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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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.

Many Culverts are in need of 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 in order 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: No progress

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: No progress

4. Description of Research Project Tasks

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

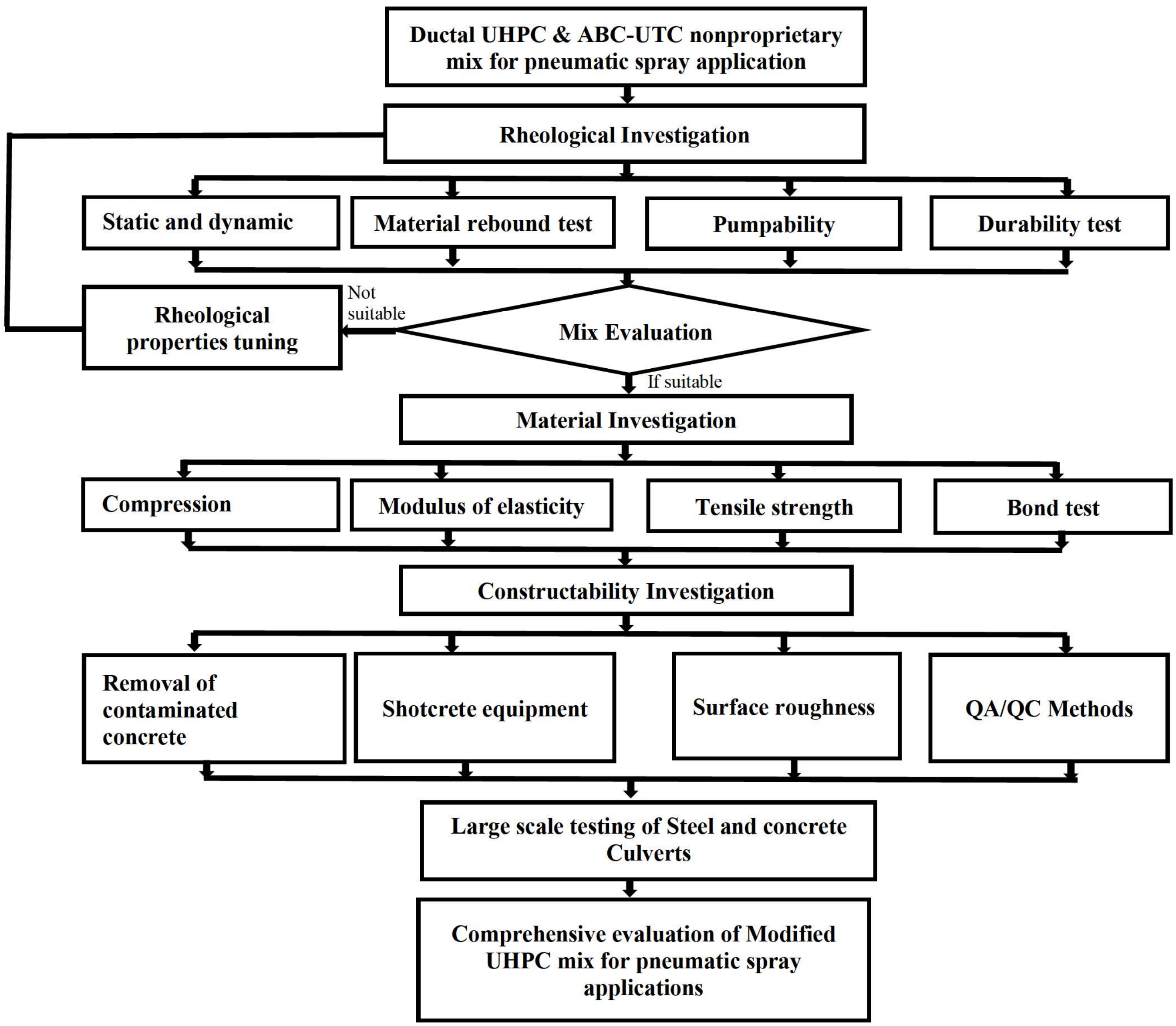

Figure 1. Flowchart of research tasks.

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 2. PVC Slipliner and Grout Injection Pipes [2]

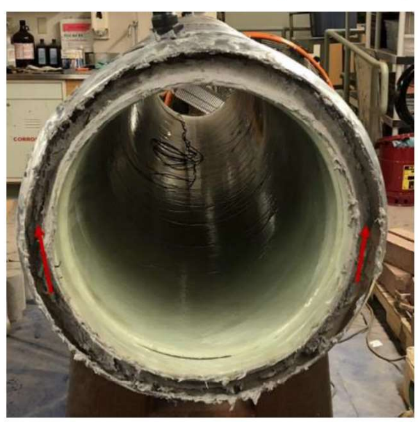

Figure 3. GFRP Slipliner using wood spacers [3]

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

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.

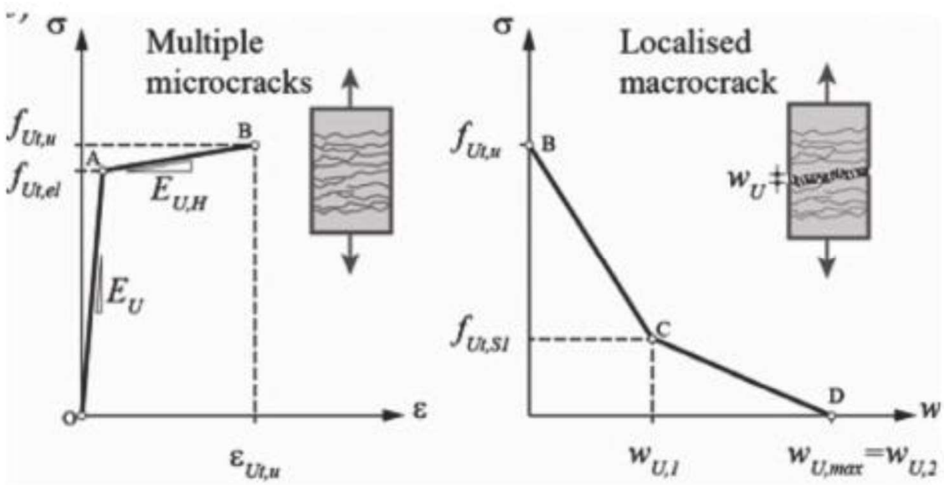

Figure 4. UHPC Tensile Behavior [5].

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. 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 for dynamic test of flowability.

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

Proposed Mix Designs

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. Higher W/C 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 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.

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, 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 fiber length only flow resistance increases. So increasing the fiber content will reduce the workability of the mix.

The investigations will be performed on the Ductal UHPC premix (JS1000), Fast Set UHPC from Ductal (JS-1212), and ABC-UTC non-proprietary UHPC mix. All the three mixtures will be using either steel fiber or synthetic/flexible fibers. The following tests will be performed to assist in this evaluation:

1. Static and dynamic flow tests will be conducted in accordance with ASTM C1437. Flowability of the pneumatically applied mixes are very critical and is a key indicator of pumpability of the UHPC. This test will be performed on various mixes in order to figure out the best mix for pumping.
2. Initial and final setting time 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 Table 3 will be prepared for rheological investigation.

Table 3. Mix designs for rheological testing

Mix Designation	Basic Mix	W/C Ratio by Weight	Super-plasticizer % by Weight	Fibers % by Weight	Date	Air Content before shotcrete	Air Content after shotcrete	Temp ⁰F	Test at Time	Flow - Static	Flow - Dynamic	No. of Cylinders
Mix # 1	Ductal Premix Fast Set	MR*	MR	6.2		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 2	Ductal Premix Fast Set	MR	MR	5.0		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 3	Ductal Premix Fast Set	MR	MR	7.5		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 4	Ductal Premix Fast Set	+0.5	MR	6.2		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 5	Ductal Premix Fast Set	+1.0	MR	6.2		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 6	Ductal Premix Fast Set	MR	+0.2	6.2		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 7	Ductal Premix Fast Set	MR	+0.4	6.2		not adjusted			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 8	Ductal Premix Fast Set	MR	MR	6.2		5%			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 9	Ductal Premix Fast Set	MR	MR	6.2		10%			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28
Mix # 10	Ductal Premix Fast Set	MR	MR	6.2-7.5		5-10%			0 min; 15 min; 30 min			1@ 3 ; 1@ 7; 3 @ 28

6.3 Material investigation

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 rheological tests and material tests will be considered in order to finalize the mixes which will be used for pneumatic application. UHPC cores which will be obtained from a test panel constructed from pneumatic spray applications 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 since the application of upgrading the underside of the existing bridge deck and superstructure elements will require either sandblasting or water-jetting.

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. Schedule

Item	% Completed
Percentage of Completion of this project to Date	20%

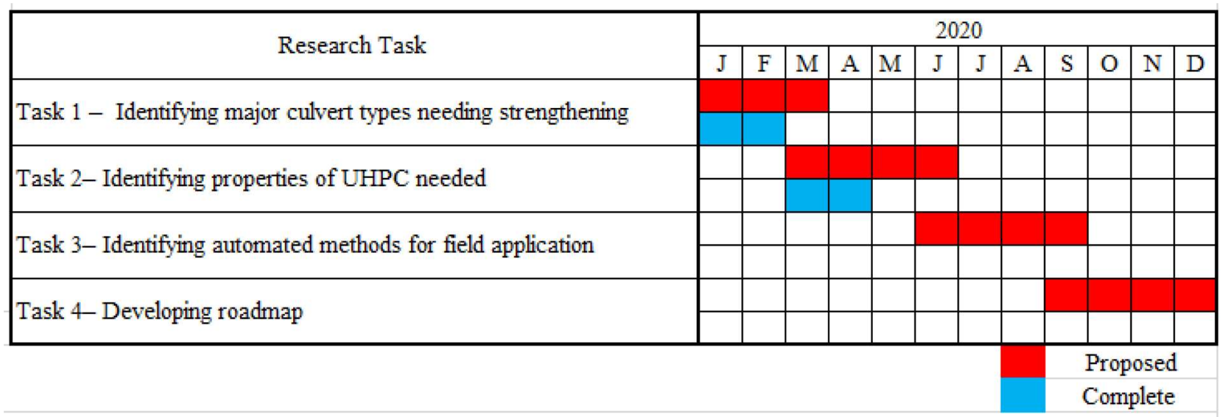

Figure 5. Schedule for future work and current progress.

8. References.

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