribbed polyvinyl chloride (PVC), welded steel, timber, and masonry. In this research primary focus will be on reinforced concrete culverts however similar strategies will be developed for steel culverts because of their high utility by state DOT's.

5.2 Causes of Culvert damage

There are many forms of damages in culverts. The main concerns are the damages related to structural loading and corrosion activity. According to Caltrans supplement to FHWA culvert repair practices manual [1] Cracks or fractures in flexible pipe culverts are likely to be caused by pipes damages during installation by equipment or rock in direct contact with pipes, excessive loading on culverts and environmental stress cracking in pipe material. Longitudinal cracking in excess of 0.1 inches in width may indicate overloading or poor bedding [1]. Poor bedding and/or poor installation may cause transverse cracks. Spalls (fractures) often occur along the edges of either longitudinal or transverse cracks when the crack is associated with overloading or poor support rather than tension cracking. Corrosion in concrete and steel culverts is a common defect. The corrosion of drainage structures is produced by acidity, alkalinity, dissolved salts, and other chemical factors presented in soil and water, these factors may be carried by groundwater, runoff waters, rain, and marine environments, affecting the service life of metal and concrete structures. Other reasons that may decrease the structural capacity of existing culverts and cause rapid deterioration and collapse include the loss or reduction of soil support, exposure and loss of reinforcement section in the invert of RC culverts resulting loss of bending moment capacity.[1]

5.3 Culvert Rehabilitation and repair

Culvert repair is a maintenance activity that keeps them in a uniformly good and safe condition and rehabilitation of a pipe takes maximum advantage of the remaining usable pipes, so that the pipe is returned to its initial condition or even better. The common methods mentioned in Culvert Repair Best Practices, Specifications and Special Provisions−Best Practices Guideline by

Minnesota Department of transportation [2] include Paved invert, Cured-in-place pipe liner, Sliplining, centrifugally cast liner etc.

Sliplining is a common method and most viable for smaller diameter non-human entry pipes 36 inches or less in diameter that are too small for invert paving. Lining using different techniques i.e. Cured in place pipes, PVC Liners (as shown in Figure 2), deformed reformed HDPE liner, machine wound plastic liner. Man-entry lining with pipe segments is also widely used. Other techniques include internal chemical grouting, internal joint sealing systems and repair sleeves, invert paving, steel armor plating and welded steel pipelines. In a recent study by Chennareddy et al. [3] corrugated steel pipelines were rehabilitated GFRP slipliner, as shown in Figure 3

Figure 3. PVC Slip liner and Grout Injection Pipes [2]

Figure 4. GFRP Slip liner using wood spacers [3]

The advantage of using UHPC in conjunction with pneumatic spray application and robotics for repair and strengthening of culverts provide advantage such as 1) access to inaccessible areas, 2) saving time, 3) no need for traffic mitigation and 4) higher strengths unlike some of the techniques mentioned hereinabove.

6. Investigations for UHPC and Pneumatic Application

6.1 Literature Review

This section is based on the findings from *"Optimization of Advanced Cementitious Material for Bridge Deck Overlays and Upgrade, Including Shotcrete [ABC-UTC-2016-C2-FIU04]"*

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

1. Material properties of UHPC,
2. Composite action of UHPC and Normal strength concrete or steel metallic,
3. Pneumatic Spray Application, and
4. Numerical Modeling of UHPC and composites.

Several researchers have studied the basic properties of UHPC mixes, including compressive strength, tensile strength, creep, durability among others. Haber et al., [4] presented a table of typical UHPC properties, as shown in Table 1.

UHPC have 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., [4] presented strengths of about 9,000 psi at 2-day.

Bruwiler [5] 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.

Table 1. Typical Properties of Field Cast UHPC Concrete adapted from Haber et al., [4]

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.

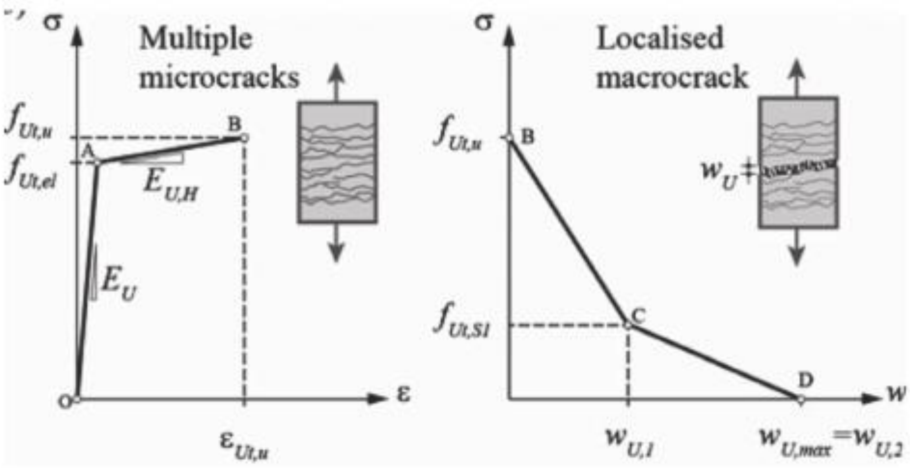


Figure 5. UHPC Tensile Behavior [5].

Al-Basha, et al., [6] 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 2. They concluded acceptable bond strengths which can be obtained between UHPC and NSC, but this strength is dependent on the surface roughness.

Table 2. Average direct tensile strengths for different textures [6].

Texture (average texture depth)	Rough (2.8 mm)	Horizontal Grooves (0.9 mm)	Chipped (1 mm)
Average Tensile Strength (MPa)	0.96	0.44	1.06

For pneumatic spray application, Kyong -Ku Yun et al. [7] 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 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. [8] 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. [9] 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

Kyong-Ku Yun et al. [10] 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.

6.2 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 [11]. 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 [12].

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 [13]. The higher the yield stress, the greater the thickness that can be built up without sloughing. This results in better “shootability”.

6.2.1 Proposed Mix Designs Based on Effects of Mix Composition 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 [14].

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.

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 theABC-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 3 and Table 4 were prepared for the initial rheological investigation.

Table 3(a). Table 3. 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 4. 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

6.3 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. UHPC cores which will be obtained from a test panel 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.

6.3.1 Rheological Test Results with Ductal Mixes

To date, compressive strength testing has been performed on cubes cast during the initial round of rheological testing. The results are summarized in Table 4.

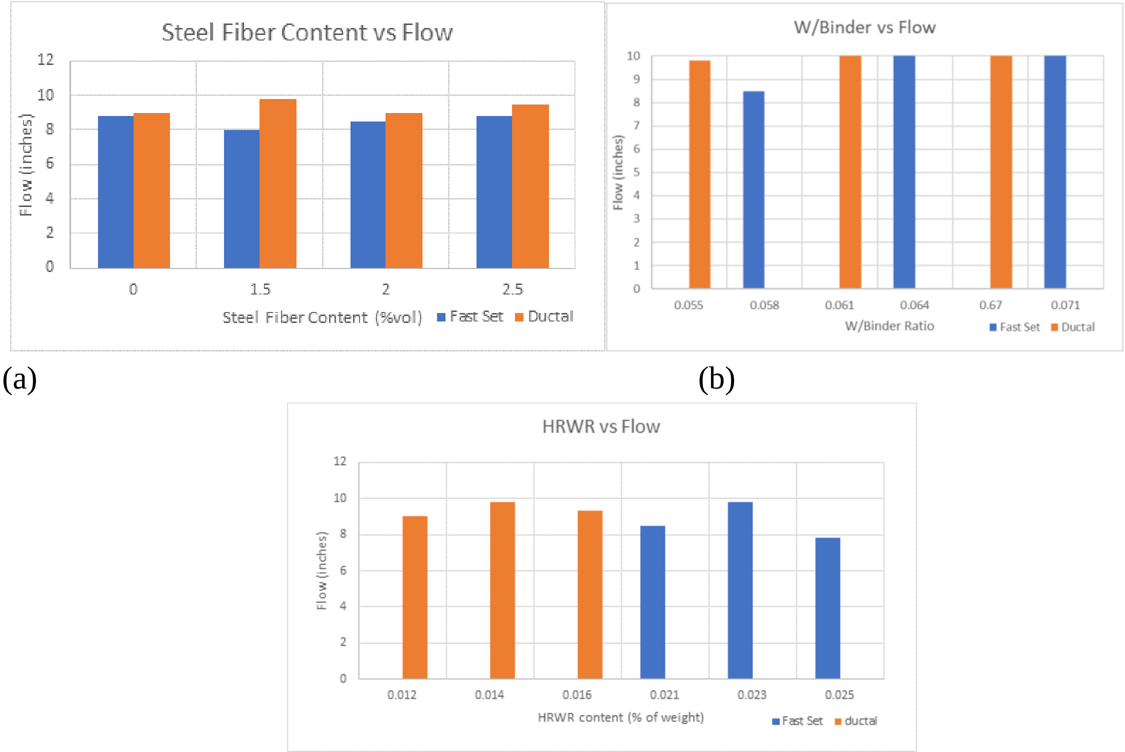
Table 5. Results of Initial Rheological Testing

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 # 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 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 # 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 6. Flowability Test Results**

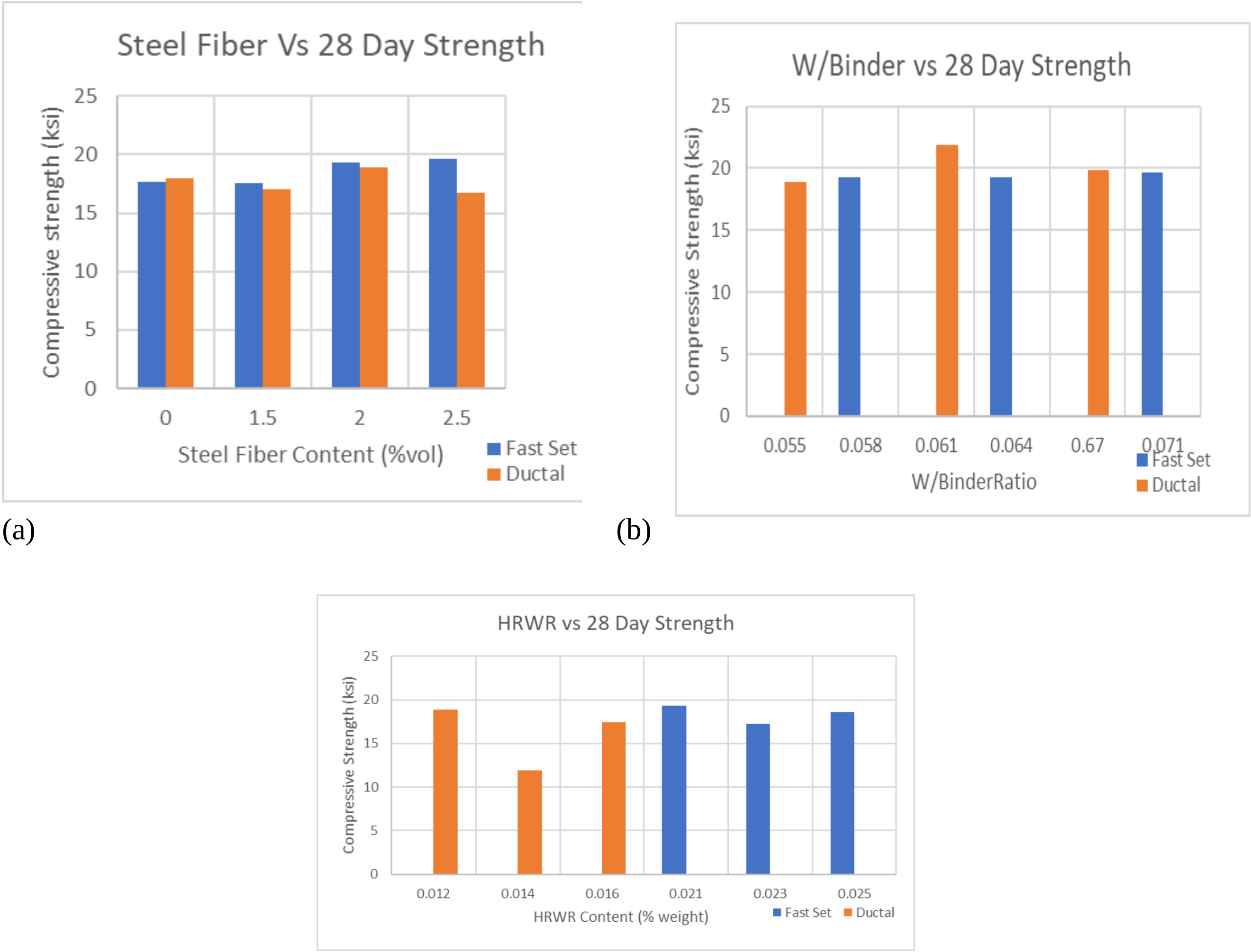
(a) **Figure 7. Flowability Testing** (b)

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 8. 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. Additional rheological testing is planned to evaluate variations in air content and the corresponding effect on flow and strength.

6.3.2 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 6. Test results are pending evaluation.

Table 6. 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 (sufficient flow), provide adequate 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 [15] and Shahrokhinasaab [16], are shown in Table 9 below.

The four 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 7. Typical Composition of Ductal [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

Effect of HRWR on Strength and Flowability – It was observed experimentally that the strength decreased with an increase in HRWR, although the strength reduction was relatively small. It can be seen in **Figure 9** below which shows the effect of HRWR proportions on strength for 60/40 and 56/44 mixes. 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. Similarly the effect of HRWR on the flowbility is shown in **Figure 10**.

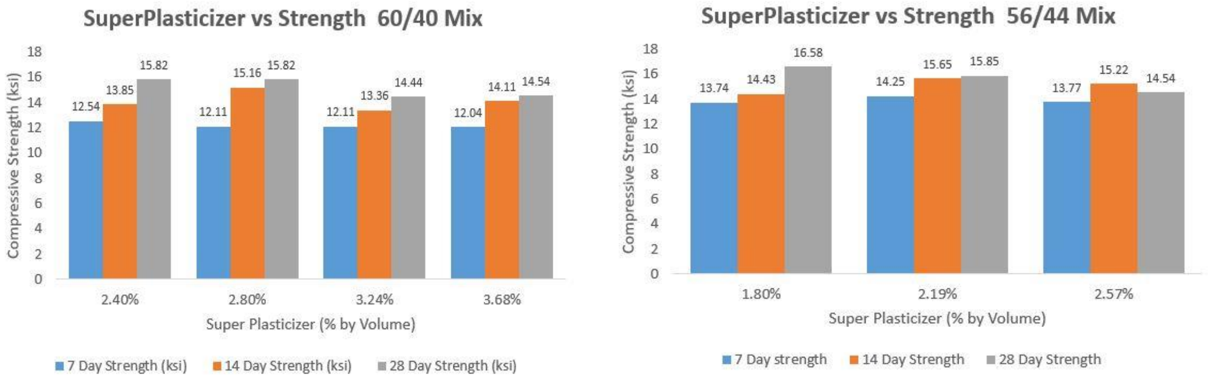


Figure 9. HRWR vs Strength

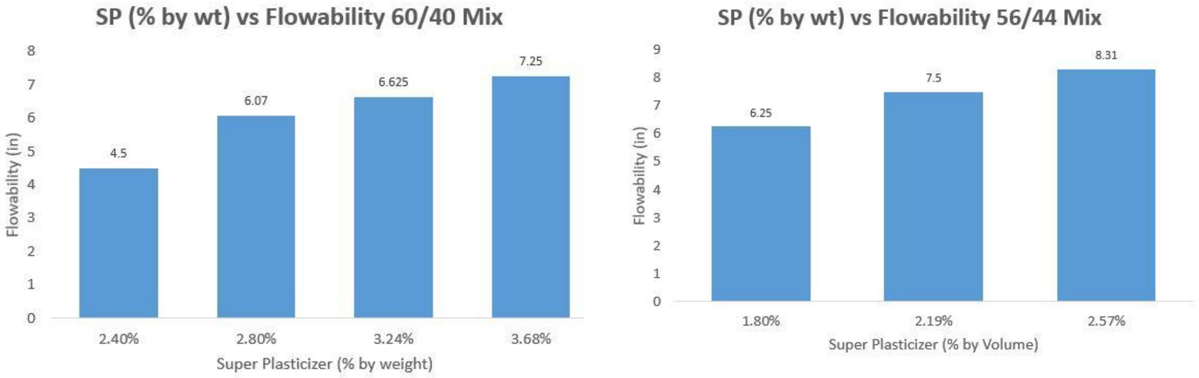


Figure 10. HRWR vs Flowability

Effect of Fiber Type on Strength and Flow- Three types of fibers were tested for different mix designs. The fiber types tested include steel, synthetic and Hybrid Fibers (combination of both steel and synthetic fibers). The trend is summarized in **Figure 11** which shows that Steel fibers gives maximum strength and flow.

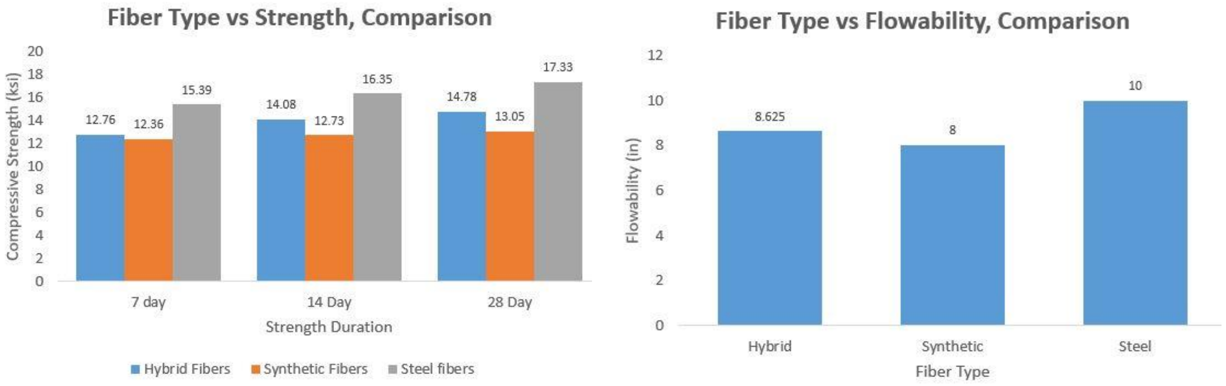


Figure 11. Effect of Fiber Type on Strength and Flow

Effect of Water to Binder ratio on Strength and Flow- The results shown are for three of the best mix designs so far tested, it has equal proportion of sand and cementitious material. This mix has given highest relative strength and flowability ranges from 5 inches to 10 inches. It was observed that the mix has given best results at Water to binder ratio of 0.18. **Figure 12** shows the relationship of W/B with strength and flow.

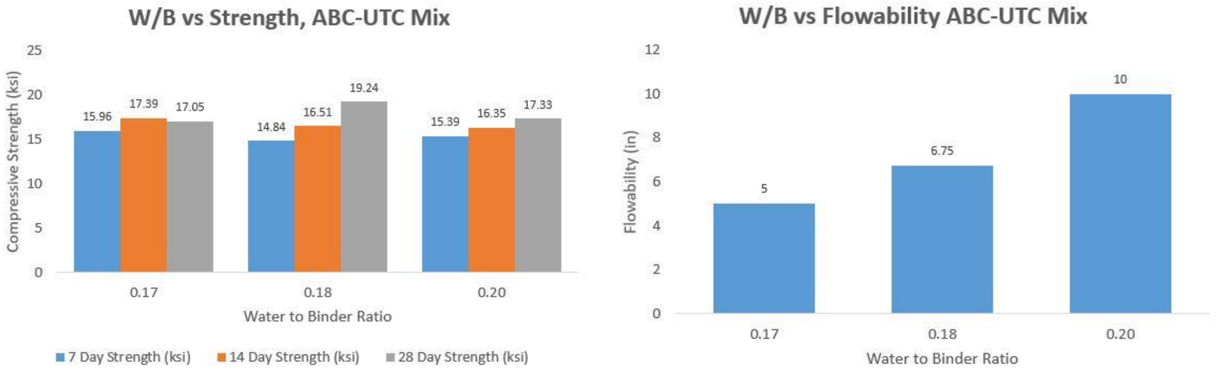


Figure 12. Effect of W/B on strength and flow

6.4 Constructability Investigation:

Pneumatic spray application of UHPC in this project is meant to repair culverts. 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 removals methods will have on strength 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.
4- Identifying quality control and quality assurance methods that can be used to assess the quality of finished products.

7. Surface roughness investigation

Concrete surface roughness and surface moisture conditions need to be quantified in the field to achieve quality finished products. 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. The roughness of the sandblasted surfaces will be measured. The slab surfaces as shown in **Figure 13** of a sister project have been scanned with a three-dimensional laser scanner as shown in **Figure 14**, 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 13. Roughness Profiles Skins

Figure 14. . Three-Dimensional Scanner

8. UHPC Application

This section is based on the findings from *"Optimization of Advanced Cementitious Material for Bridge Deck Overlays and Upgrade, Including Shotcrete [ABC-UTC-2016-C2-FIU04]"*

Rheological investigations were performed on ductal premix UHPC and ABC-UTC mix. Based on those rheological studies, mix designs were short listed subject to their suitability for shotcrete application. A trial test was conducted in order to analyze the selected UHPC mix for shootability and pumpability. The test was conducted on small beam specimen placed in horizontal and vertical position, having different roughness profiles. During the shotcrete process a significant amount of rebound was observed. The shotcrete process can be seen in the following images below. More details can be seen in the project, “Optimization of advanced cementitious material overlays and upgrades, including shotcrete” 4 quarterly report 2020.

Figure 15. Black-Jack Pump, reducer and hose.

Figure 17. Horizontal Spray

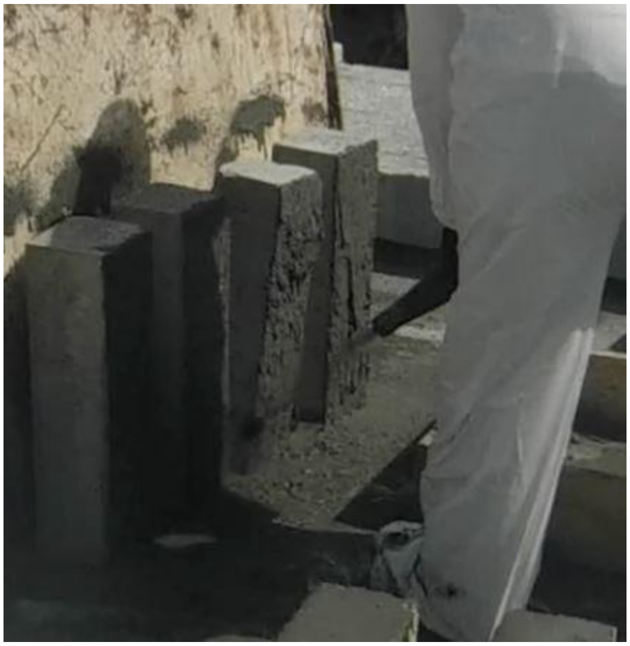


Figure 16. Horizontal Spray note Rebound

9. Automation of shotcrete

1 Reasons/Advantages for/of automation:

In most of the applications of shotcrete there is a need of an experienced and trained nozzle operator. The strain of the concrete pipe along with the air compressor hose which is applied on the worker during the process limits the quantity of concrete that can be handled. To get optimal quality and a minimum amount of rebound, the nozzle operator has to keep the right distance from and angle to the surface. Due to human influence, it is not possible to keep all the main parameters in the best possible combination. Girmscheid and Moser 2001 [15].

The other way which is also used practically is spraying by manipulator as shown below in **Figure 18**. Manipulator can reduce the strain on the worker during shotcreting. The worker steers the different joints with several joysticks to let the nozzle do the movements. The operation of the joints makes it difficult to keep the nozzle perpendicular to the surface and at the recommended distance. Even with remote control, it is still difficult to hold the quality on a steady level due to the poor visibility caused by the dust of spraying, the large distance between the nozzle operators and the spray jet, as well as the unfavorable angle of sight. [15].

So the automation of the shotcrete has been aimed to enhance the quality of the shotcrete and to improve the application technique.

Figure 18. MEYCO Robojet Manipulator. [17]

2 Progress on automation:

We are very close to narrow down selection of the best mix design for the UHPC. On the other hand, the team is also analyzing different methods for the shotcreting the UHPC mix. The team has commenced on the automation of the shotcreting process and has developed a road map for the design of the robot capable of shotcreting inside culverts of different sizes and types. The robotic shotcreting has two basic principles: improving the quality and finishing of the final shotcrete product, to ensure the safety of workers from working in hazardous environment. Ford [17]. Similarly, Nabulsi [18] showed that there is an improved shotcrete layer quality by using automation in shotcrete technology.

Initially, the robot will be planned with the focus on a Circular reinforced culvert having a radius of 5 feet. Circular shape is more suited to the currently designed robot as compared to rectangular shape in terms of keeping the distance from the nozzle of the robot to the surface of the culvert constant. Maintaining a constant distance is an important factor in the shotcrete as it reduces the rebound and retains the quality. The exact distance from the surface depends upon the velocity of the mix being shoot and the air pressure. Generally, it has been observed that the nozzle may maintain a distance of 1-2 feet away from the surface of the shoot. The designed system should be able to shoot a culvert of a length of 15 feet in length. There is an estimated speed of rotation of the nozzle which is around 5-10 revolutions per minute. At the final phase of design, the robot is expected to spray uniform thickness with a nice finish.

Based on the some of the basic design considerations explained above the robot mainly will consist of a boom, the lance, nozzle and a rover in which this assembly will be mounted. A basic conceptual design is shown in **Figure 19**below.

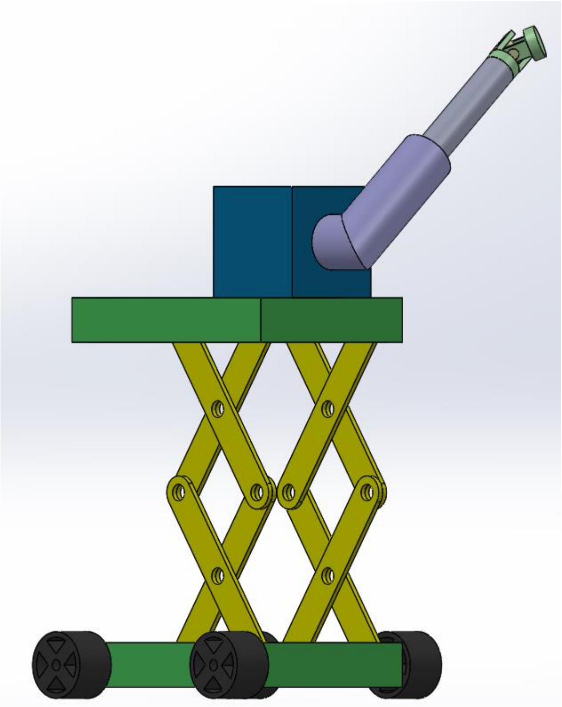


Figure 19. Conceptual Design of the shotcrete robot.

Different designs of the shotcrete robot were analyzed. The one which is shown above in **Figure 19**, has a scissor lift base. Subsequently scissor lift was removed and replaced with a simpler mechanism. Scissor lifts add an extra joint that could cause potential failure, especially if cement covers the arms. Scissor lift would also need to be reinforced to withstand the lateral loads. **Figure 20**, shows simpler mechanism that would eliminate any clogging due to cement debris. Rotating pipe fixtures have been added to nozzle to ensure correct angle with wall. This causes the nozzle to be off center which will be a problem when applying cement to culverts.

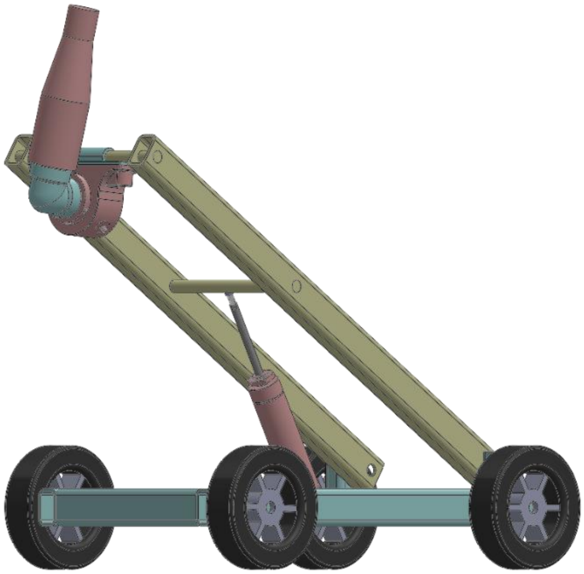


Figure 20. Conceptual Design of the shotcrete robot with Boom arm.

The robot designs which are shown in Figure 13 and Figure 14 above were analyzed for stability. It was understood that the current designs with the boom arm might have instability during the shotcrete process inside the culvert. In order to revise the design to have something more stable, several robots currently being used for inspection of narrow structures were analyzed. The inspiration of the next robot design for the shotcrete of culvert was taken from pipe crawlers as shown below in Figure 15.

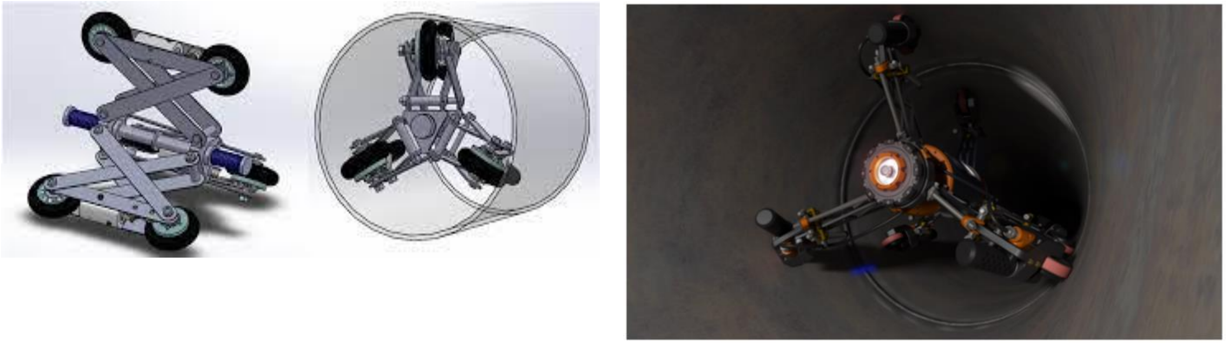


Figure 21. Pipe Crawlers

The robot which was envisioned from pipe crawler concept would have Passive spring system to overcome any debris or imperfections inside the culvert. The spring system is designed with a tolerance of 0.5 in, so once released it can lock itself with the surface of the culvert. The robot has pivot type passive spring system, so that only one spring will be connected to each wheel. The spring will approximately have a constant value of 432 lb/in. A conceptual design of the robot is show in Figure 16 below.

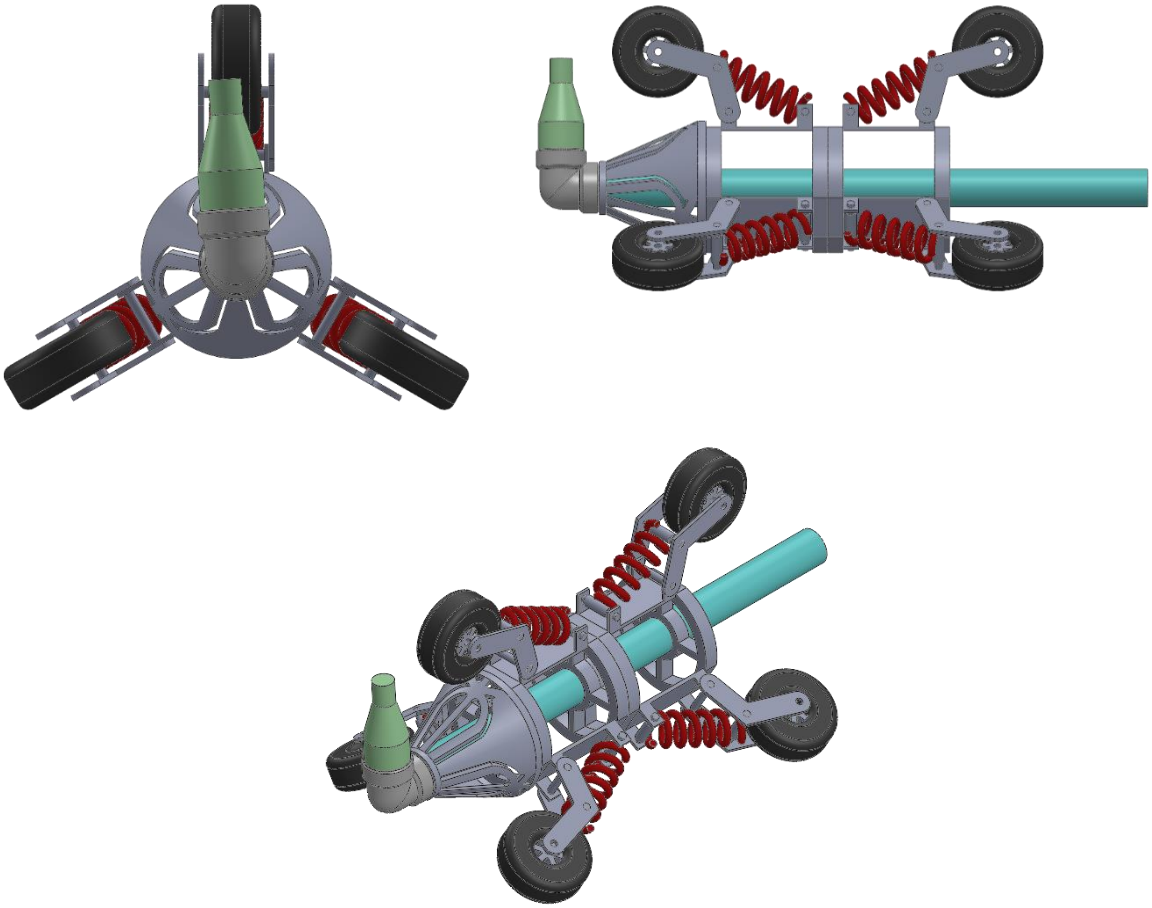


Figure 22. Robot with passive spring locking system

The modifications and advancements have continued to be made. Subsequently, the main body of the robot underwent a change. The concept of boom arm has been brought back. As upon analysis of the version shown above showed that the robot would not be able to be used for different sizes of the culvert. The boom arm will give ability to the robot to adjust itself according to different sizes and possibly shapes of the culvert.Swivel couplers have also been incorporated in the design for the first time, just to allow different motions of the robot. The design shown in **Figure 20** has been modified into something more efficient as shown in **Figure 23**.

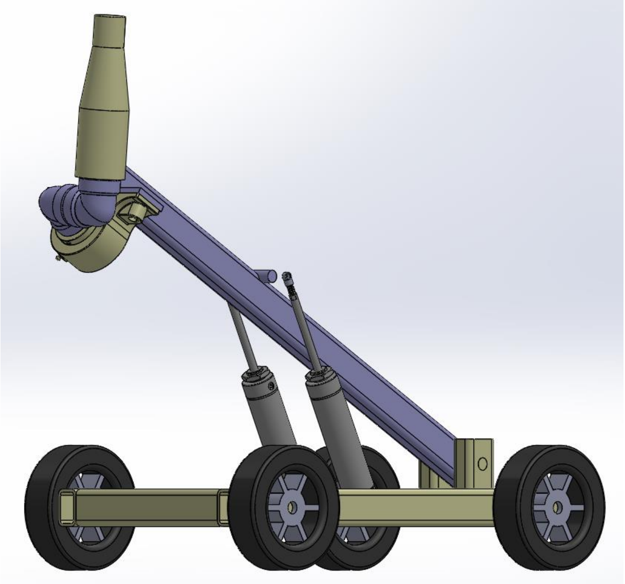


Figure 23. Boom Arm with Single Frame

3 Final Design of Shotcrete Robot

The automation process of the UHPC shotcreting was finalized after a series of modifications and advancements as explained above. The shotcrete robot is designed in such a way that it can be used with the existing uhpc pump owned by the research group as shown above in **Figure 15**. The idea of this robot has been evolved from the pipe crawler concept and is shown below **Figure 24**. It has a capability to fit in and apply UHPC pneumatically from 3 to 6 ft. diameter culverts. The four wheels are powered by individual hydraulic motors capable of moving the robot at a speed of 3 feet per second (crawl speed). The nozzle of the robot has 2 rotational axes of freedom.

The robot design has been tested under pumpability test of the boom arm which has already been constructed. The boom arm is shown in **Figure 25**. The necessity of this pumpability test was felt as there were many 90 degree bends in the boom pipe of the proposed robot. It was observed that the pump was able to pump UHPC through all the bends and length of the pipe.

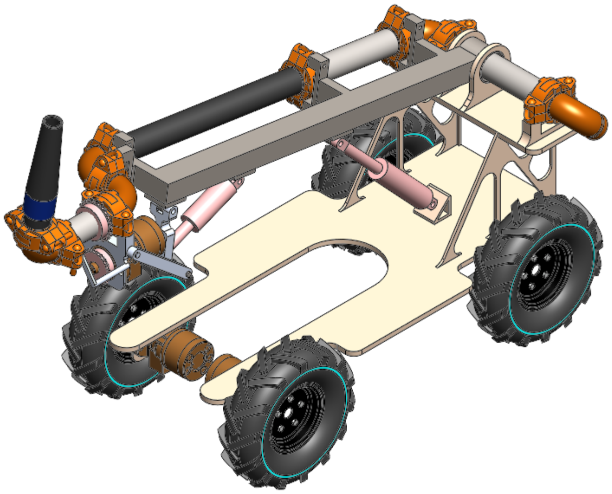


Figure 24. The Final Robot Design

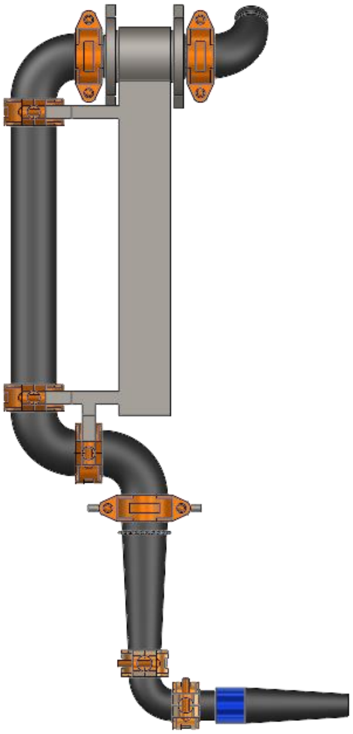
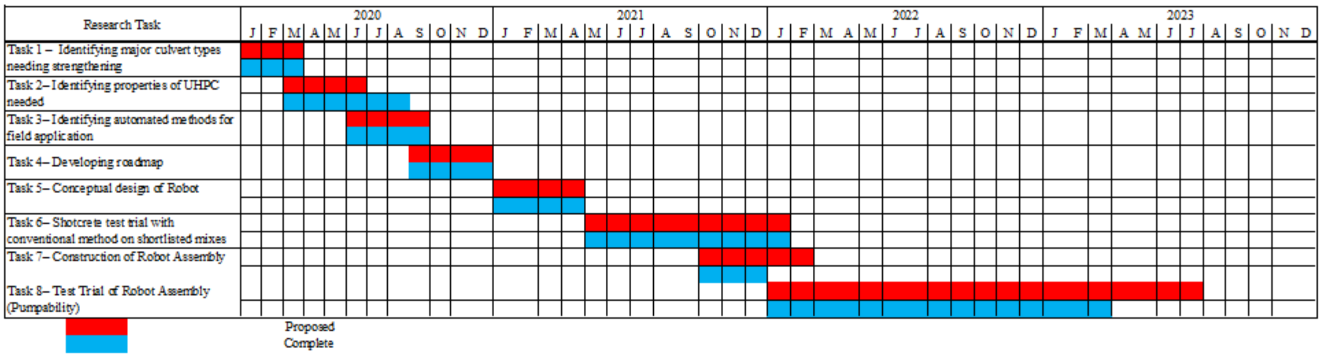


Figure 25. Robotic Boom arm

10. Schedule

Item	% Completed
Percentage of Completion of this project to Date	85%



Research Task	2020											
	J	F	M	A	M	J	J	A	S	O	N	D
Task 1 – Identifying major culvert types needing strengthening	🟥	🟥	🟥									
	🟦	🟦	🟦									
Task 2– Identifying properties of UHPC needed			🟥	🟥	🟥	🟥						
			🟦	🟦	🟦	🟦	🟦	🟦				
Task 3– Identifying automated methods for field application						🟥	🟥	🟥	🟥			
						🟦	🟦	🟦	🟦			
Task 4– Developing roadmap									🟥	🟥	🟥	🟥
									🟦	🟦	🟦	🟦
Task 5– Conceptual design of Robot												
Task 6– Shotcrete test trial with conventional method on shortlisted mixes												
Task 7– Construction of Robot Assembly												
Task 8– Test Trial of Robot Assembly (Pumpability)												

Research Task	2021											
	J	F	M	A	M	J	J	A	S	O	N	D
Task 1 – Identifying major culvert types needing strengthening												
Task 2– Identifying properties of UHPC needed												
Task 3– Identifying automated methods for field application												
Task 4– Developing roadmap												
Task 5– Conceptual design of Robot	🟥	🟥	🟥	🟥								
	🟦	🟦	🟦	🟦								
Task 6– Shotcrete test trial with conventional method on shortlisted mixes					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Task 7– Construction of Robot Assembly										🟥	🟥	🟥
										🟦	🟦	🟦
Task 8– Test Trial of Robot Assembly (Pumpability)												

Research Task	2022											
	J	F	M	A	M	J	J	A	S	O	N	D
Task 1 – Identifying major culvert types needing strengthening												
Task 2– Identifying properties of UHPC needed												
Task 3– Identifying automated methods for field application												
Task 4– Developing roadmap												
Task 5– Conceptual design of Robot												
Task 6– Shotcrete test trial with conventional method on shortlisted mixes	🟥											
	🟦											
Task 7– Construction of Robot Assembly	🟥	🟥										
Task 8– Test Trial of Robot Assembly (Pumpability)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Research Task	2023											
	J	F	M	A	M	J	J	A	S	O	N	D
Task 1 – Identifying major culvert types needing strengthening												
Task 2– Identifying properties of UHPC needed												
Task 3– Identifying automated methods for field application												
Task 4– Developing roadmap												
Task 5– Conceptual design of Robot												
Task 6– Shotcrete test trial with conventional method on shortlisted mixes												
Task 7– Construction of Robot Assembly												
Task 8– Test Trial of Robot Assembly (Pumpability)	🟥	🟥	🟥	🟥	🟥	🟥	🟥					
	🟦	🟦	🟦									

🟥 Proposed
🟦 Complete

Figure 26. Schedule for future work and current progress.

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