OPTIMIZATION OF ADVANCED CEMENTITIOUS MATERIAL OVERLAYS AND UPGRADES, INCLUDING SHOTCRETE

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

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

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
Dr. Atorod Azizinamini
ABC-UTC
Florida International University
Miami, FL

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1. Background and Introduction

Ultra-High-Performance 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. UHPC provides a higher strength for the composite bridge deck section and mitigates additional corrosion by inhibiting penetration of additional chloride ions.

Deck overlays have been placed over deteriorated and damaged bridge decks for many years in order to extend the deck service life. Recently, UHPC mixes have been developed that can be applied with pneumatic spray application methods. Such repair methods may be applicable to horizontal, vertical, inclined, and overhead surfaces. This will reduce formwork effort and permit application in difficult access locations.

This research project addresses the considerations required for successful pneumatic application of UHPC as an alternative repair method for deck overlays, girders, and other repairs and upgrades including the underside of bridge decks.

This study includes rheological and laboratory testing, small scale and large-scale testing, finite element analysis, and testing of full size specimens to develop application procedures. The study will consist of the following activities:

- Investigate UHPC application with shotcrete techniques.
- Evaluate material properties of the pneumatically applied material and compare to the material properties of conventionally applied material.
- Develop UHPC shotcrete techniques and mix designs for repair of the underside of bridge decks.
- Determine the section capacity of the composite section between UHPC deck overlay, normal strength concrete in the dec, and repairs to the underside of the deck with UHPC.
- Evaluate the impact on repair performance due to thickness variations resulting from hydro-blasting and other methods of removing deteriorated concrete and surface preparation.
- Determine the impact to the moment capacity of the deck due to the roughness of the interfacial surface between UHPC and normal strength concrete.
- Identify the optimal surface roughness with regard to moment capacity and tensile strength at the interface of UHPC applied with shotcrete methods and normal strength concrete.
- Evaluate the chloride ion penetration rates of shotcrete applied UHPC.

2. 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.

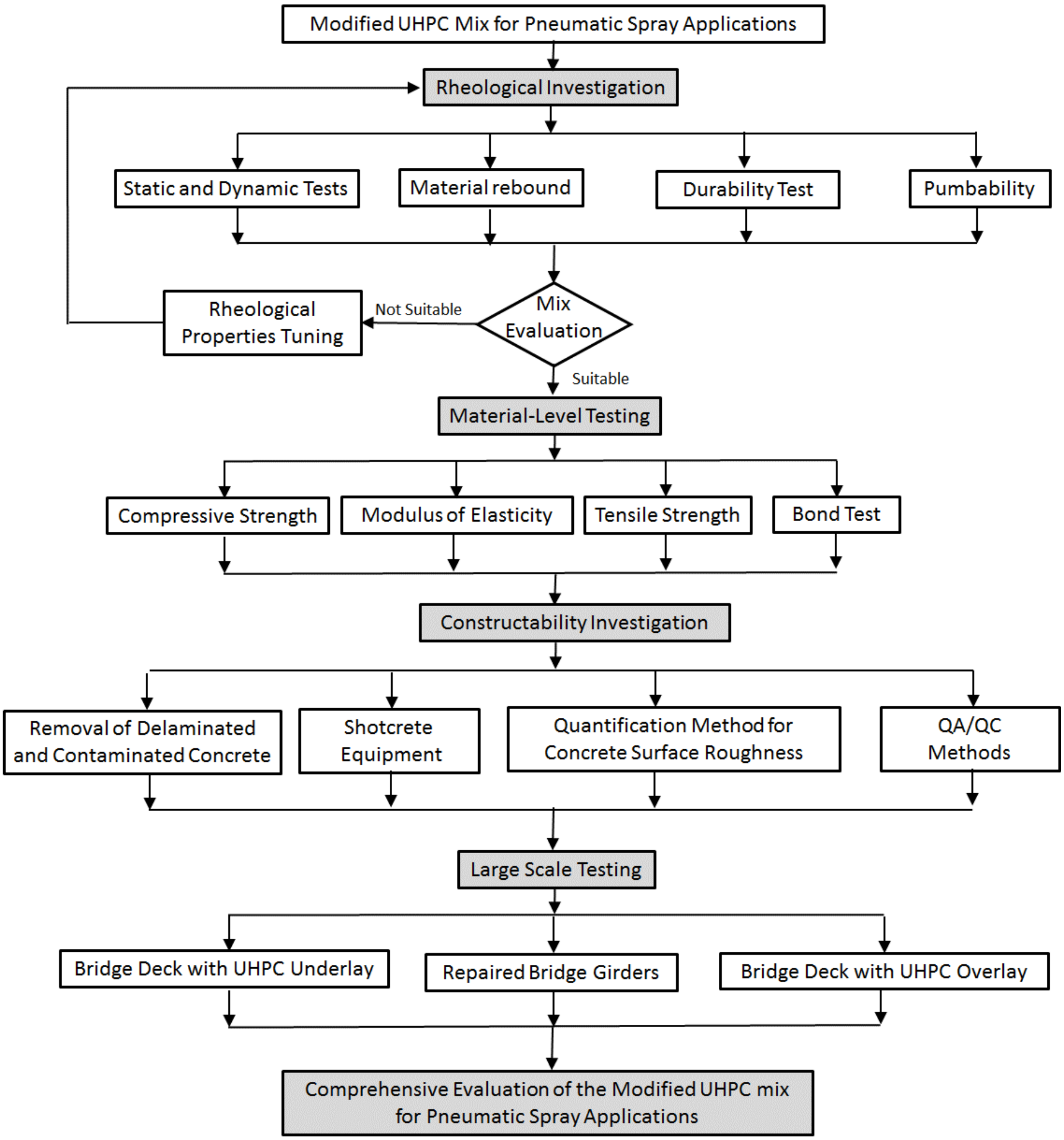


Figure 1. Flowchart of research tasks.

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

1 Rheological investigation

Rheological investigations for this project have been performed 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 [1]. For self-compacting high-performance concrete such as UHPC, a static and dynamic flow test is prescribed by ASTM C1437. The minimum dynamic flow value desired for pumping a high-performance concrete such as UHPC is considered to be 9 in. [2].

Shootability of the mix is a quantitative measure of how well the material stays in place after application and includes the concepts of material rebound and cohesion. The existence of a yield stress value is good explanation of cohesion of the mix and 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".

2 Rheological Testing on Mix Designs

Rheological testing has been performed on a total of 16 Ductal mixes and 46 ABC-UTC mixes. Typical mix design proportions for Ductal mix are presented below in Table 1.

Table 1. Mix proportions used to mix 1 m^3 of UHPC, from Farzad, et. al., [4].

Constituent	Proportion (lbs/m^3)	Proportion (lbs/cy)
Ductal Premix	4684.8	3581.3
Ice (water)	256.3	195.9
HRWR (Superplasticizer)	64.0	48.9
Steel Fiber	333.4 (2%) and 666.7 (4%)	254.9 (2%)

Two Ductal UHPC premixes, JS-1000 and JS-1212 Fast Set, were studied by varying the high range water reducer (HRWR), steel fiber content, and the water/binder ratio.

Rheological testing was conducted on the ABC-UTC non-proprietary UHPC mixes developed at FIU. The ABC-UTC mix designs consist of 4 subgroups, based on the sand-to-binder ratios. The binder includes cement, slag, and silica fume. These subgroups are 60:40, 56:44, 50:50 and 57:43. Basic mix designs are presented below in Table 2.

Table 2. ABC-UTC Mix Designs

Mix Design	Cement	Slag	Silica Fume	Water	Sand	Steel Fiber	HRWR
60:40	943.67	471.83	157.28	298.83	2359.17	283.24	46.80
56:44	956.88	478.44	159.49	303.02	2057.00	264.40	32.40
57:43	1200.00	0	390.00	184.00	2075.00	263.00	179.03
50:50	1179.6	589.80	196.60	393.20	1966.00	255.00	37.25

Note: Values shown are lbs/cu. yd.

Several parameters were varied, including steel fiber content, HRWR content, water/binder ratio (w/b), synthetic fiber content, and a viscosity modifying admixture (VMA). The ABC-UTC mixes were prepared with local materials, including sand, cement, silica fume and available HRWR. 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 when static flow results were high, as 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 made with the Ductal mixes containing steel fiber. The cubes were tested in accordance with ASTM C-109.
3. Compressive strength testing of the ABC-UTC mixes were performed on 4x8 cylinders in accordance with ASTM C-39. Cylinders were also tested for the Ductal mixes without steel fiber.

The mix designs listed in Tables 3 and 4 were prepared for the initial rheological investigation.

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 (yd^3)
Mix 1	3375.00	197.10	27.54	18.36	35.64	239.76	3893.40	1.00
Mix 2	3421.98	199.80	28.08	18.90	35.64	188.46	3893.40	1.00
Mix 3	3311.82	193.32	27.00	17.82	34.56	308.34	3893.40	1.00
Mix 4	3357.18	216.54	27.54	18.36	35.10	238.68	3893.40	1.00
Mix 5	3338.82	235.98	27.54	18.36	35.10	237.06	3893.40	1.00
Mix 6	3367.98	196.56	30.24	20.52	38.88	239.22	3893.40	1.00
Mix 7	3360.96	196.02	33.48	22.14	42.66	238.68	3893.40	1.00
Mix 11	3821.76	222.84	31.32	20.88	`40.14	0.00	4136.40	1.00

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 (yd^3)
Mix 12	3375.00	184.14	46.44	239.76	3844.80	1.00
Mix 13	3419.28	186.84	46.98	189.54	3839.40	1.00
Mix 14	3318.30	181.44	45.36	298.08	3844.80	1.00
Mix 15	3356.64	204.12	45.90	238.14	3844.80	1.00
Mix 16	3338.82	223.02	45.90	237.06	3844.80	1.00
Mix 17	3367.98	184.14	54.00	239.22	3844.80	1.00
Mix 18	3361.50	183.60	61.56	238.68	3844.80	1.00
Mix 22	3824.28	208.80	52.38	0.00	4086.00	1.00

3 Material Investigation

3.1.1 Rheological Test Results with Ductal mixes.

To date, compressive strength testing has been performed on the Ductal premixes during the initial round of rheological testing. The results are summarized in Table 5.

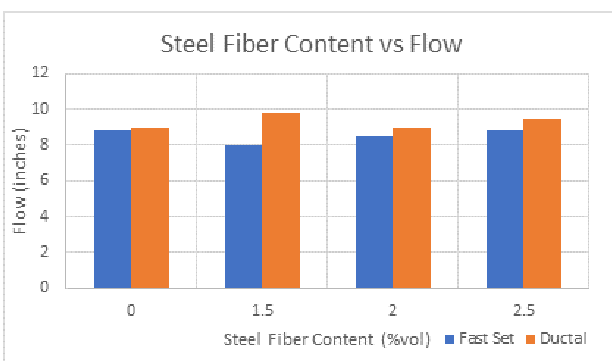
Table 5. Rheological Testing Summary – Ductal Mixes

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	0.058	0.021	6.2	2	8.5	13.18	19.30
Mix # 2	JS1212	0.058	0.021	5	1.5	8.0	14.21	17.60

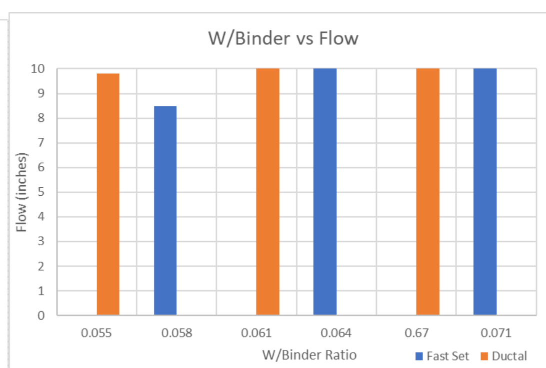
Mix Designation	Basic Mix	W/Binder Ratio by Weight	HRWR % by Weight	Steel Fibers % by Weight	Steel Fibers % by Vol	Flow Test Value (avg) (inches)	Compressive Strength (ksi)	
							7 days	28 days
Mix # 3	JS1212	0.058	0.021	7.5	2.5	8.8	14.91	19.68
Mix # 4	JS1212	0.064	0.021	6.2	2	>10	12.91	19.31
Mix # 5	JS1212	0.071	0.021	6.2	2	>10	11.92	19.70
Mix # 6	JS1212	0.058	0.023	6.2	2	9.8	14.29	17.23
Mix # 7	JS1212	0.058	0.025	6.2	2	7.8	7.90	18.64
Mix # 8	JS1212	0.058	0.022	0	0	8.8	16.90	17.70
Mix # 9	JS1000	0.055	0.012	6.2	2	9.0	15.98	18.85
Mix # 10	JS1000	0.055	0.012	5.0	1.5	9.8	14.77	16.99
Mix # 11	JS1000	0.055	0.012	7.5	2.5	9.5	12.06	16.69
Mix # 12	JS1000	0.061	0.012	6.2	2	>10	15.02	21.84
Mix # 13	JS1000	0.067	0.012	6.2	2	>10	12.90	19.84
Mix # 14	JS1000	0.055	0.014	6.2	2	9.8	10.18	11.92
Mix # 15	JS1000	0.055	0.016	6.2	2	9.3	13.05	17.38
Mix # 16	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 2a. 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.



(a)



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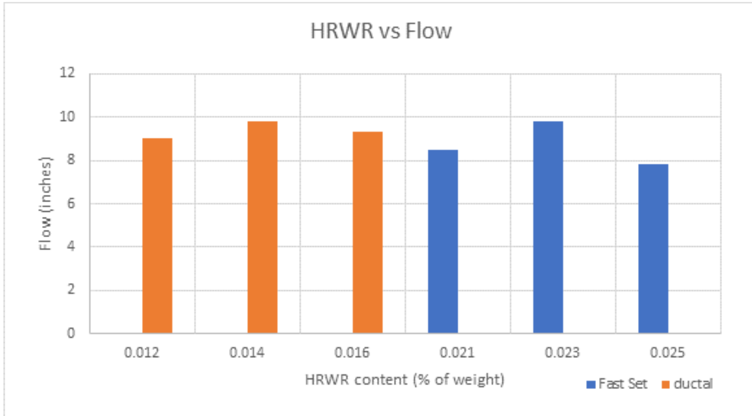

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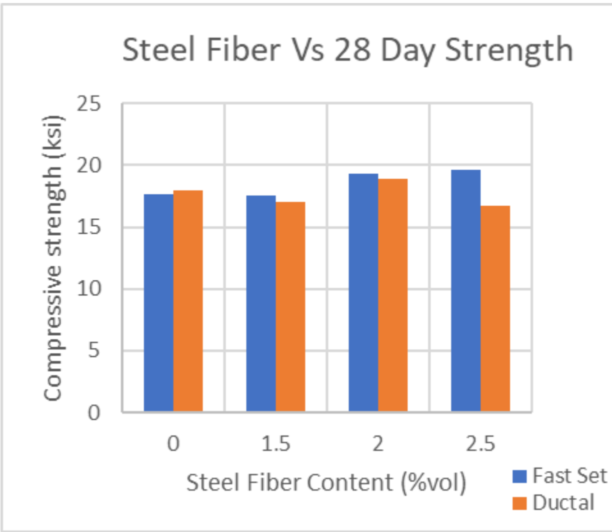
Figure 2. Flowability Test Results

W/Binder Ratio and Flowability -Variations in the W/Binder ratio were also tested for flowability. Results are shown in Figure 2b. 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 2c.

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 3.

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 [3]. The JS1212 Fast Set mixes showed higher strength than the JS1000 mixes.



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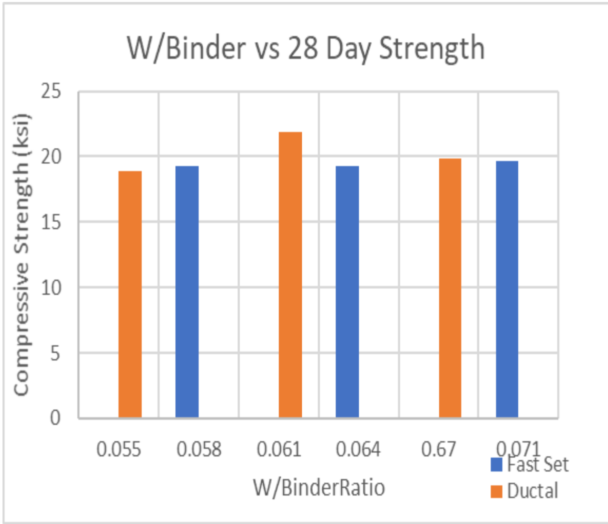

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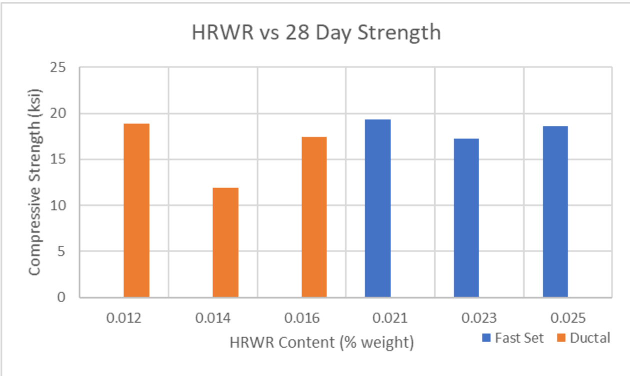

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Figure 3. Compressive Strength Test Results

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 Water/Binder ratio tested.

HRWR and Strength - The strength decreased with an increase in HRWR, for both Ductal UHPC mixes, 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 was 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 46 non-proprietary mix designs developed under the ABC-UTC program at FIU to date. A summary of these tests is shown on Table 6.

Table 6. Rheological Testing Summary - ABC-UTC Mixes

ABC-UTC Mix No.	MIX ID	CAST DATE:	Cement (lbs/cu.yd)	Slag (lbs/cu.yd)	Silica Fume (lbs/cu.yd)	Water (lbs/cu.yd)	Sand (lbs/cu.yd)	Steel Fiber (#/cy)	Syn. Fiber (#/cy)	HRWR (weight) (#/cy)	VMA (weight) (#/cy)
1	SEs60c40.19.26	12/11/2020	943.67	471.83	157.28	298.83	2359.17	283.24	-	46.80	
2	SEs60c40.19.15+	12/14/2020	962.93	481.46	160.49	304.92	2407.32	271.80	-	40.14	
3	SEs60c40.19.26	1/5/2020	943.67	471.83	157.28	298.83	2359.17	283.24	-	46.80	
4	SEs60c40.19.30	1/6/2020	943.67	471.83	157.28	298.83	2359.17	284.30	-	54.00	
5	SEs60c40.19.35	1/7/2020	943.67	471.83	157.28	298.83	2359.17	285.62	-	63.00	
6	SEs60c40.19.40	1/8/2020	943.67	471.83	157.28	298.83	2359.17	286.94	-	72.00	
7	SEs56c44.19.26	1/15/2021	956.88	478.44	159.49	303.02	2057.00	266.69	-	46.80	
8	SEs56c44.19.26	1/19/2021	956.88	478.44	159.49	303.02	2057.00	266.69	-	46.80	
9	SEs56c44.19.22	1/21/2021	956.88	478.44	159.49	303.02	2057.00	265.64	-	39.60	
10	SEs56c44.19.18	1/22/2021	956.88	478.44	159.49	303.02	2057.00	264.60	-	32.40	
11	Es56c44.19.26	1/15/2021	959.00	477.00	159.00	307.00	2100.00	0.00	-	46.80	
12	Es56c44.19.26	1/15/2021	956.88	478.44	159.49	303.02	2057.00	266.69	-	46.80	
13	SY0.5Es56c44.19.26	4/23/2021	971.53	485.76	161.93	307.65	2088.49	-	7.81	46.80	
14	SY1.5Es56c44.19.18	5/11/2021	961.76	480.88	160.30	304.56	2067.50	-	23.26	32.40	
15	SY0.5Es56c44.19.18	5/7/2021	971.53	485.76	161.93	307.65	2088.49	-	7.75	32.40	
16	SY1Es56c44.19.18	5/10/2021	966.65	483.32	161.11	306.11	2077.99	-	15.50	32.40	
17	SY1.5Es56c44.19.26	4/27/2021	961.76	480.88	160.30	304.56	2067.50	-	23.44	46.80	
18	S1H0.5Es56c44.19.26	4/30/2021	961.76	480.88	160.30	304.56	2067.50	133.35	7.81	46.80	
19	S0.5H0.5Es56c44.19.26	5/3/2021	966.65	483.32	161.11	306.11	2077.99	66.67	7.81	46.80	
20	S1.5H0.5Es56c44.19.26	5/4/2021	956.88	478.44	159.49	303.02	2057.00	200.02	7.81	46.80	
21	SY1Es56c44.19.26	4/26/2021	966.65	483.32	161.11	306.11	2077.99	-	15.63	46.80	
22	S0.5H0.5Es56c44.19.18	5/18/2021	966.65	483.32	161.11	306.11	2077.99	66.15	7.75	32.40	
23	S1H0.5Es56c44.19.18	5/19/2021	961.76	480.88	160.30	304.56	2067.50	132.29	7.75	32.40	
24	S1.5H0.5Es56c44.19.18	5/20/2021	956.88	478.44	159.49	303.02	2057.00	198.44	7.75	32.40	
25	Jun-29	6/29/2021	1179.60	589.80	196.60	393.20	1966.00	255.20	-	37.25	
26	Jun-30	6/30/2021	1203.19	601.60	200.53	401.06	2005.32	0	-	25.33	
27	Jul-01	7/1/2021	1179.60	589.80	196.60	393.20	1966.00	255.20	-	31.04	
27	Es W/B 0.17	11/2/2021	1179.60	589.8	196.60	334.22	1966.00	255	-	37.25	
28	Jul-02	7/2/2021	1203.19	601.60	200.53	401.06	2005.32	0	-	31.66	
29	ABC=D Sp .80	7/21/2021	1200.00	0	390.00	184.00	2075.00	263.00	-	132.99	
30	ABC=D Sp 1.06	7/21/2021	1200.00	0	390.00	184.00	2075.00	263.00	-	179.03	
31	ABC=D Sp 1.06 sy F	7/22/2021	1217.88	0	395.81	193.28	2105.92	-	7.99	182.70	
32	ABC=D Sp 175% W/B=0.14	7/26/2021	1200.00	0	390.00	220.80	2075.00	263.00	-	179.03	
33	ABC=D Sp 175% W/B=0.16,Sy F	7/27/2021	1217.88	0	395.81	257.70	2105.92	-	8.29	182.70	
34	ABC=D Sp 175% W/B=0.20,Sy F	7/27/2021	1217.88	0	395.81	322.13	2105.92	-	8.59	182.70	
35	ABC=D Sp 175% W/B=0.20	7/29/2021	1200.00	0	390.00	317.40	2075.00	263.00		179.03	
39	ABC=D Sp 175% W/B=0..12	8/26/2021	1200.00	0	390.00	190.80	2075.00	263.00		179.03	
36	MFA S47, W/B=0.16	8/3/2021	1279.58	0	548.39	292.48	1827.98	0		47.98	
37	MFA S91, W/B=0.16	8/4/2021	1248.27	0	534.97	285.32	1783.24	0		90.95	
38	MFA S112, W/B=0.16	8/5/2021	1232.73	0	528.31	281.77	1761.04	0		112.27	
40	Esmail's Mix Hillmiere prsentation	9/2/2021	1179.60	589.8	196.60	393.20	1966.00	255	-	37.25	
41	Es Mix (NF) Shoot day (pumpability test)09/17	9/17/2021	1179.60	589.8	196.60	393.20	1966.00	0	-	37.25	
42	Es W/B 0.16+.02	10/19/2021	1179.60	589.8	196.60	353.88	1966.00	255	-	37.25	
43	Es W/B 0.18 with VMA	11/10/2021	1179.60	589.8	196.60	353.88	1966.00	287		37.25	5.74
44	Es W/B 0.18 NF with VMA	11/17/2021	1179.60	589.8	196.60	353.88	1966.00	0		37.25	5.74

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 4. 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.

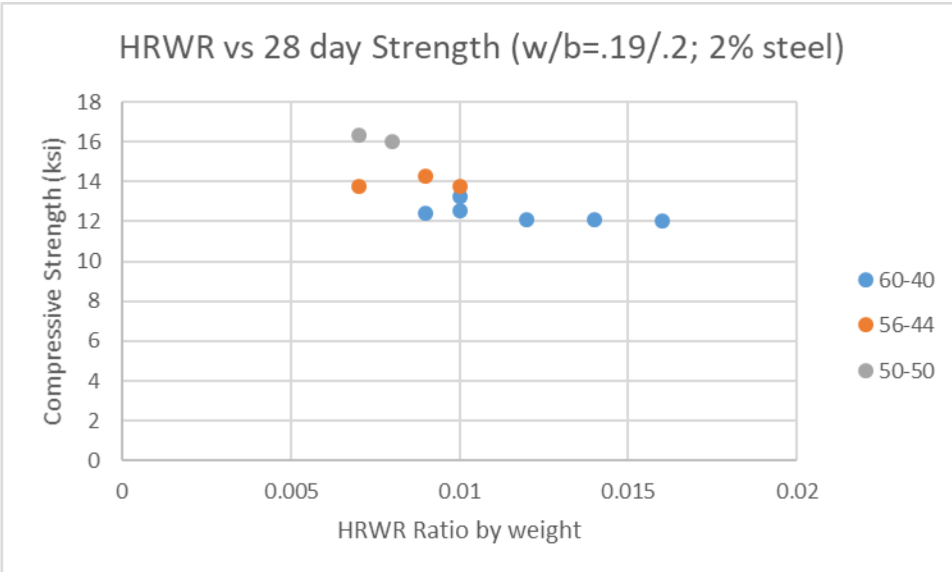

Figure 4. HRWR vs Strength.

Fiber Content and Strength. The effect of fiber content on the 28-day compressive strength is presented in Figure 5 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.

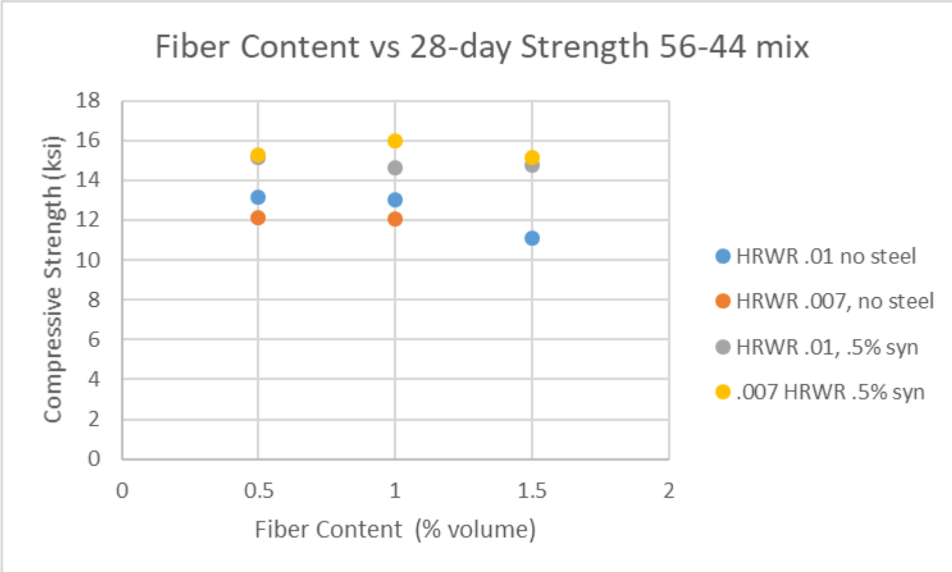

Figure 5. Fiber Content and 28- Strength.

Fiber Content and Flow. The graph below in Figure 6 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%.

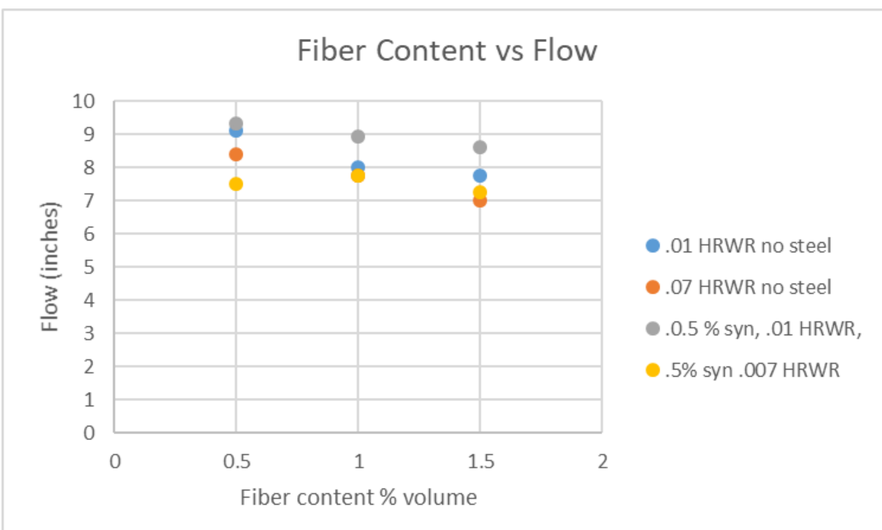

Figure 6. Fiber Content vs Flow.

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 7 shows a large increase with flow as the w/b ratio increases from 0.12 to 0.20.

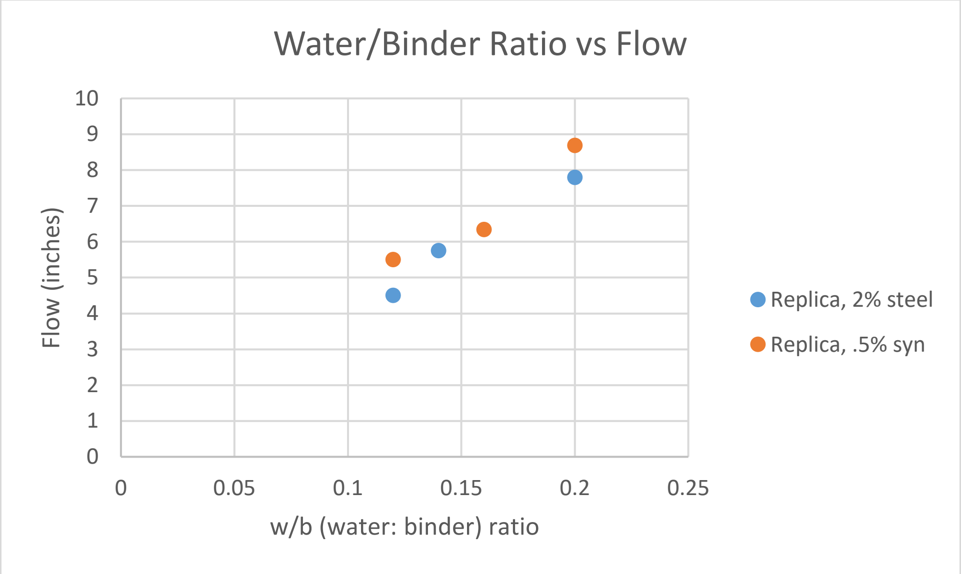

Figure 7. Water to Binder Ratio vs Flow, 57:43 Mix.

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 8 below.

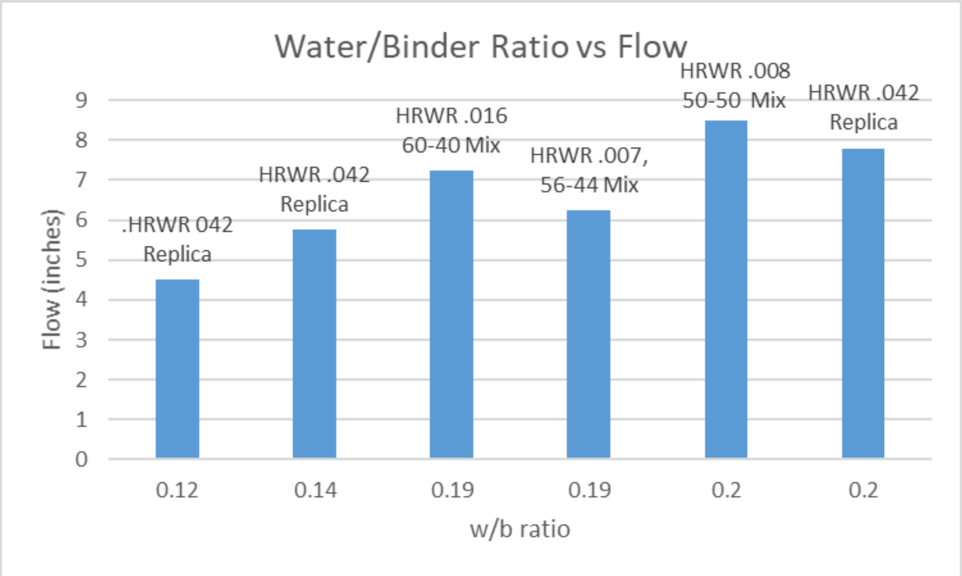

Figure 8. Water to Binder Ratio vs Flow.

VMA content was varied on one mix. The change in viscosity was not measured. However, the mixes were placed on a sloping concrete surface to observe the relative differences in viscosity. Figure 9 shows this clearly.

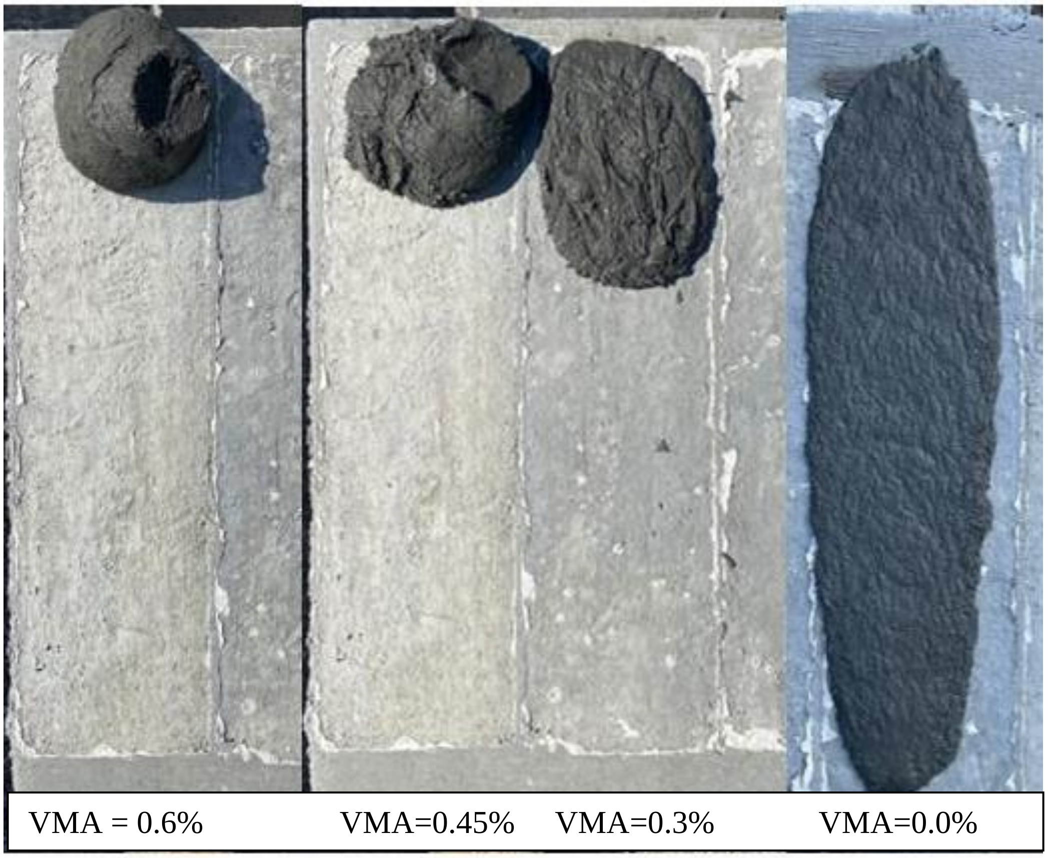

Figure 9. Variation in VMA Content.

4. Specimens for Spray-Applied UHPC

4 Small Scale Specimens

Eighteen (18) flexural beam specimens were made. Normal Strength Concrete (NSC) was placed in 16 beam molds on top of roughness profile molds. The molds provide repeatable roughness profiles. Spacers were also included to provide either ½ inch or 1 inch thick layers of UHPC. Two beams are full depth normal strength concrete 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.

Conventionally placed UHPC was placed as overlays on 6 of the beams. Spray applied Ductal UHPC was sprayed onto the other 10 samples. Testing will be conducted on sets of beams with varying roughness profiles on the interface between the NSC and UHPC.

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 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.

Roughness Measurements

The roughness of the sandblasted and roughness profile 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 has been reduced to quantify the roughness in following steps. The results are shown in Table 7, below.

- The scanner data files were imported in Cloud Compare software
- A 3D image was prepared with Cloud Compare software from the scanner measurements.
- The 3D image was cropped to the sample surfaces.
- The 3D image of the measured surfaces was exported to an excel spreadsheet in the form of 3 dimensional coordinates (x, y, z).
- The X, Y, and Z coordinates were rotated so that 2 dimensional coordinates are normalized and the skew angles removed.
- The roughness calculations were made on the X-Z coordinates.
- The maximum surface roughness amplitude, R was calculated.

Table 7. Roughness Measurement Summary

Roughness Profile	Maximum Amplitude (inches)
Profile 1	0.26
Profile 2	0.28
Profile 3	0.34
Profile 4	0.80
Sandblast	0.49

5 Large Scale Specimens

Full-scale specimens have been cast to simulate deck overlays. UHPC will be pneumatically applied to sandblasted surfaces of 2 samples. The third sample will be a control sample. Large-scale specimens representing a 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- .

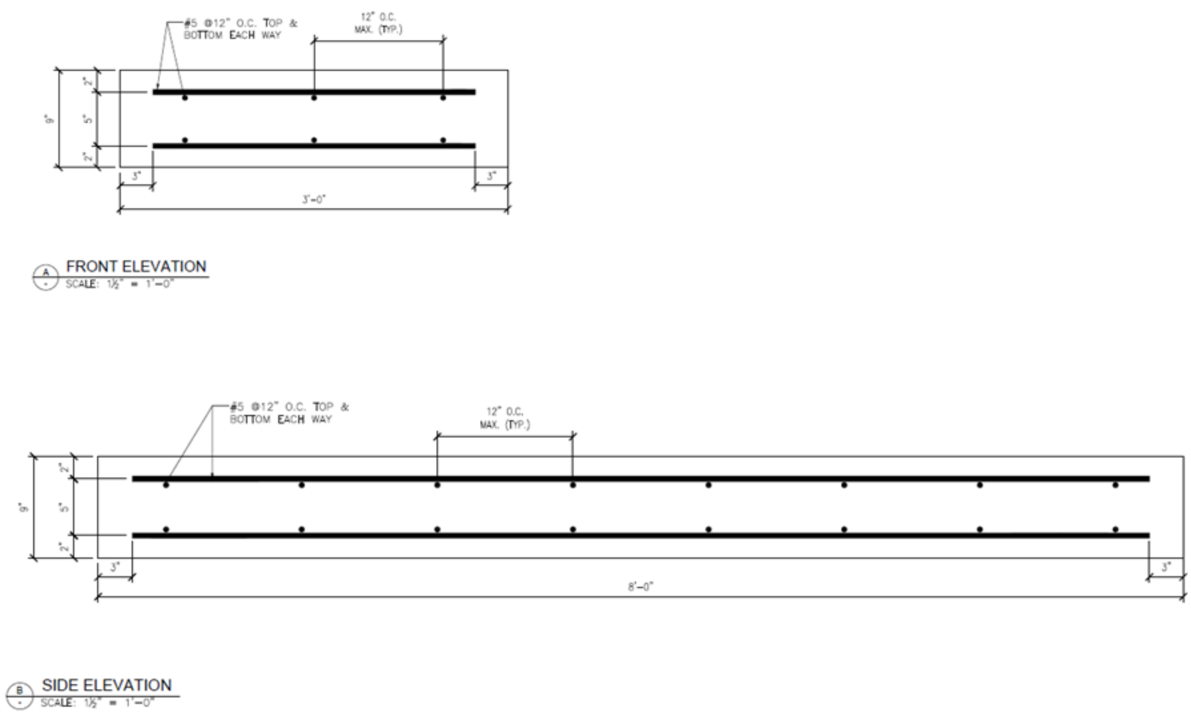

Figure 10. Details of the first specimen (Benchmark)

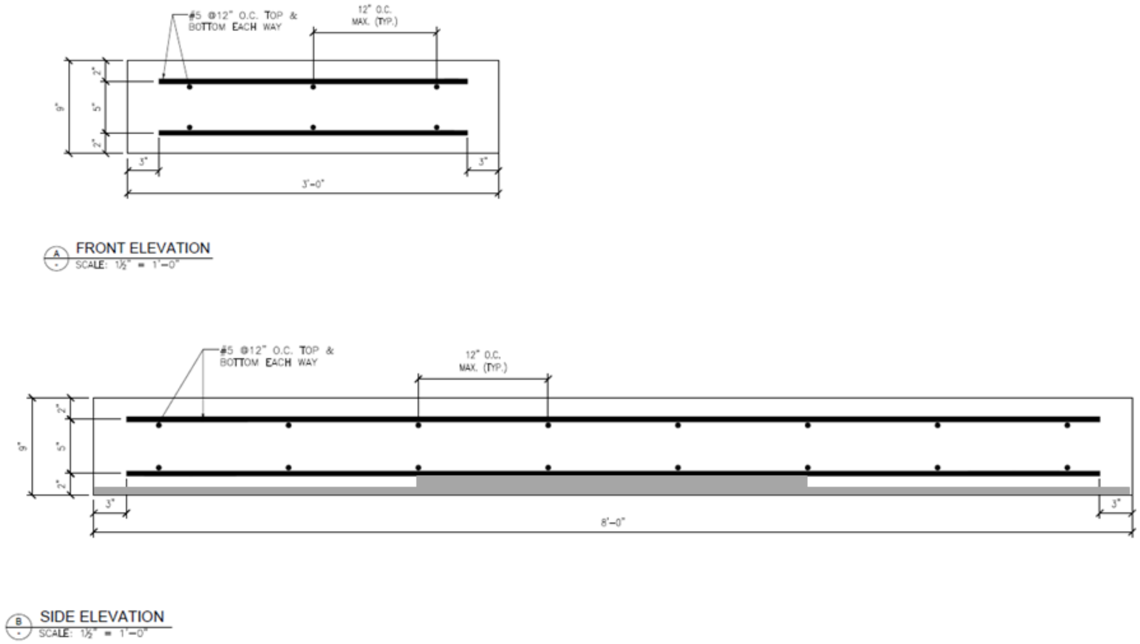

Figure 11. Details of the second specimen (bottom repair)

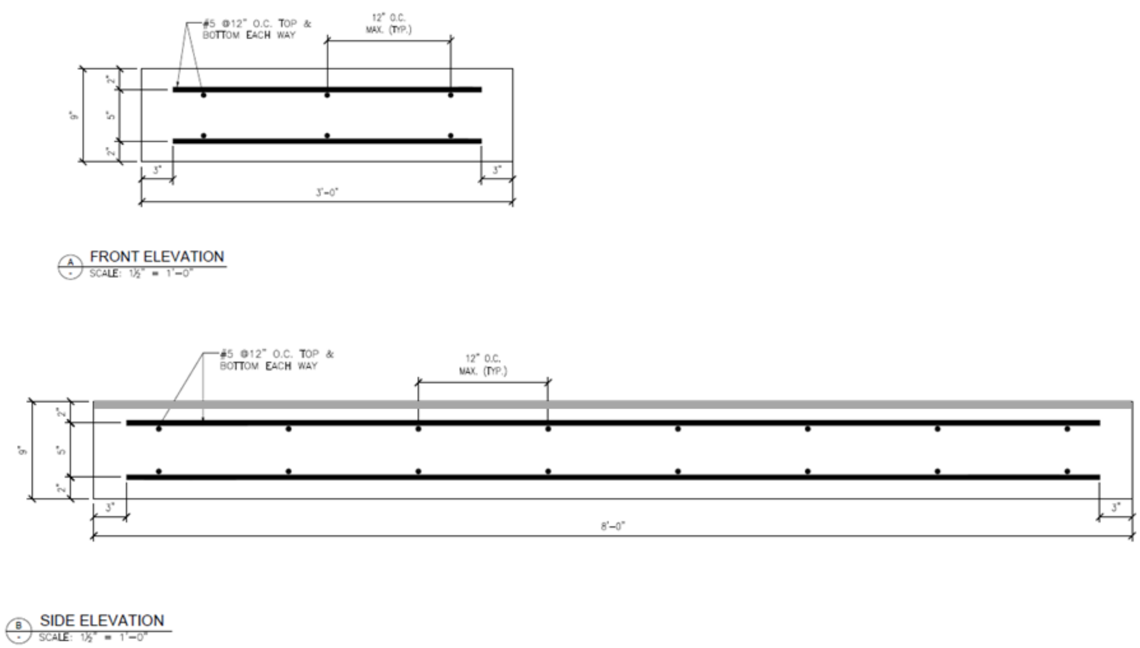

Figure 12. Details of the second specimen (Bridge Overlay)

Two additional specimens (Figures 13-14) have been made. 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 on one surface of the slabs with the roughness profile skins discussed above. 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 13a shows the skins in the bottom of the form prior to casting. Figure 13b 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, a FARO Focus terrestrial laser scanner. The scanner is shown in Figure 14. The data has been reduced to quantify the roughness as discussed above.

(a) (b)

Figure 13. Roughness Profiles Skins

Figure 14. Three-Dimensional Scanner

5. UHPC Shotcrete Application

5.1 Equipment and Set-Up

A small concrete pump was purchased for this research. It was manufactured by Black-Jack pumps and is a single cylinder, auto reciprocating pump. The pump discharge is 2-inch diameter. Initially, a reducer to 1 ½- inch diameter was installed at the discharge, connected to a 1 ½-inch hose. The shotcrete nozzle is also 1-1/2 -inch diameter. After the system plugged with steel fibers, the system was upgraded to a 2-inch diameter hose and nozzle. Wet spray nozzles are available commercially in 1 ½ -inch and 2-inch diameters. The air compressor is rated at 100-125 cfm at 110 psig. It is diesel powered.

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.

5.2 Pneumatic Application

Pneumatic application of UHPC has been completed, and several "shoots" have taken place. A summary of each event is shown below in Table 8. Nine (9) "shoots" have been made and 3 pumpability tests have been performed.

Table 8. Summary of Applications

Shoot No.	Date	Material	Mix No.	Target	Comments
1	10/8/20	Grout		Grout Box	Equipment test, small compressor
2	10/15/20	J1212	1	Grout Box	Set up while in Hopper
3	10/30/20	J1000 w/o steel	22	Flex Beams	UHPC ran down target face
	10/30/20	J1000 w/ steel	18	Flex Beams	UHPC ran down target face less than w/o steel
4	1/29/21	J1000 w/ steel	18		Plug in pump discharge tube
5	4/16/21	ABC-UTC	ABC-11	Grout Box	Plug in hose
6	7/20/21	ABC-UTC	ABC-11		Commercial pump plugged
P 1	8/20/21	ABC-UTC			Pumpability test
P 2	9/17/21	ABC-UTC			Pumpability test
7	10/12/21	ABC-UTC	ABC-11	Grout Box, Profile panel	UHPC ran down target face
P 3	11/4/21	ABC-UTC			Pumpability test
8	11/8/21	ABC-UTC	ABC-40	Grout Box, Profile panel	UHPC ran down target face
9	11/22/21	ABC-UTC w/VMA	ABC-43	Grout Box, Profile panel	UHPC ran down target face not as much as previous shoots
10	1/19/22	ABC-UTC w/VMA	ABC-43	2' x 16' panel	Applied 3 coats
11	3/8/22	ABC-UTC w/VMA	ABC-43	Large Sample	2 batches mixed, built up gradually, some drips removed after 1st pass

Notes: P indicates pumpability test only, without air compressor. ABC- UTC mixes have 2% steel

A UHPC shotcrete operation was performed on October 30, 2020. Two of the flexure beam specimens were sprayed as targets, one vertically down and one horizontally with mix that did not have steel fiber. 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.

A second batch was then mixed. This batch included steel fibers at 2% by weight. 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.

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 9.

Table 9. 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 15. Horizontal application on flexural beam samples

5.3 Flexure Tests on Small Scale Specimens

The flexure beams were tested on FIU's UTM. They were tested with the third point loading as described in ASTM C-78 [27] and illustrated below in Figure 16. Results of the tests are presented below in the load deflection graphs. Table 10 lists the beams and the parameters cast into the beams.

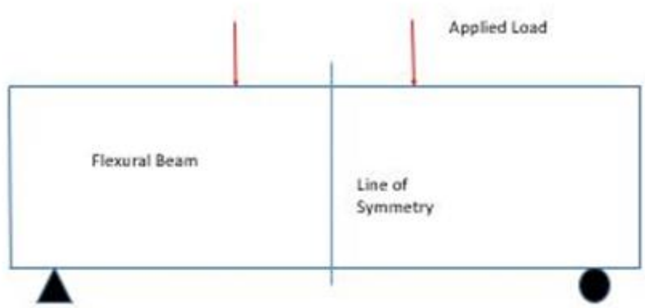

Figure 16. Third Point Loading Setup

Testing of composite flexural beams has been performed. The flexure beams were tested in FIU's Universal testing machine to obtain load-deflection data. Flexural strength and Modulus of Rupture of NSC Beams with ½-inch (13 mm) and 1-inch (25 mm) of UHPC overlays were evaluated experimentally. The test setup is shown in Figure 16. Results of the testing are presented in Table 10.

It should be noted that the flexural beams had reinforcing steel in the bottom chord. Therefore, the Modulus of Rupture values are high. The modulus of rupture is associated with the tensile behavior of non-reinforced concrete. The calculated values are not true values of the modulus of rupture; however, the values are useful for illustrative and comparative purposes.

Table 10. Summary of Flexural Beams

Beam Designation	Overlay Thickness (inches/mm)	Roughness Profile	Re-bar Location wrt Overlay	Proposed Overlay Application	NSC Thickness (inches/mm)	UHPC Thickness (inches/mm)	Modulus of Rupture (psi/MPa)
1	1 (25.4)	3	adjacent	Vertical	5 (127)	.25 (6.4)	33,148 (228.5)
2	1 (25.4)	1	adjacent	Vertical	5 (127)	.31 (7.8)	27,110 (186.9)
3	0.5 (12.7)	1	adjacent	Vertical	5.5(139.7)	.47 (11.9)	41,058 (283.1)
4	1 (25.4)	2	opposite	Vertical	5 (127)	.12 (3.0)	34,691 (241.0)
5	0.5 (12.7)	3	adjacent	Horizontal	5.5(139.7)	.12 (3.0)	27,908 (192.4)
6	0.5 (12.7)	4	opposite	Horizontal	5.5(139.7)	.31 (7.8)	19,690 (135.8)
7	0.5 (12.7)	4	opposite	Horizontal	5.5(139.7)	.09 (2.3)	31,794 (219.2)
8	1 (25.4)	1	adjacent	Horizontal	5.2(133.4)	.06 (1.5)	31,509 (217.2)
9	1 (25.4)	1	adjacent	Conventional	5 (127)	1 (25.4)	40,803 (281.3)
10	1 (25.4)	2	opposite	Conventional	5 (127)	1 (25.4)	13,595 (93.7)
11	1 (25.4)	2	opposite	Conventional	5 (127)	1 (25.4)	28,042 (195.8)
12	1 (25.4)	3	opposite	Conventional	5 (127)	1 (25.4)	27,470 (189.4)
13	0	n/a	bottom	Control none	6 (152.4)	0	29,359 (202.4)
14	0	n/a	bottom	Control none	6 (152.4)	0	22,915 (158.0)

Note: Load application speed for Beam 10 was set too fast.
The Load-Deflection data is shown below in the following figures.

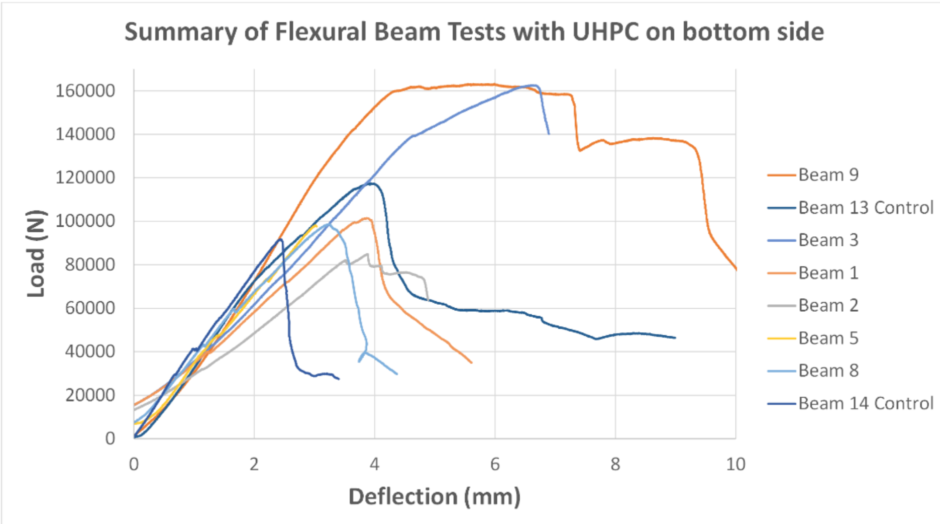

Figure 17. Summary of Flexural Beam tests with UHPC on Bottom side

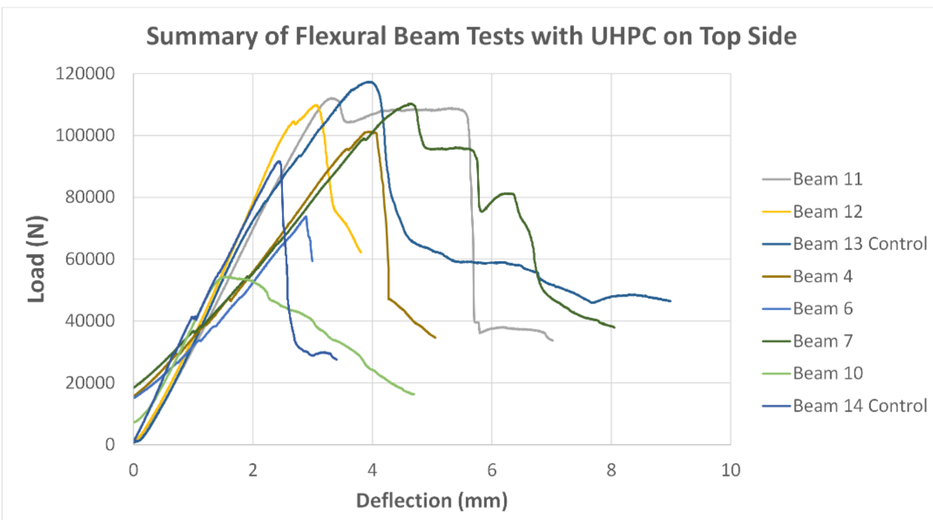

Figure 18. Summary of Flexural Beam tests with UHPC on Top side

One of the objectives of this study is to look at whether the UHPC applications improve the strength of the overall structural elements. A significant increase in strength was noted for UHPC placed on the underside of an element. A significant residual strength was also noted.

The UHPC on Beam 9 was placed conventionally, not pneumatically. The UHPC was about 1-inch (25 mm) thick and in direct contact with the rebar. The initial failure of the beam was in shear, and the UHPC failed in tension. The interface was smooth, developed with profile 1. Some delamination was observed after the tensile failure. Crushing of the concrete on the top surface was noted between the two upper rollers. This is shown in the figure above. The overall strength of beams with the UHPC placed on the surface did not exhibit strength gains. However, it is noted that the overlay material on these samples was thin.

A significant low strength was recorded for Beams 6 and 10. The load application rate for Beam 10 was set too fast and is not comparable to the other beams. Beam 6 appears to be an outlier. Beam 5 failed in shear, and the reinforcing steel cover also failed, leaving no residual strength.

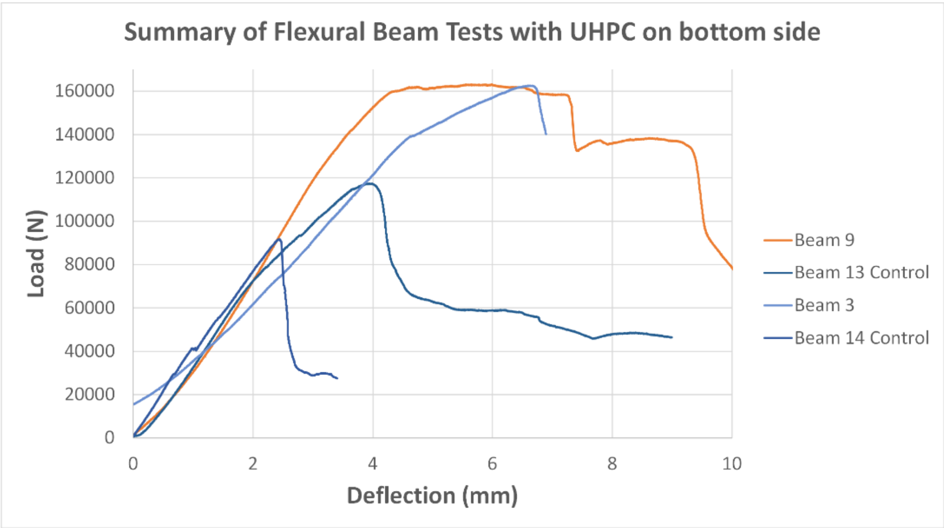

Figure 19. Summary of Flexural Beam tests with UHPC on Bottom side

Beams 9 and 3 show significant strength increase over the control beams as shown above in Figure 19. The Beam 9 underlayment was a conventional placement, not a spray application. Beam 3 was a spray application, almost a ½ inch (13mm) thick.

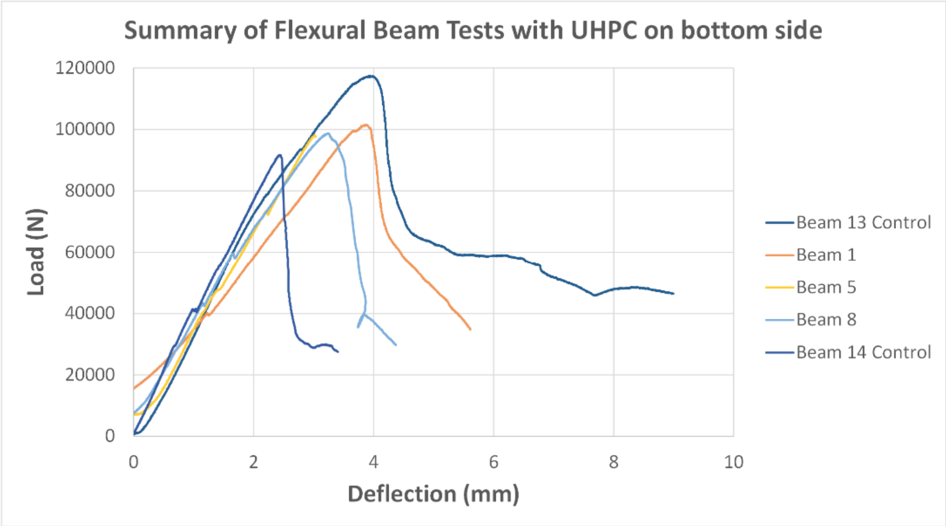

Figure 20. Summary of Flexural Beam tests with UHPC on Bottom side

Beams 1, 5, and 8 show similar strengths, with ultimate strength between the values recorded for the two control beams.

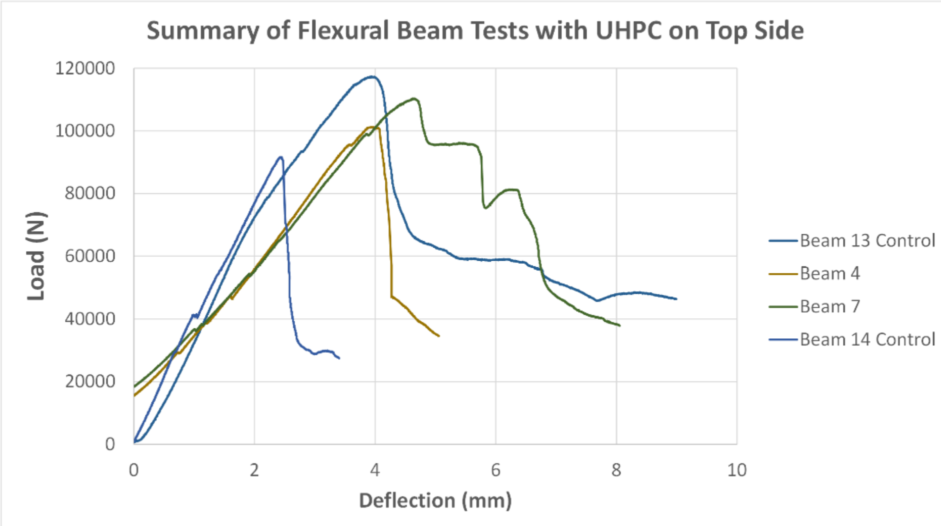

Figure 21. Summary of Flexural Beam tests with UHPC on Top side

The results of testing on Beams 4 and 7 are shown above. The UHPC on beam 4 was applied vertically downward. The UHPC on beam 7 was applied horizontally. The thickness of the UHPC was about thin,0.09 inches (2. 3mm) for beam 7 and 0.12 inches (3.0 mm) for beam 4. The results are remarkably similar, indicating the direction of spray application has little effect on the strength.

5.4 Direct Tension Testing

Direct tension testing was performed in general accordance with AASHTO T-397, Graybeal(xx). This method is performed on prisms that are 2 inches by 2 inches in cross-section and12 to 16 inches long. The samples were made with roughness interface cast into the sample, at the mid-point. One half of the sample is NSC, and the other half was cast with UHPC, containing fibers. The NSC is a 4000 psi mix. UHPC is mix no. 43. One sample has been tested to date. Results are shown in Table 11.

Table 11. Direct Tension Test Results

Roughness Profile	Tensile Strength
4	500 psi

5.5 Rapid Chlorine Ion Penetration Testing

Rapid Chlorine Ion testing was performed in general accordance with ASTM C 1202. The initial testing sequence included 4 samples. The samples were cored from the large UHPC applied pneumatically to a sand blasted surface. Two of the cores were composite samples, consisting of UHPC and normal strength concrete. A third sample was a section of the normal strength concrete cut from a core sample. The fourth sample taken from a test cylinder made from conventionally placed UHPC. The sample mix 43 included steel fibers. The samples were 4 in. diameter and 2 inches thick. The samples were removed from the apparatus and a resistivity test was performed on each sample. The results are presented in Table 12.

Table 12. Rapid Chlorine Ion Penetration Testing

Sample	Material	Test Results – Coulomb	Test Results - Ohm
Core 2	UHPC ½" thick and NSC	316.73	123.3
Core 3	UHPC ½" thick and NSC	284.81	155.2
Core 2	NSC	1173.41	35.8
Cylinder	UHPC, conventionally placed	1297.37	39.8

5.6 Large Scale Specimens

The shoot on January 19, 2022, had a thicker mix, with 0.6% VMA. The face of the target was about 2'by 16'. Spray was applied in thin strips along the full length of the target. The flow was about 6.25 inches. The W/C ratio was 0.18. Some of the material was observed to drip down the face of the sample. Additional applications of thin layers were beneficial in building up the thickness of the material. The material should not be sprayed on previous layers too quickly.

This was followed by a shoot on March 8, 2022, with the same mix. The target was one of the large samples made earlier in the study. The surface has been sand blasted. Two batches were made up and shot, with a gradual buildup of the material.

Figure 22. Showing the pneumatic application of UHPC, Third layer.

Figure 23. Showing sprayed material on large sample.

6. Numerical Analysis

The non-linear finite element program, ATENA, is available at FIU. Previously, initial applications included running a published example to learn the basics of operating the program and input basic geometry and materials.

The geometry of the control flexure beam (small scale sample) was also generated. Initially, the leather shims were not included in the model. The shims were modeled as a low strength, highly elastic cementitious material. The basic geometry is shown in Figure. 18.

The figure shows one-half of the beam, with the face on the right side of the figure representing the center line. The beam is symmetrical, allowing the half-beam to be analyzed with the proper boundary conditions. The burgundy colored bars represent the loading plates. The shims are represented by the light green elements. The plate on the lower left is the reaction point. The plate on the upper right is the location of the applied load.

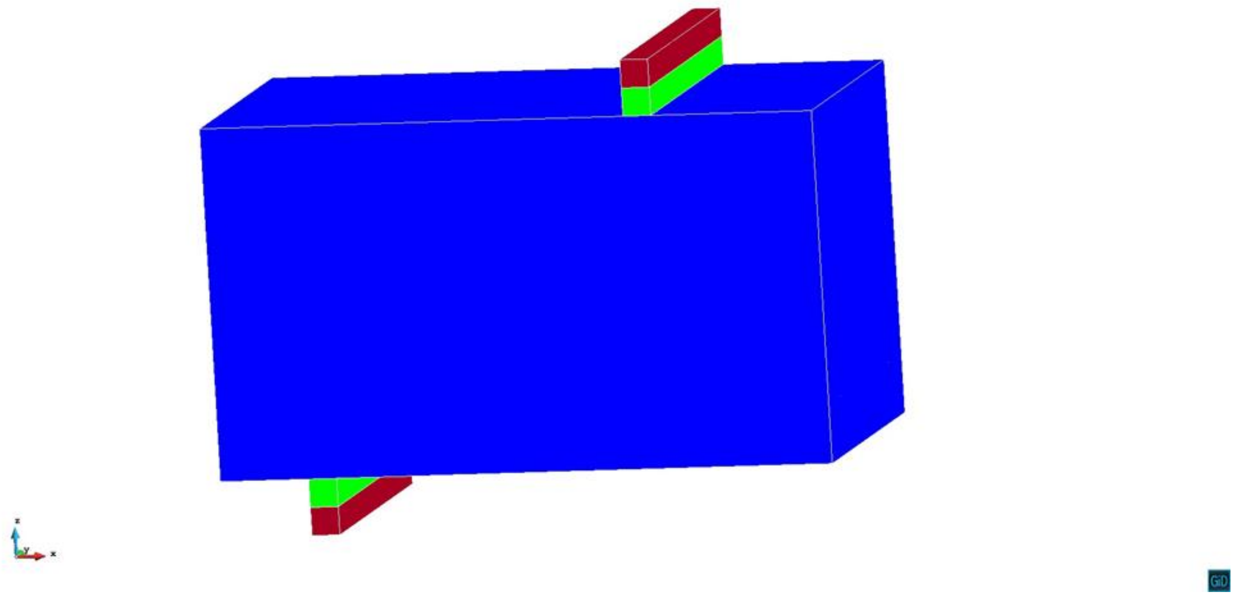

Figure 24. Basic geometry of the small scale model.

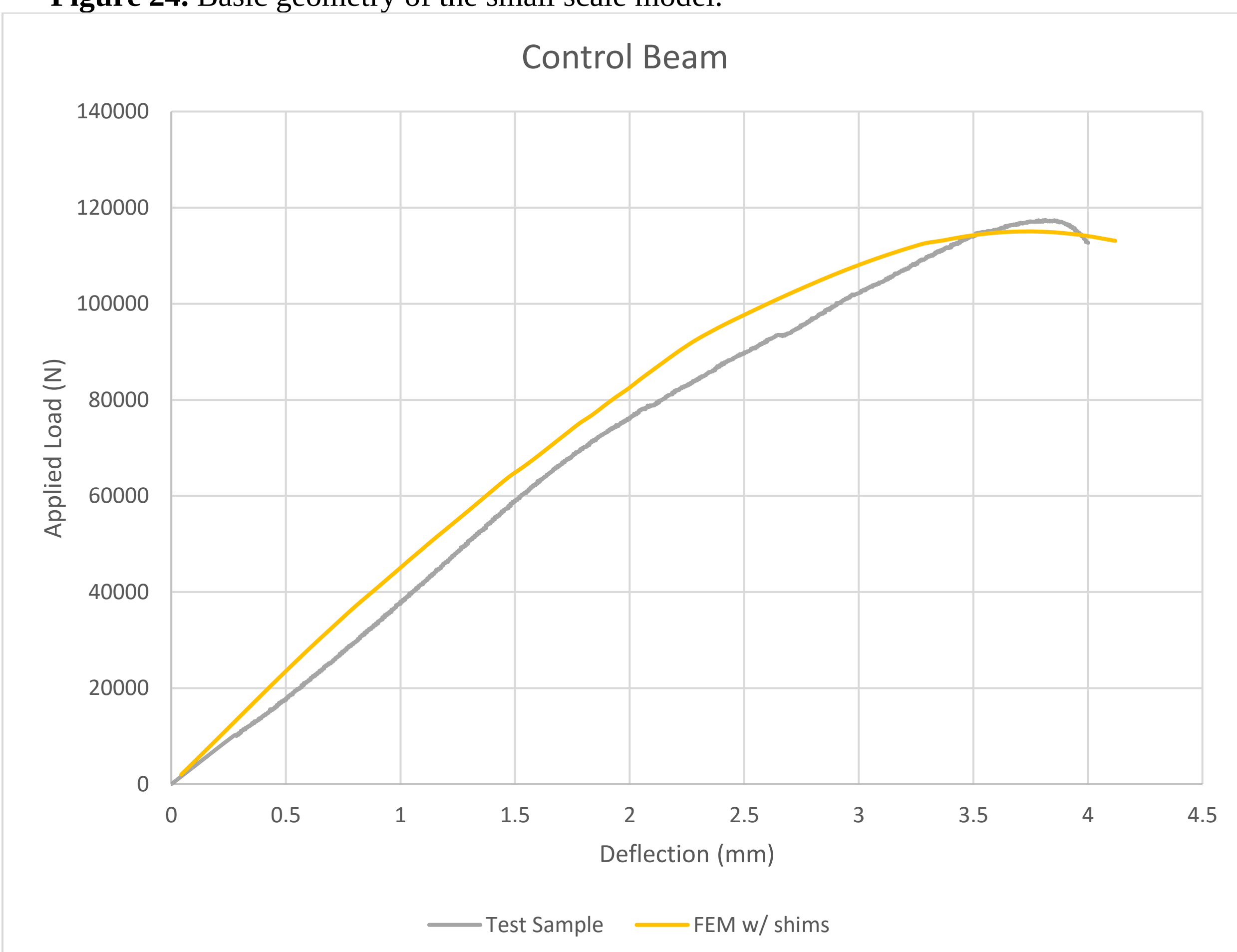

Figure 25. Control Beam Test results vs. FEM results.

The peak strength of the FEM model is similar to the Test results for the control beam. It is also noted the tested beam and the FEM model have similar stiffness and deflection. This indicates the parameters of the FEM model represent the tested beam well.

An FEM model was also developed for Beam S-2-A. UHPC was placed with conventional methods to the top surface of the beam, as shown by the pink material in Figure 26. the interface surface was modeled as a “zero-volume” contact surface. The surface interface between the UHPC and normal strength concrete is smooth, roughness profile 1. For the FEM model, the parameters of the contact surface were varied to represent a fixed condition, a sand-blasted condition and a smooth condition. The shims were modeled as discussed above for the control beam sample.

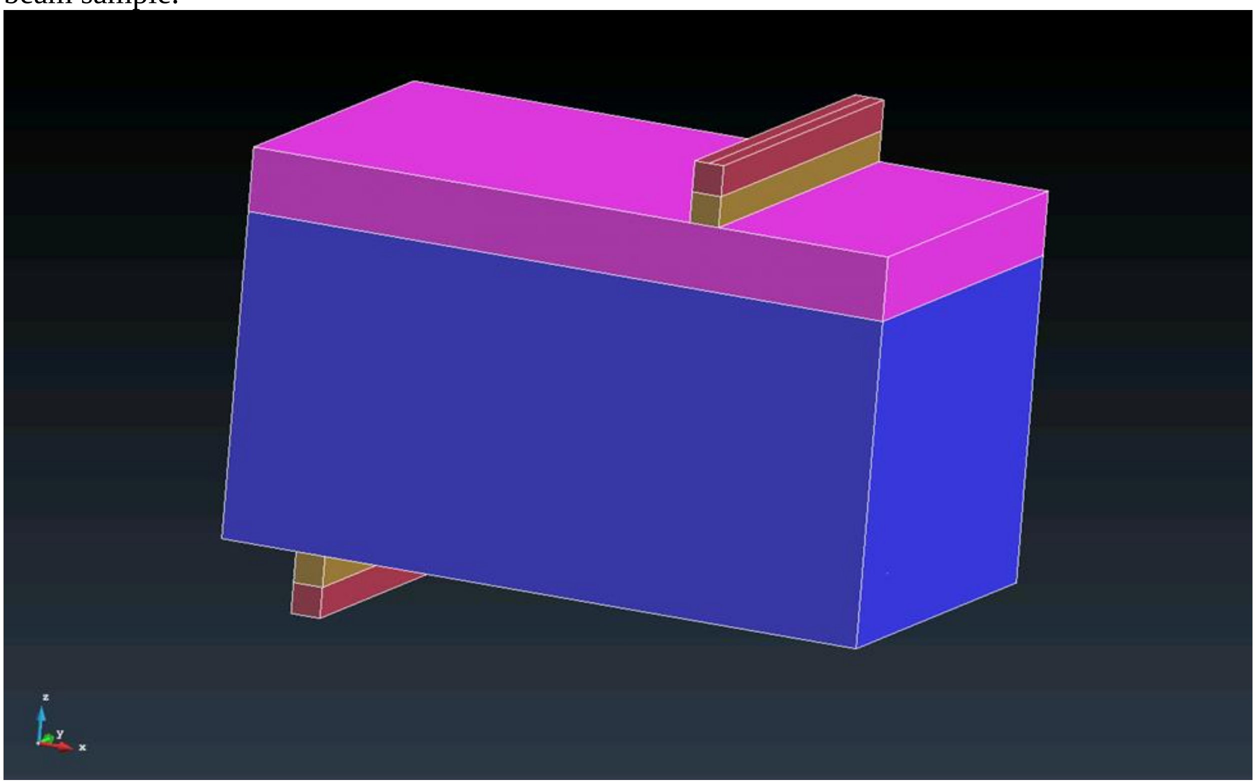

Figure 26. FEM model for Beam S-2-A.

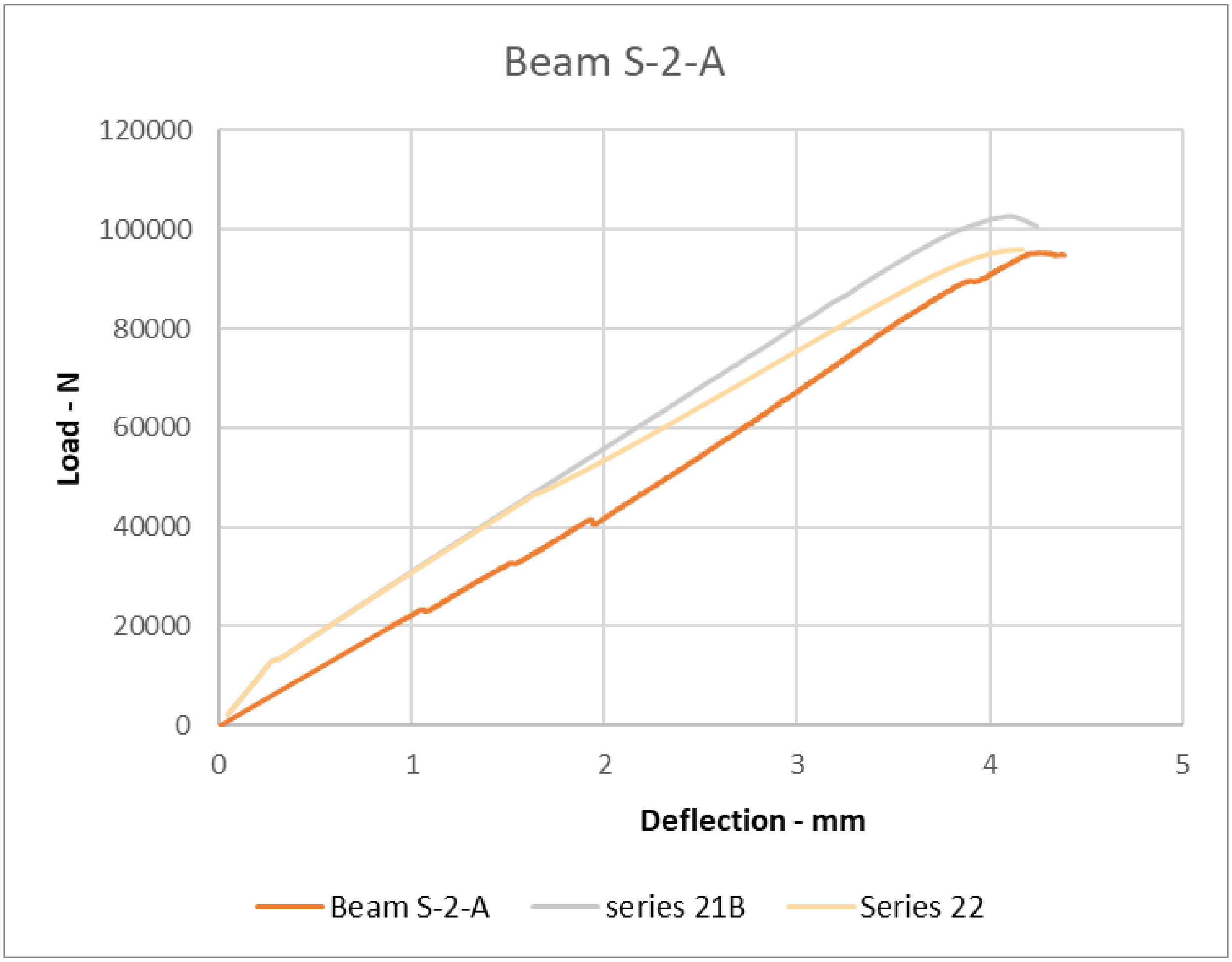

Figure 27. Beam S-2-A. Test results vs FEM model

These various interface conditions effect the maximum strength, as shown above in Figure 27. Series 21B was modeled with the rough or sandblasted parameters. Series 22 was modeled with the smooth surface parameters. It is also noted that the FEM models are marginally stiffer than the actual test results. The peak strength and deflection of the smooth surface model represent the tested beam well.

An FEM model was also developed for Beam S-1-D. UHPC was placed with conventional methods to the bottom surface of the beam, as shown by the pink material in Figure 28. Tthe interface surface was modeled as a "zero-volume" contact surface. The surface interface between the UHPC and normal strength concrete is smooth, roughness profile 1. For the FEM model, the parameters of the contact surface were varied to represent a fixed condition, a sand-blasted condition and a smooth condition. The shims were modeled as discussed above for the control beam sample.

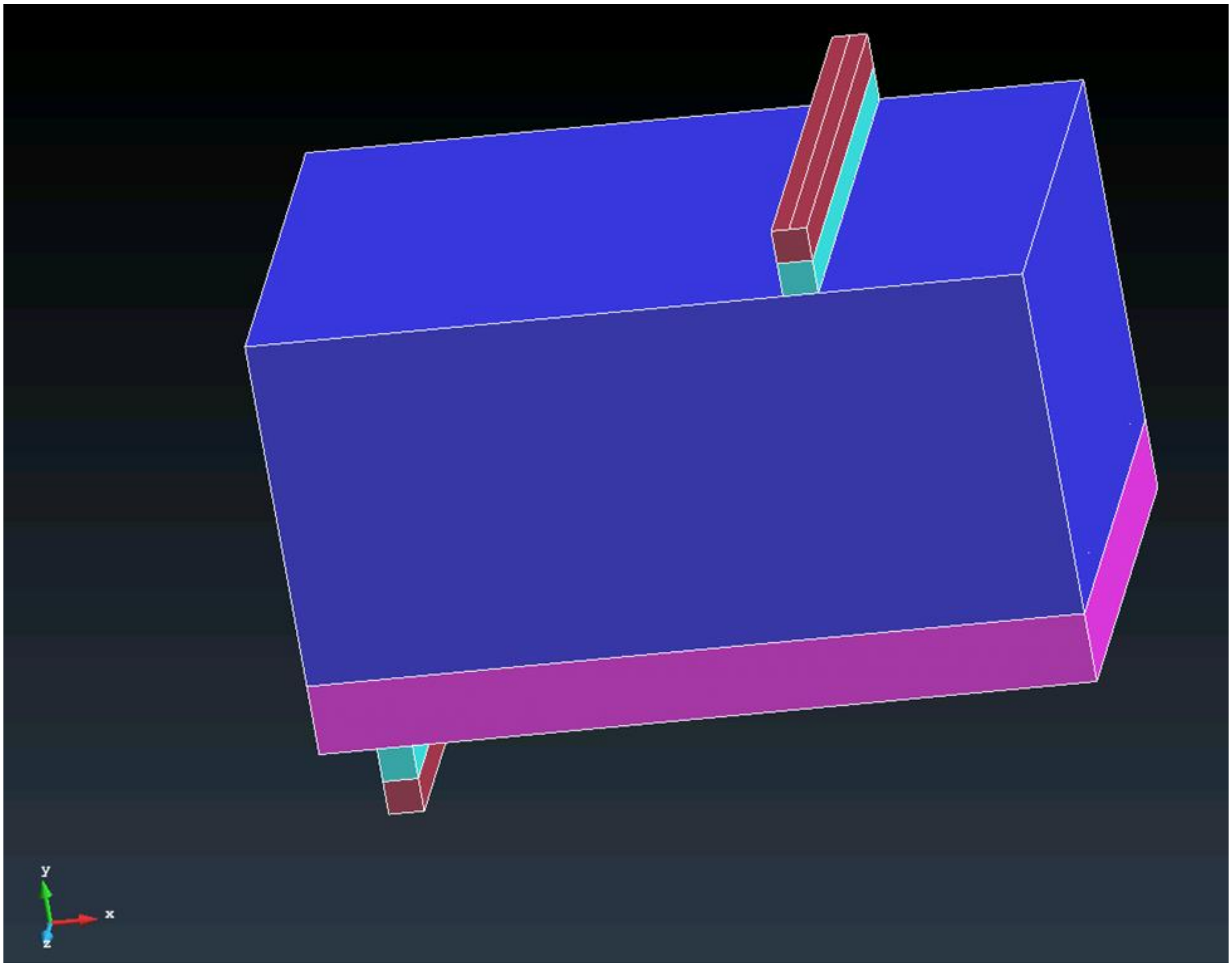

Figure 28. FEM model of Beam S-1-D.

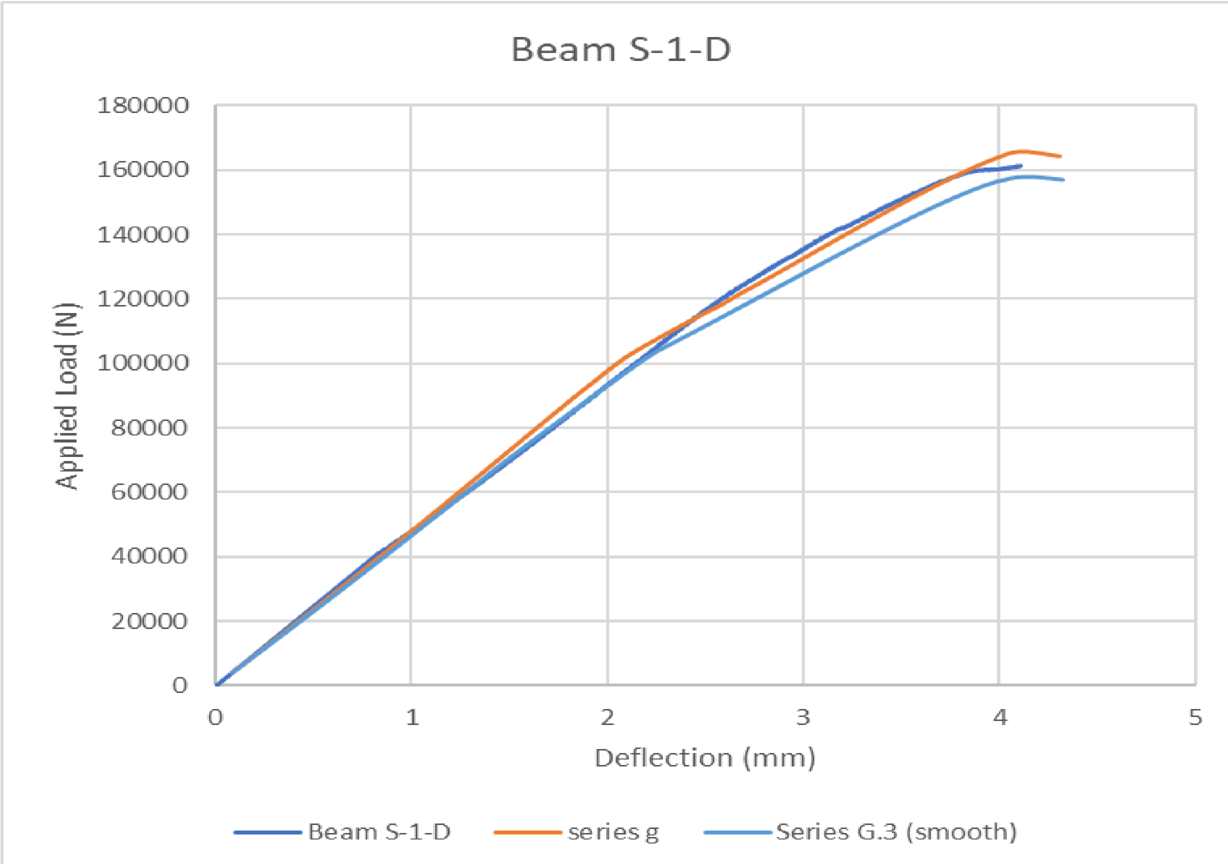

Figure 29. FEM results for Beam S-1-D.

These various interface conditions effect the maximum strength slightly, as shown above in Figure 29. Series G was modeled with the rough or sandblasted parameters. Series G.3 was modeled with the smooth surface parameters. It is also noted that the stiffness of the FEM models closely follow the actual test results. The peak strength and deflection of the smooth surface model represent the tested beam well.

7. Remaining Tasks and Schedule

Currently, a mix design has been selected and shot onto a large scale specimen. The base mix is ABC-40. Mix ABC-43 is the same base mix with a dose of VMA. Numerical analyses are in progress. The parameters obtained from the physical testing can then be applied to FEM models for analysis.

The tasks presented below still need to be finished.

- Flexure testing of the large scale “deck” samples, possibly by cutting Beam samples from the large scale sample.

- Tension testing of the UHPC/NSC interface with differing roughness profiles. Samples are being fabricated with a dog bone shape.
- Additional Rapid ion chloride testing of sprayed UHPC samples.

The estimated Timeline for completion of the various tasks is shown in Figure 30.

Item	% Completed
Percentage of Completion of this project to Date	95%

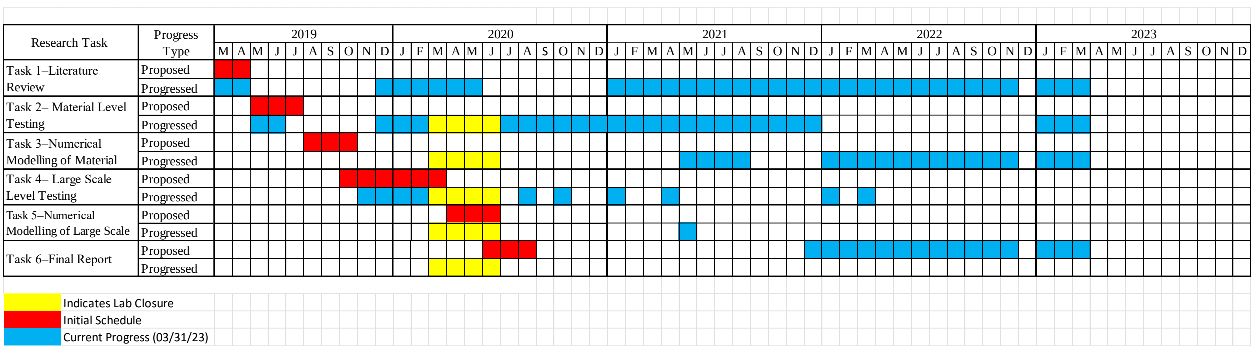

Figure 30. Project Progress.

8. References

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