Task 4 Report – Structural Testing

Exploration of UHPC Applications for Montana Bridges

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1 Introduction

Past and current research at Montana State University has been focused on several aspects of ultra-high performance concrete (UHPC). To capitalize on this research, the current research project is focused on exploring additional applications of UHPC in Montana bridges. The specific tasks associated with this research are as follows:

Task 0 – Project Management

Task 1 – Literature Review

Task 2 – Material-Level Evaluation

Intermediate Technical Panel Meeting Task

Task 3 – UHPC Overlay Projects, Material Specifications, and Implementation Issues

Task 4 – Structural Testing

Task 5 – Analysis of Results and Reporting

As discussed in the Task 3 Report, Task 4 has been modified from the original proposal and is now focused on identifying and testing structural elements in order to quantify the effects that UHPC overlays have on the behavior and capacity of existing bridge decks. This report documents the work completed as part of Task 4.

2 Previous UHPC Overlay Strength Testing

A review of previous research on slabs with UHPC overlays was conducted prior to Task 4, and was included in the previously submitted Task 1 Report. The goal of this review was to determine which aspects of UHPC overlay structural design had been experimentally tested and what additional information would be ideal to gather as part of the current study. Table 1 provides a summary of the key aspects of this literature review.

The key takeaways from the literature search were that only Iowa State University has conducted strength testing on slabs with UHPC overlays and all failures observed were shear failures initiated in the substrate concrete. The test slabs had a minimum depth of 8” (not including the overlay). Although current bridge deck design in Montana does not allow for a deck depth less than 8”, there are many older bridges with thinner decks, as they were (of course) designed based on old requirements. These bridges may be the best candidates for UHPC overlays in the future, and for this reason, the structural testing of the current project is focused on thinner decks than what have been tested by others.

Table 1: Summary of previous UHPC structural slab testing [1-3]

Org.	Testing Performed	Overlay Thickness	Results	Notes
Iowa State University	Overlay on fabricated 'precast' element. 2'x8'x8" with standard AASHTO reinforcement. Tested on 6 ft clear span, with steel plate (10"x20") in the middle for truck tire. First loaded to just above cracking values. Then loaded to cracking and failure.	1.25"	All eventually failed in shear in the NC at 70 kips. 4.4 times the design load. No slip observed. Estimated shear capacities were much lower than slant shear, due to substrate concrete failing. UHPC could experience much higher. They then created a model to estimate moment curvature that was within 10% of measured values.	Used non-thixotropic mix. Tarped cured for 2 days then air cured. Some had delamination from drying shrinkage.
Iowa State University	Continuation of above, but tested no overlay, overlay on top with reinforcement and on bottom with reinforcement.	1.5"	Observed an increase in strength, though wire mesh didn't contribute much to negative moment because the area was fairly small. More steel could help, though would increase weight.	Maybe if we tested a slab that was as thick as the ones with the overlay to better compare. Baseline without overlay also good to test.
New Mexico State University	Slab tests for shrinkage, channel girder with and without overlay. Cyclic loading, 4-point flexural testing to a set midspan deflection. 1000 load-unload cycles. 2 cycles per min for first 100. Then 4 cycles per min for next 900. Then loaded to failure.	1"	Steel helped with shrinkage. 27% increase in strength for same 0.4" deflection. Maintained elastic behavior.	Measured roughness with sand test ASTM E965. Had a 1000-kip capacity compression machine.

3 Experimental Design

3.1 Overview

Five slab designs were tested in this research. The key design parameters (span, thickness, rebar reinforcement, etc.) are based on the existing Fred Robinson Bridge, which spans the Missouri River on Highway 191 in Northeastern Montana. A cross-section of the existing bridge deck is shown in Figure 1.

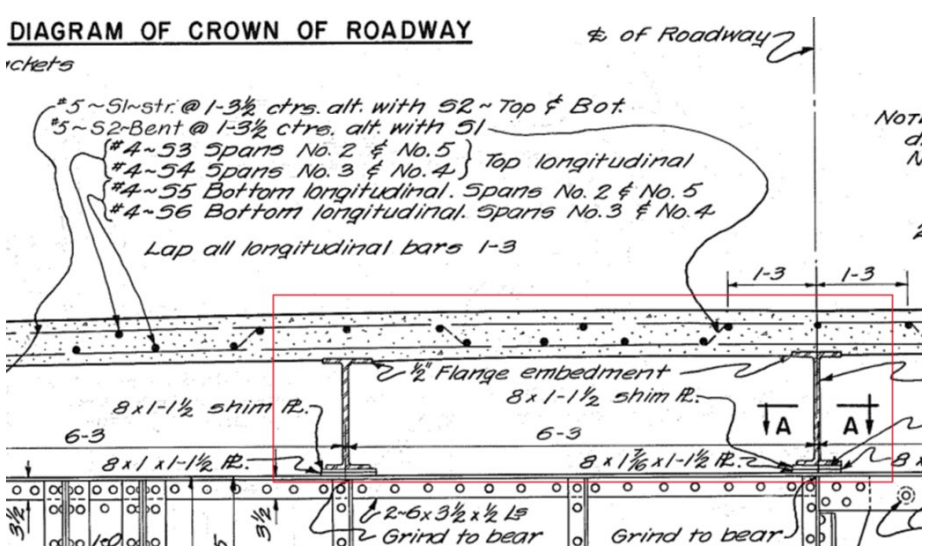


Figure 1: Section from Fred Robinson Bridge drawings. The red box shows the approximate location of the test slabs' representation of the bridge deck and the girder supports shown later in Figure 2.

The test specimens in this research represent small sections of the overall bridge deck; specifically, four of the test specimens are intended to replicate the slab sections in positive bending spanning between the girders and one of the test specimens is intended to represent the slab section in negative bending spanning over the girders. An isometric view of a typical slab specimen is shown in Figure 2. Note that more specific details of the various specimens will be covered in a later section.

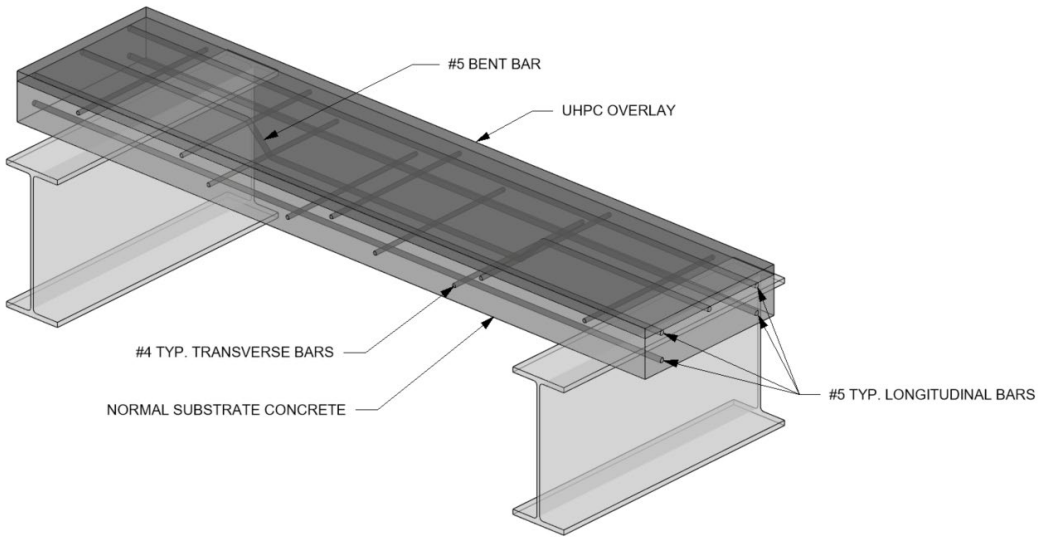


Figure 2: Test Slab Isometric View (with an example UHPC overlay shown).

3.2 Loading, Supports, and Data Acquisition

The slab specimens were tested in 3-Point bending, similar to the research conducted at Iowa State University, with the load applied following AASHTO recommendations for standard tire load and orientation. In this setup (Figure 3 and Figure 4), the specimens were simply supported, and a load was applied at midspan with a hydraulic actuator. The load was transferred to the specimen with a 10” by 20” steel plate, intended to represent a standard tire load between the girders. The specimens were tested until failure while recording the applied load and resultant displacements. The load was recorded with a load cell attached to the end of the actuator, and string potentiometers were used to record the resultant displacements. The displacements were recorded on both sides of the specimens at the midspan and on one side of the specimen at the quarter spans. A GoPro was used to record videos during all tests. All slabs were loaded to a midspan displacement of at least 3.5” (4.7% of span length).

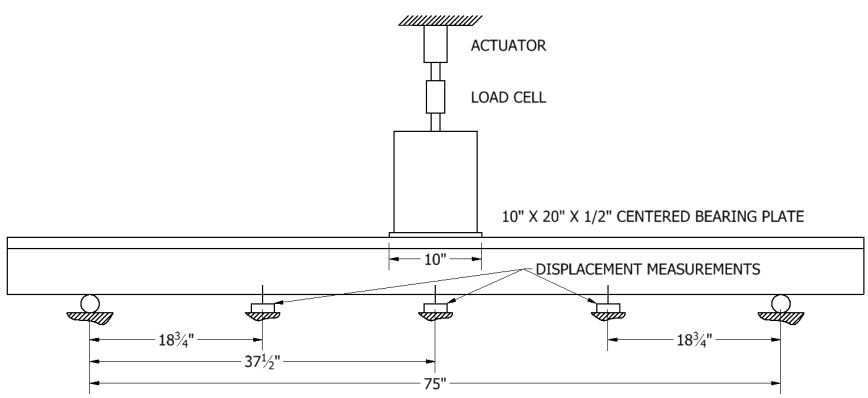
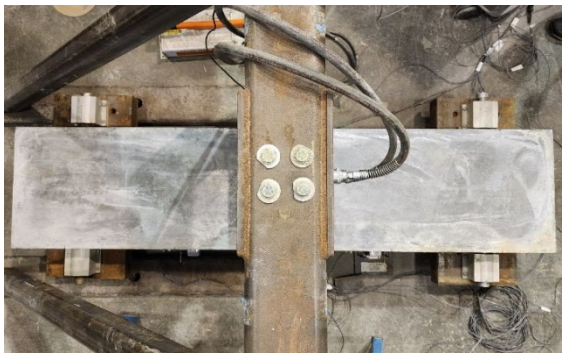


Figure 3: Schematic of test set-up.

a) Load truck and steel plate



b) Top view of slab

c) Isometric view of entire setup

Figure 4: Test set-up

3.3 Test Slab Details

As discussed above, the slab specimens are intended to represent sections of a bridge deck slab spanning between the longitudinal bridge girders (and one that represents a slab spanning over the girders subjected to negative moment). The primary slab dimensions and reinforcement details mimic those found in the existing Fred Robinson bridge. All specimens had the same width (21 inches), length (93 inches), test span (75 inches), and reinforcement details, but varied in the depth of UHPC overlay, loading condition, and concrete strength. The reinforcement details for all specimens (Figure 5) include longitudinal steel consisting of an alternating pattern of #5 grade 60 rebar. There is one set with a top and bottom bar (outside edges of the test slabs) and another with a bent that drops down between the supports (refer to bent bar label in Figure 2 isometric view). The transverse steel consists of #4 bars spread across both the top and between the bent longitudinal #5 on the bottom. The top clear cover is dependent on the overlay thickness and bottom clear cover is 1”. The longitudinal rebar for one test slab is in a flipped orientation and will be discussed below.

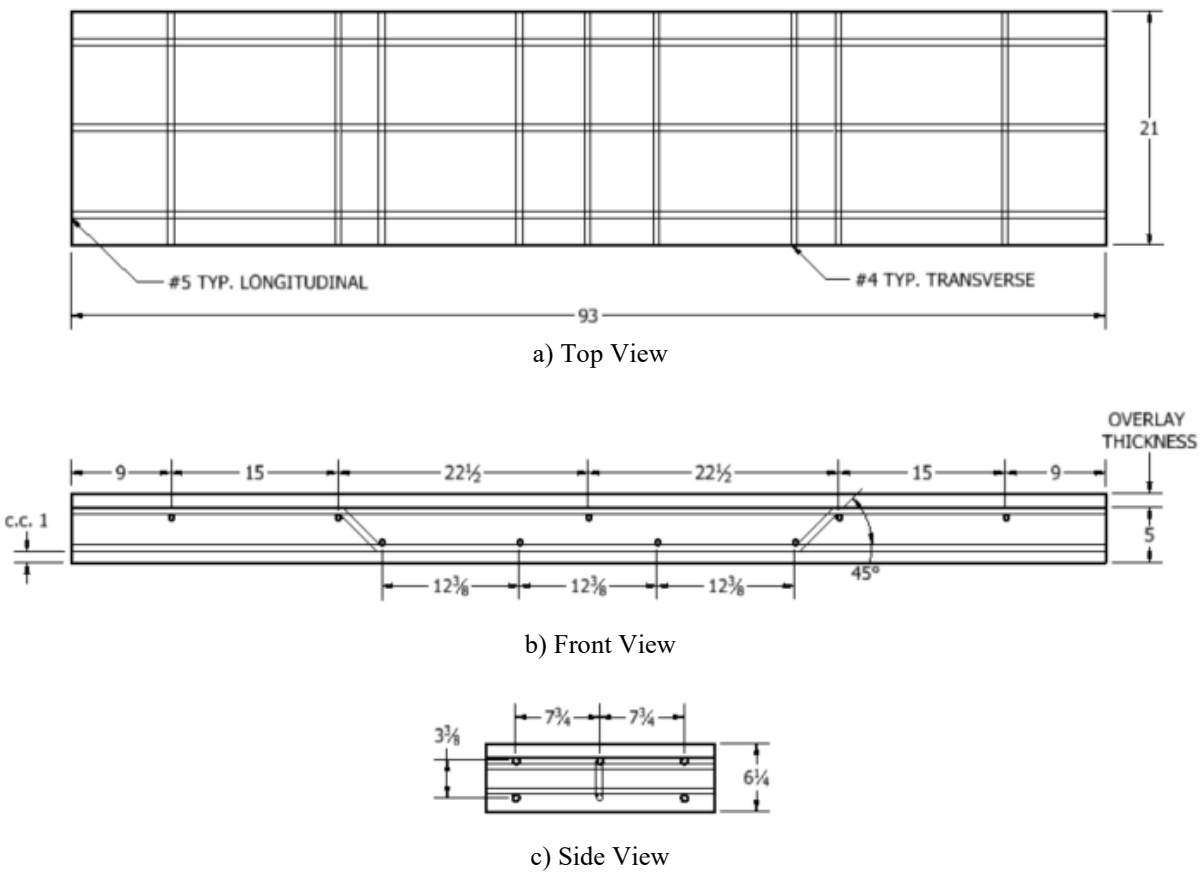


Figure 5: Test slab dimensions and reinforcement details (all dimensions shown in inches).

The 5 test specimens consisted of one control slab, two slabs with varying UHPC overlay depths, one with UHPC overlay with weak substrate concrete, and one tested in negative bending (with UHPC overlay on the bottom in test setup). The specifics of the 5 test slabs are presented below. The naming convention chosen for the slabs is Control for the control slab and then follows a "O – P/N R/W" naming convention for the overlay slabs, where the first letter signifies **O**verlay, the second letter **P**ositive or **N**egative for the moment loading, and the third letter **R**egular or **W**eak for the substrate concrete strength.

1. **Control**: a 6.25-inch thick slab made with regular-strength concrete (~4 ksi).
2. **O-PR1**: *Overlay-Positive Regular 1* – a slab specimen with target overlay thickness of 1.5 inches to be tested in positive moment with regular substrate concrete (~4 ksi).
3. **O-PR2**: *Overlay-Positive Regular 2* – a slab specimen with target overlay thickness slightly more than the 1.5 inches specified in O-PR1 to be tested in positive moment with regular substrate concrete (~4 ksi).
4. **O-PW**: *Overlay-Positive Weak* – a slab specimen with target overlay thickness slightly more than the 1.5 inches to be tested in positive moment with weak substrate concrete (~2 ksi).
5. **O-NR**: *Overlay-Negative Regular* – a slab specimen with target overlay thickness slightly more than the 1.5 inches to be tested in negative moment with regular substrate concrete (~4 ksi). Note that this

specimen was tested using the same test setup as the other specimens, but the UHPC was on the bottom of the slab during testing, and therefore in tension. Additionally, the reinforcement was flipped before casting (i.e., the center bent bar is flipped in Figure 2), so that the areas of "top" and "bottom" steel are consistent with the other slabs.

Overall, the control slab will yield a baseline for which to compare the results of the other slabs and the test results from the O-PR1 and O-PR2 slabs will yield a comparison of slightly differing overlay thicknesses. Deck concrete cores taken from older bridges can sometimes yield lower than expected strengths. The test results from the O-PW slab will shed light on how a UHPC overlay will affect the capacity on a deck with weak substrate concrete. Bridge decks are subjected to loading that causes both positive and negative moments. In the negative moment regions, the overlay will be in tension and the UHPC will increase the tensile capacity of the slab. The test results from the O-NR slab will help better understand this behavior.

4 Specimen Construction and Preparation

4.1 Formwork and Reinforcement

Figure 6 shows the formwork and reinforcement for a typical specimen during construction. The formwork was constructed using 0.75-inch plywood sheets and 2-by-8-inch fur boards. The bottom rebar was placed on 1-inch chairs at the bottom of the forms, while the top reinforcement was hung from the top of the forms, as shown. Form oil was applied to the forms prior to casting.

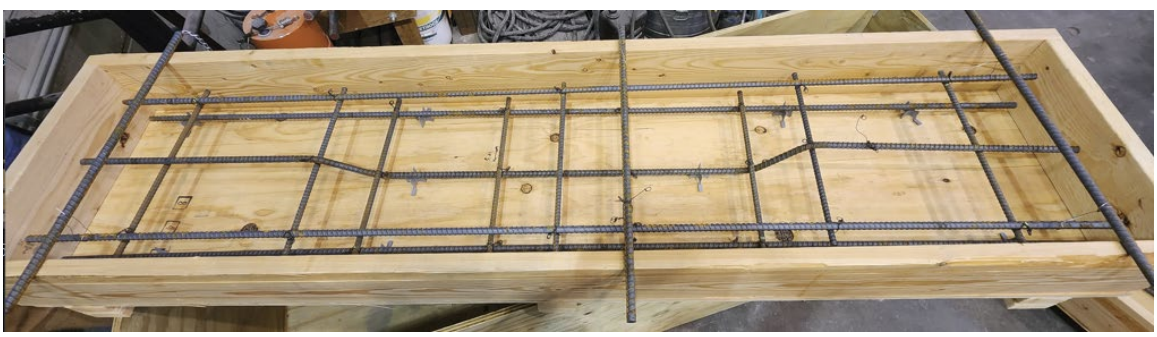


Figure 6: Example slab formwork and reinforcement before casting.

4.2 Substrate Concrete Surface Preparation

The surface of an existing slab will need to be prepared for a UHPC overlay. This process can be done several ways; however, MDT and the FHWA recommend hydrodemolition. A surface retarder (MasterFinish XR Lilac, Appendix A) was used in this research to simulate a hydrodemolitioned surface. Test panels were cast to test the surface retarder application procedures and allowable set times and to gain confidence in creating the final desired surfaces. Based on the test panel findings, the slab specimen surfaces were heavily coated and sprayed off at around 20 hours. Overall, after experimenting on the test panels (Figure 7), the researchers felt confident that the desired surface preparations would be achieved on the full-scale slabs' substrate concrete. Also, due to the recommendations on the technical data sheet, additional test panels were made when the slabs' substrate concrete was cast to have surfaces to test spray to ensure desired behavior before preparing the slabs themselves.

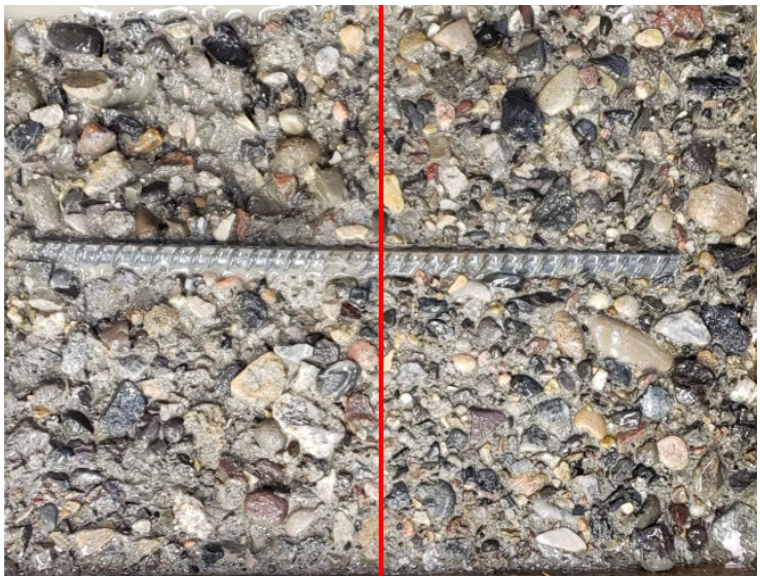


Figure 7: "Hydrodemolition" Test Slab (Left Sprayed at 7 hours. Right Sprayed at 20 hours.)

4.3 Weak Mix Concrete Trials

For the O-PW slab, a weak concrete mix was developed. Due to the atypical nature of designing a 2 ksi strength concrete, a few trial batches were performed to fine tune the mix design. Using a PCA Table 12-3, the water cement ratio of a standard 5 ksi mix from MSU was altered for a weaker mix [4]. Trial batches (0.2 ft^3 volume) were cast with water cement ratios ranging from 0.8 to 0.85 to reduce the strength. After several tests, it was decided to use the mix design shown in Table 2 for a 3-ft^3 batch, as it would yield a mix with ~2 ksi strength at the time the slab would be tested.

Table 2: Weak substrate concrete mix design for a 3 ft^3 batch

Item	Weight (lbs)
Water	44.6
Cement	55.3
Coarse Aggregate	218.4
Fine Aggregate	116.1

Additionally, the substrate concrete surface preparation technique was tested on the weak mix. A test panel was cast and prepped following the process described previously. The surface had adequate results after being sprayed at 24 hours, though it was noted that it took much longer for the surface bleed water to dissipate.

4.4 Casting Substrate Concrete

The four regular strength substrate concrete slabs (Control, O-PR1, O-PR2, and O-NR) were cast on the same day using a 4 ksi mix provided by Quality Ready Mix in Bozeman, MT. Each slab was vibrated and filled to the appropriate height (just above the rebar with concrete paste for the overlay specimens and to 6.25" for the control specimen). After all surface water had evaporated, the tops of all slabs except the control were coated with a thick layer of the surface retarder (Figure 8a). The control slab was simply covered in saran wrap. After about 20 hours, the top layers of the overlay specimens were sprayed and brushed off (Figure 8b). The slabs were all covered with saran wrap and left to cure for one additional day

before being moved, stacked, covered in wet towels, and wrapped in a thin plastic sheet (Figure 9). It should be noted that the substrate concrete depth varied along the length of individual slabs and between all of the slab specimens. This was likely due to slight differences in the location of the top rebar, and due to variations in the amount of concrete removed from the top surface. These variations in depth led to variations in the UHPC overlay thicknesses, which will be discussed in a later section.

The substrate concrete for the O-PW slab was cast on a separate day using the mix design discussed in the previous section. It should be noted that it took over an hour for the surface water to evaporate due to the high water content of the mix, after which the surface retarder was applied.

a) After surface retarder applied b) After spray/brush off

Figure 8: Example slab substrate concrete surface preparation.

Figure 9: Formwork stacked for curing.

4.5 Casting UHPC Overlays

The UHPC used for this research was a modified version of Ductal provided by LarfargeHolcim. It should be noted that Lafarge Holcim recommended a slightly different mix compared to what was tested during

Task 2 that included a small amount of Chryso Premia 150 admixture that could be added to reach the target flows of 5" for static and 7" for dynamic. The mix design for a 3-ft^3 batch is shown in Table 3. For all slabs except O-PW, the UHPC overlay was cast 14 days after the substrate had been cast. Two batches were required to overlay the specimens. The mix procedures followed those described in the Task 2 Report, with the Premia 150 admixture being added in increments after the steel fibers were mixed until the target flows were reached. The resultant static and dynamic flows for these two mixes are provided in Table 4, and examples of the static and dynamic flows are shown in Figure 10.

Table 3: Ductal-T Overlay mix design for a 3 ft^3 batch

Item	Weight (lbs)
Water	31.8
F5 Admixture	4.1
Chryso Premia 150	0.5
Steel Fibers	46.5
Ductal Premix	375.0

The UHPC overlay for the O-PW slab was cast 3 days after its substrate concrete was cast (Mix 3, Table 4), using the same UHPC mix design and procedures used in the previous specimens.

Table 4: Static and dynamic flow values

UHPC Mix (slabs)	Flow (in.)	
	Static	Dynamic
Mix 1 (O-PR2 and ~O-PR1)	6.0	8.0
Mix 2 (O-NR and ~O-PR1)	5.5	7.5
Mix 3 (O-PW)	5.0	7.0

a) Static b) Dynamic

Figure 10: Example UHPC flow tests for Mix 1.

For all UHPC mixes, the forms were aggressively hit with a rubber mallet to consolidate the material. After casting the UHPC and after the surface water evaporated, the slabs were coated with a thick layer of curing compound (WR Meadows 1600 White, recommended by Ductal, Appendix B). The slabs during and after the application of the curing compound are shown in Figure 11a and b. Additionally, the slabs were covered in a layer of plastic wrap to further protect the UHPC (Figure 11c). After 24 hours, the curing compound was sprayed off with a pressure washer and scraped with a wire brush until almost all had been removed

(Figure 12). The slabs were then covered with wet towels, stacked, and covered with a plastic sheet in the same setup as before (Figure 9).

a) Application b) Finished surface c) Covered in saran wrap

Figure 11: Applying curing compound to UHPC overlay surface.

a) Spraying off curing compound

b) Final finished surface

Figure 12: Final UHPC surface preparation steps.

4.6 As-built Dimensions and Material Properties

Key as-built dimensions and material properties are provided in Table 5. Note that the depth measurements of the substrate concrete and UHPC overlay were taken with calipers for all slabs on both sides at center span and the average values are provided in the table. For all slabs, the top steel consisted of three #5 bars and the bottom steel consisted of two #5 bars. Table 5 also includes the distance from the extreme compressive fiber to the top reinforcement, d_t, and the distance from the from the extreme compressive fiber to the bottom steel, d_b. These values along with the concrete compressive strengths are required for the ACI/FHWA comparison calculations discussed in a later section. The substrate and UHPC concretes compressive strengths were tested according to ASTM C39 and ASTM C1856 respectively. The steel rebar was tested in tension according to ASTM A370-22 and the yield strength was equal to 71.1 ksi.

Table 5: As-built Dimensions and Material Properties

		Dimensions (in.)			Slab Test Day Compressive Strength, f'c (ksi)	
Slab	**Layer**	**Midpoint Depth**	**d_t**	**d_b**	**UHPC**	**Substrate Concrete**
Control	Total	6.28	1.59	4.97	18.3	4.1
O-PR1	Substrate	4.96	1.86	5.2		
	Overlay	1.55				
	Total	6.51				
O-PR2	Substrate	4.82	2.14	5.33		
	Overlay	1.83				
	Total	6.64				
O-NR	Substrate	5.13	1.31	4.82		
	Overlay	1.55				
	Total	6.68				
O-PW	Substrate	4.50	1.54	4.42	17.6	2.7
	Overlay	1.23				
	Total	5.73				

5 Slab Test Results

As discussed above, all specimens were tested to failure in the Structures Lab at MSU. This section details the results for the individual slab specimens. The following section will discuss key takeaways from these tests.

5.1 Control

The force-displacement curve for the control specimen is shown in Figure 13. Overall, this specimen behaved and failed as expected. After applying load, flexure cracks formed at the bottom of the specimen near the center at a load of around 4 kips, marked by the change in slope of the force-deflection curve. After cracking, the slab continued to gain strength as the rebar was engaged up to 16.7 kips, at which point the steel yielded and the load began to level off. The maximum load for this specimen was 21.5 kips, which occurred at a deflection of 1.3 inches. Ultimately, the slab failed due to concrete crushing at the midspan (Figure 14) with around 4 inches of deflection. The slab demonstrated good ductility, carrying 87% of the ultimate capacity until failure.

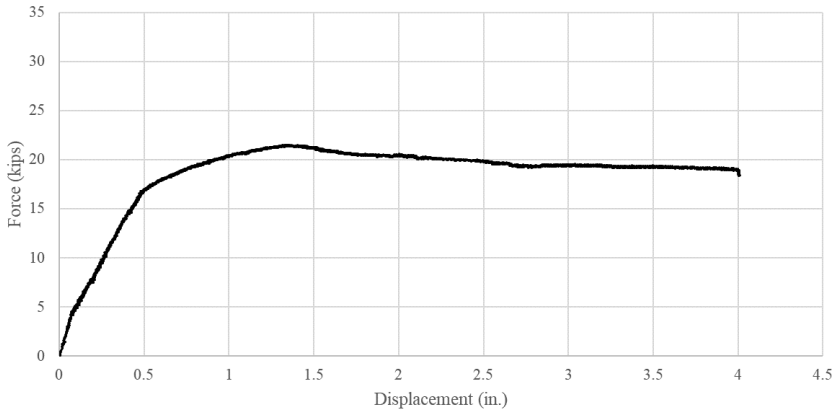


Figure 13: Control slab force-displacement graph.

a) Initial Loading

b) Concrete crushing prior to failing

Figure 14: Control slab during testing.

5.2 O-PR1 (Overlay-Positive Regular, specimen 1)

As mentioned previously, O-PR1 was similar to the control specimen but had a ~1.5 inch UHPC overlay on the top of the specimen. The force-displacement graph for this specimen is shown in Figure 15. After loading, the first sign of distress occurred when the flexural cracks formed at the bottom of the specimen (at approximately 4-5 kips). Again, this is marked by a change in stiffness at this load. The specimen continued to gain strength until the steel yielded at around 20 kips where there is a gradual reduction of stiffness. The specimen then continued to gain strength until it ultimately failed due to the formation of a shear crack in the substrate concrete. This shear crack then propagated to the bond interface between the UHPC and substrate concrete, which then led to the UHPC overlay debonding across the center of the specimen (Figure 16b). The ultimate load occurred at 29.4 kips and at a displacement of around 3.3 inches.

It should be noted that there was no distress observed in the UHPC prior to the debonding caused by the shear-crack propagation. It should also be noted that the slab specimen continued to carry 83% of the maximum load even after the sudden drop of load due to the formation of the shear crack. The slab then sustained load after debonding at a capacity close to that of the control slab. After the brittle drop in load, the slab recovered and sustained around 83% of the maximum load until testing was stopped at a displacement of 4.1 inches.

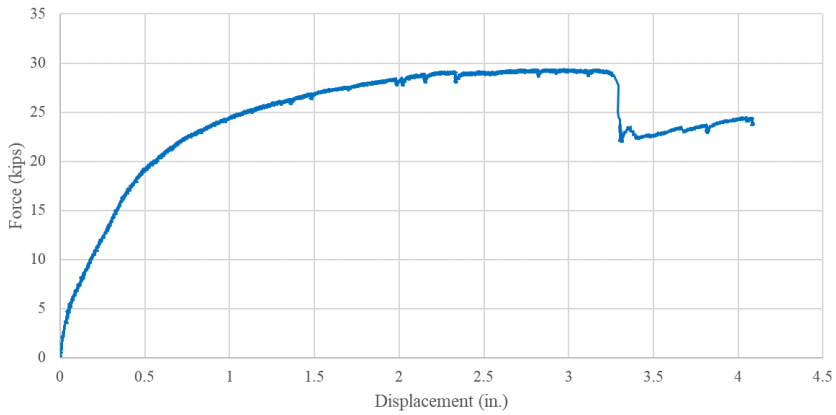


Figure 15: O-PR1 slab force-displacement graph.

a) Initial Loading

c) Shear crack formation

c) Crack widening/spreading at the end of testing

Figure 16: O-PR1 slab during testing.

5.3 O-PR2 (Overlay-Positive Regular, specimen 2)

As mentioned previously, O-PR2 was very similar to O-PR1 but had had a slightly thicker UHPC overlay on the top of the specimen, thus its behavior was very similar. The force-displacement graph for this specimen is shown in Figure 17. After loading, the first sign of distress again occurred when the flexural cracks formed at the bottom of the specimen (at approximately 4-5 kips). Again, this is marked by a change in stiffness at this load. The specimen continued to gain strength until the steel yielded at around 21 kips where there is a gradual reduction of stiffness. The specimen then continued to gain strength until it ultimately failed due to the formation of a shear crack in the substrate concrete. This shear crack propagated to the UHPC overlay, where unlike what was observed in O-PR1, it continued into the UHPC (Figure 18b). The shear crack formed at a load of 32.5 kips and a displacement of around 2.3 inches. It should be noted though, that the slab continued to carry a significant load after the initial formation of the shear crack, and ultimately failed when the shear crack completely propagated through the UHPC.

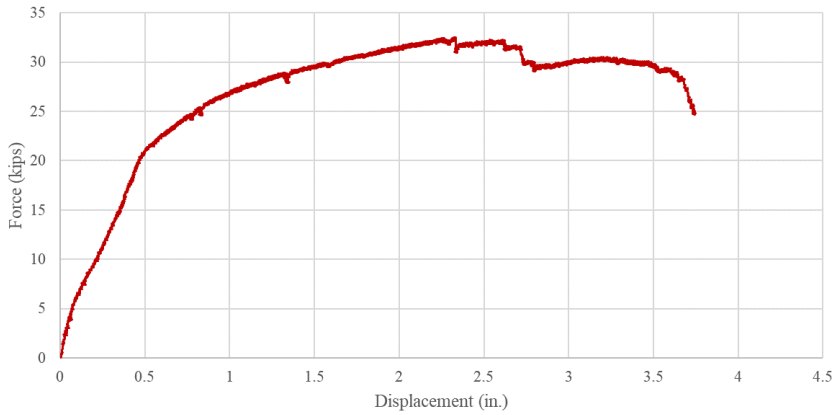


Figure 17: O-PR2 slab force-displacement graph.

a) Flexural cracks initially forming

b) Shear crack extending through the overlay

Figure 18: O-PR2 slab during testing.

5.4 O-PW (Overlay-Positive Weak)

The O-PW slab was similar to the previous two UHPC overlay slabs with the exception of the strength of the substrate concrete. In this specimen, the substrate concrete had a strength of 2.7 ksi. The force-displacement curve of this specimen is provided in Figure 19. Under loading, the first observed damage was the formation of flexural cracks at around 2.5 kips, again marked by the change in stiffness at around this load. It should be noted that this flexural crack formed at about half of what was observed for the previous two specimens, which is directly attributed to the significantly weaker substrate concrete. Again, this specimen continued to gain strength until the longitudinal reinforcement yielded, after which the stiffness of the specimen gradually decreased. Ultimately, a shear crack formed in the substrate concrete at a maximum load of 22.9 kips and a displacement of 2.6 inches. The shear crack propagated through the

UHPC overlay on one side and along the interface on the other side (Figure 20); however, in this case, this propagation occurred almost instantaneously, and therefore there is a significant drop in capacity immediately after the formation of this initial shear crack.

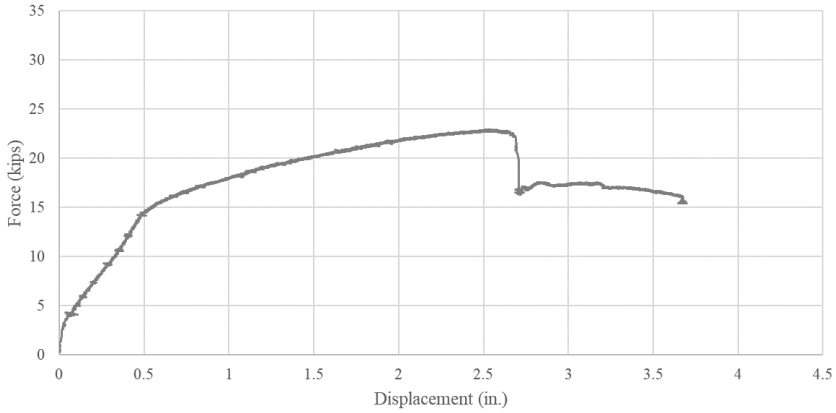


Figure 19: O-PW slab force-displacement graph.

a) Flexural cracks initially forming

b) Shear crack on one end of slab

c) Shear crack on other end of slab

Figure 20: O-PW slab during testing.

5.5 O-NR (Overlay-Negative Regular)

As discussed above, the O-NR slab was tested in a way to simulate a negative moment over the bridge girders. This specimen was tested using the same loading scheme used in the previous tests; however, the overlay was located on the bottom of the specimen, and the reinforcement was adjusted accordingly. The force-deflection curve for this test is provided in Figure 21, and Figure 22 shows the observed damage in the specimen. As expected, the behavior of this specimen was unique relative to the other specimens tested in this research. In this specimen, no flexural cracks formed immediately after loading due to the high tensile capacity of the UHPC overlay. Note the lack of a marked change in stiffness immediately after loading. That is, the initial stiffness is maintained until the UHPC begins cracking at around 20 kips, followed by a slight reduction in stiffness until reaching a peak load of 29.8 kips at a displacement of 0.55 inches. At which point, the UHPC cracks completely and there is a sharp loss of capacity, as observed in Figure 21. The capacity dropped to 18.0 kips, and then behaved very similar to the control specimen. This is expected since after the cracking of the UHPC the only thing carrying the load is the substrate concrete.

The specimen ultimately failed at a deflection of 3.5 inches due to crushing of the concrete at the top of the specimen. It should be noted that this slab could fail with little to no warning since the post-cracked moment of this specimen is significantly less than its cracking moment. However, this situation may be acceptable if the strengthened capacity including the UHPC far exceeds the expected demand on the slab. Additionally, although ACI sets strict requirements for beam failures, the requirements are less stringent for slabs, as there is more inherent redundancy in the system. Design engineers should acknowledge this behavior when considering a UHPC bridge deck overlay.

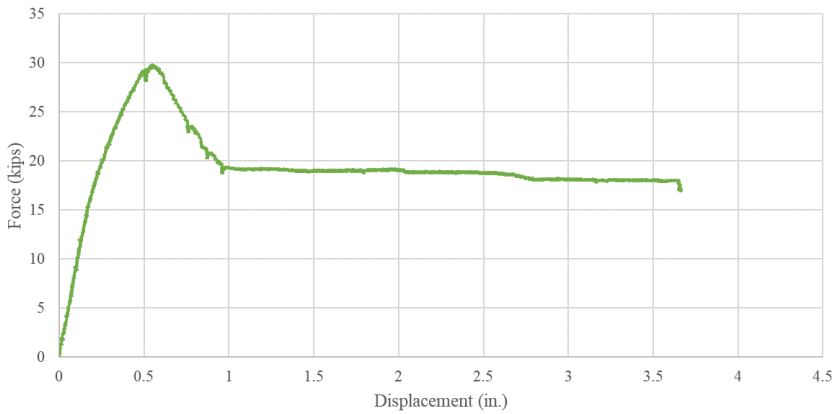
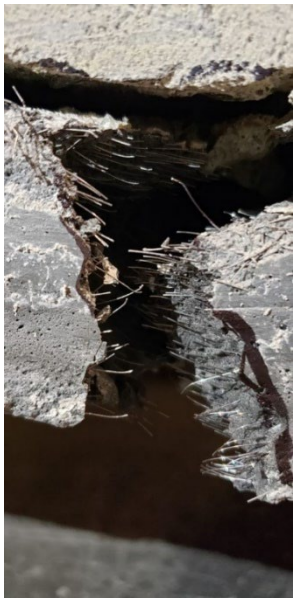


Figure 21: O-NR slab force-displacement graph.

a) Initial loading

b) Crack progressing through UHPC with steel fibers spanning



c) UHPC completely split

d) Midspan after failure, showing crushed concrete

Figure 22: O-NR slab during testing.

6 Discussion of Results

The following subsections discuss the key takeaways from this test series.

6.1 Overall Comparison and Observed Failure Mechanisms

All five force-displacement curves are shown in Figure 23, and Figure 24 is a plot of the resultant deflections along the length of all five specimens at a load of 12.5 kips. As can be observed in these plots,

all specimens had similar initial stiffnesses prior to cracking, and all but the O-NR specimen had a marked reduction in stiffness below 5 kips due to flexural cracking. Note that the O-NR specimen did not crack completely until a load of nearly 30 kips due to the increased tensile capacity of the UHPC overlay, as will be discussed in greater detail below.

Regarding failure mechanisms, the Control slab failed due to concrete crushing in the compression zone at midspan, while the three positive moment slabs with overlays had initial failures due to shear in the substrate concrete. The fact that these specimens failed in shear rather than from concrete crushing is most likely due to the increased ultimate strain of UHPC and the subsequent delay in the onset of crushing. After the shear failures and subsequent drops in load, the three overlay specimens were able to partially recover, and hold load up to at least 3.5 inches of midspan deflection. It is important to note that although these specimens failed in shear, their overall behavior was still ductile due to the longitudinal steel yielding prior to failure. It should also be noted that although the overlay was observed to debond from the substrate concrete during shear failures, this apparent debonding is most likely due to dowel action on the longitudinal reinforcement, which is located at the interface between substrate concrete and UHPC overlay. More details will be discussed in a later section when the test results are compared to calculations.

As stated above, due to the much higher tensile capacity of the UHPC, the O-NR slab does not initially crack until a much higher load (~16 kips) compared to the other slabs (~4 kips). This result highlights the benefits that a UHPC overlay will have on both a large increase in stiffness and delaying the onset of initial surface cracking during negative bending. After the O-NR specimen reached a peak load of nearly 30 kips, there is a sudden drop in capacity when the tensile load is transferred solely to the longitudinal reinforcement. After this crack forms, the specimen behaves very similar to the control specimen, ultimately failing due to concrete crushing at the midspan.

The following subsections further discuss the effects that various parameters have on the overall performance of the slab specimens.

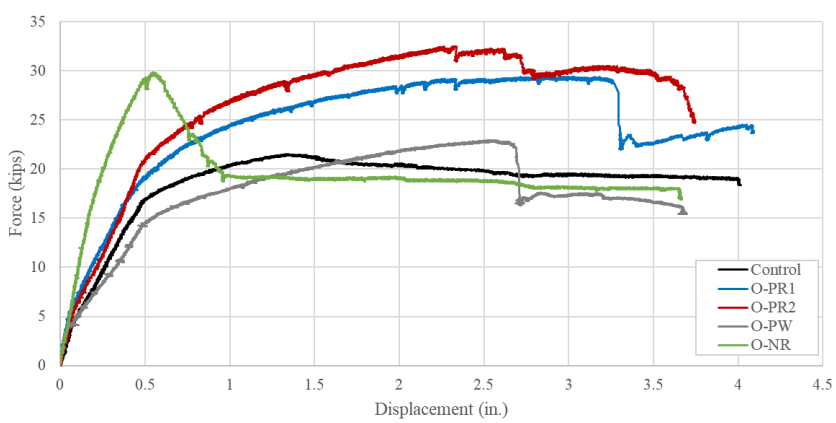


Figure 23: Comparison of all test slabs (force-displacement graphs).

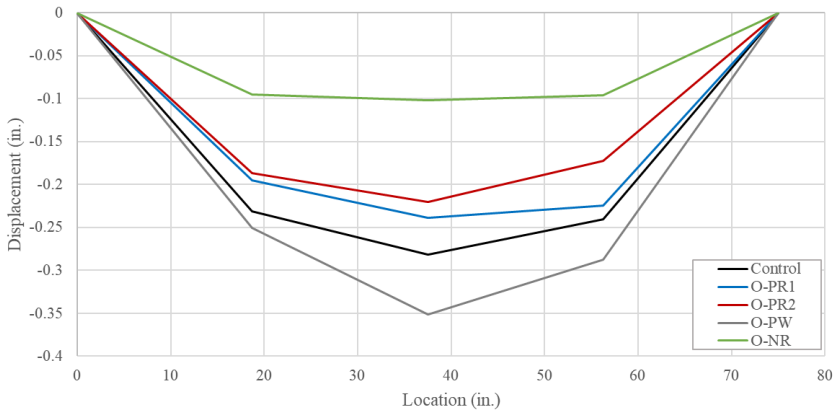


Figure 24: Deflections along the test span for all test slabs at 12.5 kips of load. Deflections were measured at 1/4 lengths (1/4, 1/2, and 3/4), or 18.75", 37.5", and 56.25" along the 75" span length.

6.2 Effects of UHPC Overlay Presence and Thickness

Figure 25 directly compares the force-displacement plots of the Control, O-PR1, and O-PR2 slabs to demonstrate the effect of replacing the top surface of the substrate concrete with a UHPC overlay. Both overlay specimens were stiffer and had higher ultimate capacities than the control specimen. Relative to strength, the O-PR1 and O-PR2 specimens were observed to be 37% and 51% stronger than the control specimen. These differences in stiffness and strength are most likely due to the UHPC overlay specimens being slightly deeper than the control specimen (6.51 in. and 6.64 in. vs. 6.28 in. for the control), and the fact that the UHPC is inherently stiffer and stronger than the conventional concrete in the control specimen. It should be noted, however, that concrete strength does not typically have a significant effect on capacity. That being said, an increase in compressive strength would decrease the size of the compression block at the top of the specimen, thus increasing the moment arm between the compression force and the tensile force. Further, UHPC has a higher ultimate strain than conventional concrete, thus delaying the onset of crushing in the overlay. This delay in concrete crushing could also explain the differences in the observed failure mechanisms. That is, the control specimen failed due to concrete crushing, while the delayed onset of crushing in the overlay specimens forced the failure mechanism into the substrate concrete where it failed due to shear.

Another comparison made on Figure 25 is between O-PR1 and O-PR2, demonstrating the effects that the UHPC overlay thickness has on the slab performances. O-PR1 and O-PR2 slabs had total depths of 6.51 in. and 6.64 in., respectively, and overlay thicknesses of 1.55 in. and 1.83 in., respectively. Therefore, as expected, the deeper specimen had a slightly higher capacity (10.5% stronger).

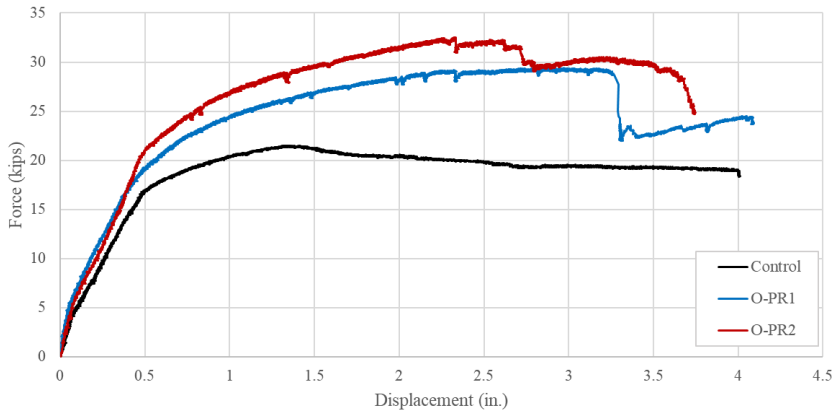


Figure 25: Control, O-PR1, and O-PR2 force- displacement graphs.

6.3 Effect of substrate concrete strength

Figure 26 directly compares the force-displacement plots of the Control, O-PR1, and O-PW specimens to demonstrate the effects that the substrate concrete compressive strength has on the flexural performance of the slabs. As expected, O-PR1 was stiffer and stronger than O-PW due to the increased stiffness and strength of the stronger concrete and due to the increased depth of this specimen. O-PR1 was 28.2% stronger than the O-PW specimen.

The Control and O-PW slabs performed similarly despite the large difference in substrate concrete strengths (4.1 ksi Control vs. 2.7 ksi O-PW) and total differences in overall depths (6.28 inches for Control vs. 5.73 inches for O-PW). Both specimens had similar stiffnesses and ultimate capacities were 21.5 kips and 22.9 kips, within 6.7%. This outcome demonstrates that a bridge deck made with weaker strength concrete can achieve a similar performance to a deck made with stronger conventional concrete when reinforced with a thin UHPC overlay. This finding holds significant potential for the rehabilitation of existing bridge decks made with weak concrete.

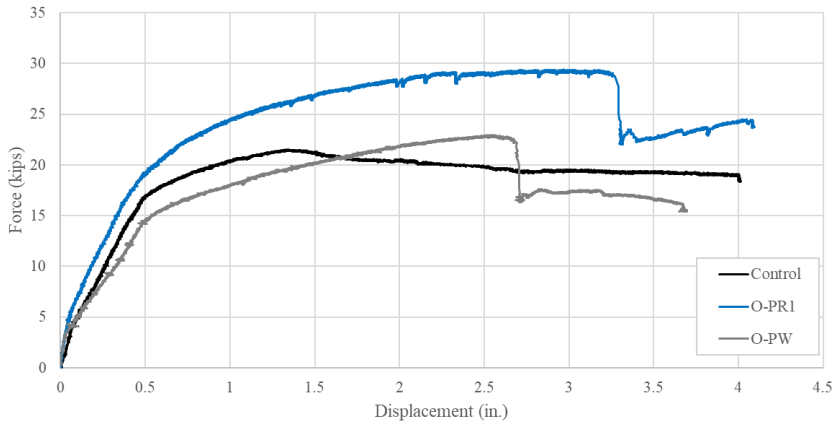


Figure 26: Control, O-PR1, and O-PW force-displacement graphs.

6.4 ACI/FHWA Predicted Capacities

The expected flexural and transverse shear capacities of the slab specimens were calculated according to methods prescribed ACI 318-19. Note that these calculations used the as-built dimensions and measured material properties on the day of testing, as presented in Section 4.6.

For flexural capacity, the Whitney stress block (with code-prescribed parameters) was used to model the concrete (both substrate and UHPC), and the steel was modeled as elastic-perfectly plastic. It should be noted that the mechanics in the negative moment specimen (O-NR) differ from those of the positive moment specimens, and these mechanics change throughout loading. That is, in this specimen and this loading configuration, the UHPC is at the bottom of the member in tension. The behavior of this specimen remained linear until the tensile capacity of the UHPC was reached, at which point the UHPC cracked and there was a sharp drop in capacity. After cracking, the UHPC has no effect on the behavior of the slab and the mechanics are then similar to that of the control specimen. For this specimen, the ultimate moment capacity is calculated according to the mechanics proposed by the FHWA [5], which accounts for the tensile capacity of the UHPC (Figure 27).

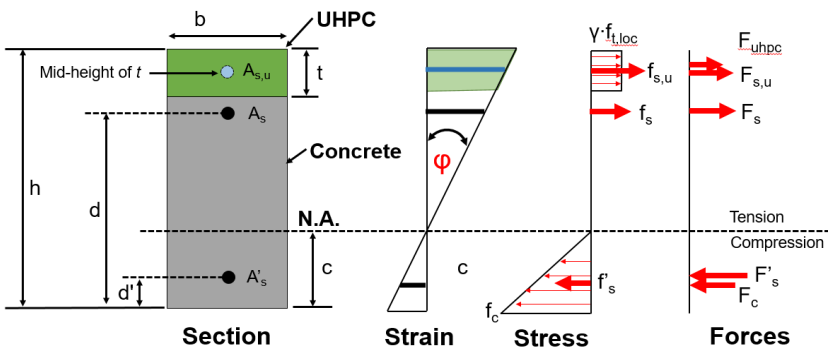


Figure 27: Assumed mechanics for negative moment capacity calculations, including UHPC tensile strength for UHPC bridge deck overlays [5].

The transverse shear capacity for each specimen was calculated as $V_c = 8\lambda_s \rho_w^{1/3} \sqrt{f_c'} b_w d$ (ACI 318-19), assuming the slab does not meet $A_{v,min}$, using the concrete compressive strength of the substrate concrete and ignoring the increased concrete strength of the UHPC. This assumption is conservative and is consistent with observed failures in which shear cracks initiated in the substrate concrete.

The predicted capacities using the methods discussed above are provided in Table 6, along with the measured capacities obtained from the tests. Included in this table are the ratios of measured to predicted capacities (Meas/Pred), and the observed failure mechanisms.

Table 6: Measured vs. Predicted Slab Capacities

Slab	Failure Mechanism	Measured Values			Moment Calculations		Shear Calculations	
		Measured P (kips)	Measured Moment (k-ft)	Measured Vc (kips)	Predicted Mn (k-ft)	Meas/Pred	Predicted Vc (kips)	Meas/Pred
Control	Concrete crushing	21.5	31.4	10.8	25.6	1.22	11.1	0.97
O-PR1	Shear in substrate	29.4	42.9	14.7	33.9	1.26	11.4	1.29
O-PR2	Shear in substrate	32.5	47.4	16.3	35.7	1.33	11.6	1.40
O-PW	Shear in substrate	22.9	33.4	11.5	28.4	1.18	10.2	1.12
O-NR	Cracking/ Concrete Crushing	29.8	43.5	14.9	45.4	0.96	10.9	1.37

For the positive moment specimens, the calculated flexural and shear capacities were close to the observed capacities and conservative. The ACI capacity calculations accurately predicted the expected failure responses in all positive specimens except in O-PW; however, the O-PW Meas/Pred ratios for moment and shear were very close.

As for the negative moment specimen, the FHWA predicted capacity (assuming a tensile stress of 3 ksi) was very close to the observed capacity, with a Meas/Pred ratio of 0.96. Note that for the negative moment specimen, these capacities are referring to the cracking capacity of the slab. As discussed previously, this specimen remained linear until the UHPC cracked in tension, leading to a shift in mechanics and ultimately a significant drop in capacity. This behavior (pre-crack capacity exceeding cracked capacity) could lead to a brittle failure with little to no warning. However, this situation may be acceptable if the cracking moment far exceeds the expected demand on the slab, and/or if the slab was designed to carry no more than the cracked capacity. It is also worth noting the calculated capacity of this specimen, ignoring the UHPC in tension, was determined to be 24.3 k-ft, which is close to the observed cracked capacity of 28 k-ft.

It should be noted that while some of the specimens showed signs of the UHPC overlay debonding, it was determined that this debonding was not associated with interface shear. As detailed in Appendix C, the calculated interface shear capacity was approximately 20 times higher than the interface shear demand on the specimens at the highest loads experienced by the slabs. The debonding was most likely attributed to dowel action on the longitudinal reinforcement initiated by the propagation of shear cracks.

7 Conclusions

In this study, a series of tests were conducted on five reinforced concrete slab specimens to evaluate the performance of bridge decks with ultra-high-performance concrete (UHPC) overlays. The slab specimens were subjected to flexural loading, simulating the loading conditions of bridge decks between longitudinal girders. The test series aimed to investigate the effects of various parameters, such as the presence of a UHPC overlay, overlay thickness, substrate concrete strength, and the difference between positive and negative moment behavior.

The test specimens included a control specimen without a UHPC overlay, two specimens with different UHPC overlay thicknesses (O-PR1 and O-PR2), a specimen with a lower substrate concrete strength (O-PW), and a specimen subjected to negative moment loading (O-NR). The slabs were instrumented to measure force and the subsequent deflections along their span. The results from the tests were analyzed in terms of stiffness, strength, failure mechanisms, and general behavior. The experimental results were also compared with the capacities predicted by the ACI 318-19 design code and the FHWA method for negative moment capacity calculations.

The key conclusions drawn from the study are as follows:

1. The inclusion of a UHPC overlay significantly improved the stiffness and ultimate capacity of the positive moment slab specimens. The O-PR1 and O-PR2 specimens exhibited 37% and 51% higher strengths, respectively, compared to the control specimen. Further, it was observed that an increase in UHPC overlay thickness resulted in a 10.5% increase in strength for the O-PR2 specimen compared to the O-PR1 specimen.

2. The observed failure mechanisms of the positive moment slab specimens varied depending on the presence of a UHPC overlay and other influencing factors. The Control slab, without a UHPC overlay, failed due to concrete crushing in the compression zone at midspan. In contrast, the three slabs with UHPC overlays (O-PR1, O-PR2, and O-PW) ultimately failed due to shear in the substrate concrete. This difference in failure mechanisms can be attributed to the increased ultimate strain of UHPC, which delayed the onset of concrete crushing in the overlay specimens. This delay in crushing forced the failure mechanism into the substrate concrete, where it failed due to shear, well after the longitudinal steel had yielded and there were significant deflections.
3. The O-NR specimen, subjected to negative moment loading, did not form significant flexural cracks until a load of nearly 30 kips, owing to the high tensile capacity of the UHPC overlay. After this crack formed, there was a significant drop in capacity, and the specimen behaved similarly to the control specimen and ultimately failed due to concrete crushing at the midspan. It should be noted that this behavior (pre-crack capacity exceeding cracked capacity) could lead to a brittle failure with little to no warning. However, this situation may be acceptable if the cracking moment far exceeds the expected demand on the slab, and/or if the slab was designed to carry no more than the cracked capacity. There is inherent redundancy in a slab system, but design engineers should acknowledge this potential brittle behavior when considering a UHPC bridge deck overlay.
4. The Control and O-PW slabs performed similarly despite the large difference in substrate concrete strengths (4.1 ksi Control vs. 2.7 ksi O-PW) and differences in overall depths; indicating that a bridge deck constructed with lower-strength concrete retrofitted with a thin UHPC overlay can exhibit comparable performance to a deck built with higher-strength conventional concrete.
5. Regarding the efficacy of capacity calculations, the ACI calculations were in line with the test results for the positive moment specimens and were conservative, with Meas/Pred ratios ranging between 1.12-1.40. For the negative moment specimen, the FHWA predicted capacity closely matched the observed capacity, with a Meas/Pred ratio of 0.96, when accounting for the tensile capacity of the UHPC.

Overall, UHPC overlays were shown to be a potential option for retrofitting existing bridge decks, as they significantly improved the performance of the concrete slabs, allowing for increased strength and durability. However, the specific benefits should be evaluated on a case-by-case basis, taking into account factors such as cost, construction constraints, and the specific demands of the project.

8 References

1. Sritharan, S., & Aaleti, S. *Investigation of a Suitable Shear Friction Interface betweeen UHPC and Normal Strength Concrete for Bridge Deck Applications.* 2017, Ames, IA: Civil, Construction, and Environmental Engineering.
2. Sritharan, S., Wibowo, H., & Keierleber, B. *Use of Ultra-High-Performance Concrete for Bridge Deck Overlays.* 2018, Ames, IA: Bridge Engineering Center Institute for Transporation.
3. Newston, C. M., & Weldon, B. D. *Bridge Deck Overlays Using Ultra-High Performace Concrete.* 2018, Baton Rouge, LA: Transportation Consortium of South-Central States.
4. Komatka, S. H., & Wilson, M. L. *Design and Control of Concrete Mixtures*. EB001, 15th edition, 2011, Skokie, IL: Portland Cement Association.
5. Ocel, J., Foden, A., and Gentz, C. "Ultra-High Performance Concrete (UHPC) for Bridge Preservation and Repair." An EDC-6 Workshop Developed for: Montana Department of Transportation, 16 August 2022, Federal Highway Administration, Helena, MT.

Appendix A: MasterFinish XR Spec Sheet

3 | 03 30 00 Cast-in-Place Concrete
03 40 00 Precast Concrete

MASTER® BUILDERS SOLUTIONS

MasterFinish® XR

Water-based retarder for exposed-aggregate concrete

Formerly MBT X-Poz-R*

Description

MasterFinish XR is a water-based top surface and/or form retarder used to produce uniform exposed-aggregate finishes on architectural or ornamental concrete.

Applications

Recommended for use in:

- Architectural concrete
- Ornamental concrete
- Face-up exposed-aggregate applications
- Steps
- Construction joints

Location

- Horizontal

Substrate

- Steel forms
- Fiberglass forms
- Concrete forms
- Wood forms
- Styrofoam forms
- Urethane form liners
- Fresh concrete

Features

- Versatile
- Excellent for use on Styrofoam or urethane form liners
- Ease of application
- Economical
- Wide range of etches available
- No need to wash off top surface on the same day
- Water-based

Benefits

- Can be used on a wide variety of form materials on small applications
- Extends the life of the forms
- Excellent top surface results
- No mold release needed
- Variety of exposed aggregate appearances
- Easy for scheduling labor
- No solvent, no odor; no fume or flammability problems

Color

The material in every container of MasterFinish XR retarder is color-coded to show specific degrees of penetration. Each container bears the name of the color on the label. The lid is also colored to match the material inside.

Color Coding Information

Color (Code)	Depth of Etch	Aggregate Size* in. (mm)
Lilac (38)	Light	1/4 – 3/8 (6 – 10)
Pink (48)	Medium Light	3/8 – 1/2 (10 – 13)

Recommended aggregate size

A brand of MBCC GROUP

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MasterFinish XR

Technical Data Sheet

Guidelines for Use

Yield: 150 - 200 ft^2/gal (3.7 - 4.9 m^2/L).

Surface Preparation: Forms must be clean, dry and non-porous. Seal porous forms of wood or concrete with MasterFinish PT 100 protective coating, specially formulated to use under a retarder. Once MasterFinish XR retarder has been applied to the form or formliner, it must be protected against rain, condensation, accidental contact with water, etc.

Mixing: Mix thoroughly before use with a mechanical mixer. The retarder can also be mixed by pouring back and forth between buckets.

Application:

1. Apply MasterFinish XR retarder in a thin uniform coat by spray, brush or roller at a rate of 150 - 200 ft^2/gal (3.7 - 4.9 m^2/L) (8 mils (0.2 mm) on wet film thickness gauge). This coverage should be achieved by applying two light coats with a short (3/8 in. (10 mm)) nap roller.
2. Allow the first coat to dry for 30-60 minutes or until dry to touch before applying second coat.
3. The second coat should be applied perpendicular to the first coat with light roller pressure (too thick a coating is undesirable).
4. After the second coat is dry (approximately 30-60 minutes), the concrete or face mix may be placed. If the placing of concrete is delayed any unusual length of time, protect the retarder surface from rain or water.
5. When the element is lifted or the forms are removed, the retarded surface concrete is easily removed by sandblasting, high pressure water-washing or dry-brushing.

Top Surface Application:

1. Paint sprayer must be used. MasterFinish XR retarder may be thinned with water up to 20% to accommodate spraying, but must be mixed thoroughly.
2. Place the concrete and screed, float or trowel level. Do not tamp or overwork the top surface as this drives the aggregate down away from the top surface and thereby diminishes the depth and uniformity of exposure.
3. Use a wood float or bull float to work the top surface. Do not overwork the surface with a steel trowel as this tends to seal the top surface thereby restricting the penetration of the chemical retarder, thus restricting the penetration of the MasterFinish XR retarder.
4. As soon as surface water has disappeared (normally no more than 30 minutes), spray until the color of the retarder just "hides" the area to be exposed. Protect areas adjacent to the job from overspray which may stain these areas. Apply at the rate of 150- 200 ft^2/gal (3.7 – 4.9 m^2/L) (8 mils (0.2 mm) on wet film thickness gauge.)

To Expose Aggregate:

1. Under normal conditions, after the concrete has set overnight, direct a jet of water from a garden hose over the surface of the slab while scrubbing with a coarse floor brush to remove the retarded concrete paste.
2. The concrete not in contact with MasterFinish XR retarder will set firmly to resist erosion; the embedded exposed aggregates will hold securely when the concrete has fully cured.
3. Since retarded concrete will eventually harden, the surface should be checked periodically to determine degree of etch by washing a small area. When the temperature is high, or high early cement is used, check the surface earlier.
4. If the depth is excessive, wait a couple of hours and check the etch again.

Clean Up: Clean all tools and spray equipment with soap and water immediately after use.

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MasterFinish XR Technical Data Sheet

For Best Performance

- Not suitable for large panels (larger than 4 ft by 4 ft (1.2 m by 1.2 m)).
- MasterFinish XR retarder will freeze at low temperatures. Allow to thaw and mechanically mix to bring back to original consistency.
- In conditions of high ambient temperatures or wind, concrete should be covered with black plastic sheeting.
- Recommended maximum concrete temperature is 110 °F (43 °C).
- Do not store in metal spray equipment more than 2-3 hours or in direct sunlight.
- Make certain the most current versions of product data sheet and safety data sheet are being used; call your local sales representative to verify the most current versions.

Mock Up

- Skill and practice are necessary to produce any high quality architectural finish. Samples and mock-ups duplicating actual production conditions are essential to obtain a representative finish for approval prior to commencing production.
- Some important variables that should be controlled as close to actual cast conditions include: retarder coverage rate and method of application, mixture proportions and slump, admixtures, temperature of plastic and cured concrete, vibration, thickness of the element, length of time in form and method of cleaning. This is especially important with light etches which are particularly affected by changing conditions.
- Changes in mixture proportions (cement, sand, aggregate, water), admixture content, temperature and any other factor influencing compressive strength development should be kept to a minimum. If white cement (Type III) is used in the face mix, consult your local sales representative.

Storage and Handling

Storage Temperature: Store in unopened container in a cool, clean, dry area between 40 and 110 °F (4 and 43 °C). Keep containers tightly sealed after opening to maintain shelf life freshness. **Protect from freezing**.

Shelf Life: 2 years when properly stored.

In case of spillage, clean and dispose of in accordance with local, state and federal applicable regulations.

Packaging

5 gal (18.9 L) pails

230 gal (870 L) totes

VOC Content

10 g/L or 0.08 lb/gal, less water and exempt solvents.

Related Documents

Safety Data Sheets: MasterFinish XR retarder

Additional Information

For suggested specification information or for additional product data on MasterFinish XR retarder, contact your local sales representative.

Master Builders Solutions, a brand of MBCC Group, is a global leader of innovative chemistry systems and formulations for construction, maintenance, repair and restoration of structures. The Admixture Systems business provides advanced products, solutions and expertise that improve durability, water resistance, energy efficiency, safety, sustainability and aesthetics of concrete structures, above and below ground, helping customers to achieve reduced operating costs, improved efficiency and enhanced finished products.

Utilizing worldwide resources, the Master Builders Solutions community of experts are passionate about providing solutions to challenges within all stages of construction, as well as the life cycle of a structure. At Master Builders Solutions we create sustainable solutions for construction around the globe.

www.master-builders-solutions.com/en-us page 3 of 4

MasterFinish XR

Technical Data Sheet

Limited Warranty Notice

Master Builders Solutions Admixtures US, LLC ("Master Builders Solutions") warrants this product to be free from manufacturing defects and to meet the technical properties on the current Technical Data Guide, if used as directed within shelf life. Satisfactory results depend not only on quality products but also upon many factors beyond our control. MASTER BUILDERS SOLUTIONS MAKES NO OTHER WARRANTY OR GUARANTEE, EXPRESS OR IMPLIED, INCLUDING WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE WITH RESPECT TO ITS PRODUCTS. The sole and exclusive remedy of Purchaser for any claim concerning this product, including but not limited to, claims alleging breach of warranty, negligence, strict liability or otherwise, is shipment to purchaser of product equal to the amount of product that fails to meet this warranty or refund of the original purchase price of product that fails to meet this warranty, at the sole option of Master Builders Solutions. Any claims concerning this product must be received in writing within one (1) year from the date of shipment and any claims not presented within that period are waived by Purchaser. MASTER BUILDERS SOLUTIONS WILL NOT BE RESPONSIBLE FOR ANY SPECIAL, INCIDENTAL, CONSEQUENTIAL (INCLUDING LOST PROFITS) OR PUNITIVE DAMAGES OF ANY KIND.

Purchaser must determine the suitability of the products for the intended use and assumes all risks and liabilities in connection therewith. This information and all further technical advice are based on Master Builders Solutions' present knowledge and experience. However, Master Builders Solutions assumes no liability for providing such information and advice including the extent to which such information and advice may relate to existing third party intellectual property rights, especially patent rights, nor shall any legal relationship be created by or arise from the provision of such information and advice. Master Builders Solutions reserves the right to make any changes according to technological progress or further developments. The Purchaser of the Product(s) must test the product(s) for suitability for the intended application and purpose before proceeding with a full application of the product(s). Performance of the product described herein should be verified by testing and carried out by qualified experts.

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Brampton, Ontario L6T 4M7
CANADA ■ 289-360-1300

Appendix B: WR Meadows 1600 White Product Data

PRODUCT DATA

W. R. MEADOWS. SEALTIGHT

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AUGUST 2016
(Supersedes August 2008)

1600-WHITE

Wax-Based, Water Emulsion Concrete Curing Compound

DESCRIPTION

The 1600-WHITE series of water-based, white-pigmented concrete curing compounds are wax-based dispersions with selected white pigments. When properly applied, 1600-WHITE forms a premium-grade membrane, which optimizes water retention. The white pigment reflects the sun's rays to help keep the concrete surface cooler and prevent excessive heat buildup.

USES

1600-WHITE is ideal for application on exterior, horizontal surfaces, such as highways, airports, and street and curb paving. 1600-WHITE is not recommended for residential applications. The product provides optimum curing when protection from the sun's heat is desired.

FEATURES/BENEFITS

- When properly applied, provides a premium-grade film, which optimizes water retention.
- Protects by reflecting the sun's rays to keep the concrete surface cooler and prevent excessive heat buildup, which can cause thermal cracking.
- Furnished as a ready-to-use, true water-based compound.
- Produces hard, dense concrete ... minimizes hair checking, thermal cracking, dusting, and other defects.
- Offers a compressive strength significantly greater than improperly or uncured concrete.
- Increases tensile strength for greater resistance to cracking and surface crazing.
- Improves resistance to the abrasion and corrosive actions of salts and chemicals ... minimizes shrinkage.
- Applies quickly and easily with conventional commercial spray equipment.
- VOC compliant.

PACKAGING

5 Gallon (18.93 L) Pails
55 Gallon (208.20 L) Drums

COVERAGE

Approximately 200 ft.^{2}/gal. (4.91 m^2/L). Coverage rates may have to be adjusted in windy conditions.

SHELF LIFE

When stored indoors in original, unopened containers at temperatures between 40° - 90° F (4° - 32° C), optimum performance and best use is obtained within one year of date of manufacture.

TECHNICAL DATA

VOC Content: 59 g/L

SPECIFICATIONS

- ASTM C 309, Type 2, Class A
- AASHTO M 148, Type 2, Class A
- FAA Spec. Item P-610-2.11 (e)
- Complies with all current federal, state, and local maximum allowable VOC requirements, including U.S. EPA, LADCO, SCAQMD, and OTC.

APPLICATION

Surface Preparation … Application equipment must be clean and free of any previously used materials.

Mixing … Any settling or separation in the container must be re-dispersed with gentle agitation prior to use. CAUTION: TO AVOID FOAMING, DO NOT MIX EXCESSIVELY. DO NOT THIN.

Application Method … Spray on in one even coat with a hand or power sprayer, such as a Chapin 1949, as soon as the surface water disappears from concrete surface. Use a spray nozzle that produces a flow of 0.5 GPM (1.89 LPM) under 40 psi (.276 MPa) of pressure.

CONTINUED ON REVERSE SIDE…

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Drying Time … Typically dries in two hours, depending on jobsite conditions (temperature, wind, etc.). Restrict foot traffic for at least four hours.

Cleanup … Immediately clean tools, equipment and overspray with soap and warm water.

PRECAUTIONS
KEEP FROM FREEZING. Do not apply when the temperature of the air and/or the concrete is less than 40° F (4° C). DO NOT MIX OR DILUTE WITH ANY OTHER PRODUCTS OR LIQUIDS. Do not use on surfaces that are later to be painted, tiled, hardened, sealed, or treated in any manner. Do not use on patios, sidewalks, or other areas where there is typically no wheel traffic to abrade the white film surface. Not recommended for use on residential applications.

HEALTH AND SAFETY
Direct contact may result in mild irritation. Read and follow all application, label, precautions, and health and safety information prior to use. Refer to Safety Data Sheet for complete health and safety information.

LEED INFORMATION
May help contribute to LEED credits:
- IEQ Credit 4.2: Low-Emitting Materials - Paints and Coatings
- MR Credit 2: Construction Waste Management
- MR Credit 5: Regional Materials

For most current data sheet, further LEED information, and SDS, visit www.wrmeadows.com.

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Environmentally Responsible Products for Concrete Performance

LIMITED WARRANTY
W. R. MEADOWS, INC. warrants at the time and place we make shipment, our material will be of good quality and will conform with our published specifications in force on the date of acceptance of the order. Read complete warranty. Copy furnished upon request.

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Appendix C: Interface Shear Calculations

Crack propagations along the UHPC-substrate interface were observed in some of the test slabs and therefore, calculations were performed to estimate the horizontal shear stresses at the interface at the time of failure and compare these values to the shear bond strength investigated in Task 2. A similar process was followed as discussed in detail by researchers at Iowa State University [1], following ACI 318 and using the following final equation:

$$V_h = \frac{V}{bd_e}$$

where V_h is the resultant horizontal shear stress, V is the vertical shear force (half of the measured P maximum load for each slab test), b is the width (21 inches for all slabs), and d_e is the distance between the centroid of the tension steel to the mid-thickness of the overlay (overall depth, minus the bottom clear cover, minus half the bar diameter, minus half the overlay thickness). The values used in the calculations are summarized in Table 7.

Table 7: Summary of Interface Shear Calculations

Slab	V (kips)	b (in.)	d_e (in.)	V_h (psi)
O-PR1	14.7	21	4.42	158
O-PR2	16.3	21	4.41	175
O-PW	11.5	21	3.80	143
O-NR	14.9	21	4.59	154

Overall, the maximum horizontal shear stresses at the interfaces ranged between 143-175 psi for all slabs. The average minimum bond shear stress for the Ductal UHPC was found to be 3.24 ksi and was discussed in detail in Task 2 Report. Therefore, the shear bond strength was on average 20.6 times that of the observed horizontal shear stresses at the interfaces during the slab tests. Similar to Iowa's findings [1], these results show that if the shear failures in the substrate concrete had not occurred, the UHPC overlay slabs could have resisted much higher loads before bond failure could have initiated at the interfaces.