MONITORING OF UHPC CONNECTIONS ON EUFAULA SPILLWAY BRIDGE

FINAL REPORT

ODOT TASK ORDER NUMBER 2160-20-08

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Submitted by:

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2003)

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The project described in this report was part of an implementation of ultra-high performance concrete (UHPC) during replacement of the S.H. 71 over Eufaula Spillway Bridge by the U.S. Army Corps of Engineers (USACE) with the Oklahoma Department of Transportation (ODOT) as an interested party. The existing bridge was an eleven-span steel girder bridge with a concrete deck. The system consisted of two primary steel girders and both longitudinal and transverse floor beams. Significant deterioration of the girders had been observed prompting replacement. Due to the significant space constraints resulting from the spillway gates and associated equipment, the design for the replacement bridge was selected to also consist of a two-girder system and utilize the original piers (with modification). However, precast, prestressed beams were utilized for the primary girders and full depth precast, prestressed deck panels were designed to span between the two girders. The panels and girders were connected with UHPC to create a composite system. This was the first time UHPC was used in this application in Oklahoma and the primary contractor on this project also had no previous experience using and placing UHPC. This Task Order allowed for an expert on UHPC from the University of Oklahoma to provide input on the required mock-up test, be on site to observe during UHPC placement, provide input during the process, and monitor performance of both the mock-up and bridge joints.

Several issues were identified during mock-up construction that could be corrected before placement on the bridge. This included procedures used for charging the mixers, transport from the mixers to the formwork, and materials used to form the joints. Several lessons learned were identified during the process of casting the mock-up and bridge joints that are documented in the report. In general, the bridge UHPC joints were placed successfully and performed very well. Cores taken from the mock-up joints indicated excellent bond between the UHPC and the deck panel concrete. Only one crack was observed on the in-place bridge joints.

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1.0 Introduction

1.1 Overview

The project described in this report was part of an implementation of ultra-high performance concrete (UHPC) during replacement of the S.H. 71 over Eufaula Spillway Bridge by the U.S. Army Corps of Engineers (USACE) with the Oklahoma Department of Transportation (ODOT) as an interested party. Figure 1 shows an overview of the bridge site after the original bridge had been removed. The existing bridge was an eleven span steel girder bridge with a concrete deck. The system consisted of two primary steel girders and both longitudinal and transverse floor beams. Significant deterioration of the girders had been observed prompting replacement. Due to the significant space constraints resulting from the spillway gates and associated equipment, the design for the replacement bridge was selected to also consist of a two-girder system and utilize the original piers (with modification). However, precast, prestressed beams were utilized for the primary girders and 14 in. thick full depth precast, prestressed deck panels were designed to span between the two girders. The panels and girders were connected with UHPC to create a composite system. In general, the bridge was laid out such that a deck panel spanned the pier between each two sequential spans so that the deck was continuous across the two spans.

Figure 1. Lake Eufaula spillway after demolition of existing bridge

This was the first time UHPC was used in this application in Oklahoma. The USACE also required a mock-up test of a full slab panel connection before placement of the bridge deck joints. This project allowed an expert from the University of Oklahoma to provide input on the mock-up test, be on site to observe during UHPC placement, provide input during the process, and monitor performance of both the mock-up and bridge joints. Services provided included providing technical input on placement methods and general use of UHPC on the Eufaula Spillway Bridge replacement, providing monitoring of the UHPC mock-up and bridge connections, and conducting limited quality assurance compression testing. The OU research team was involved in the planning process, was present at multiple pre-construction meetings, was on site on the day of mock-up casting, was on site for two of the deck joint placements and monitored performance of the mock-up over time.

Primary activities of this Task Order were originally planned to occur in November and December 2020 but were shifted to April to October 2021 with the adjustment of the construction timeline and mock-up placement by the primary contractor.

1.2 Problem Statement

The full-depth precast deck panels connected with UHPC used for the Eufaula Overflow bridge was the first time UHPC was used in this application in Oklahoma. The primary contractor on this project also had no previous experience using and placing UHPC. This Task Order allowed for an expert from the University of Oklahoma to provide input on the required mock-up test, be on site to observe during UHPC placement, provide input during the process, and monitor performance of both the mock-up and bridge joints.

1.3 Project Objectives

The objectives of the Task Order were designed to leverage the experience of the PI to provide technical input with potential to help avoid problems during UHPC placement. Independent observations by a technical expert would also provide lessons learned that can be used by ODOT to conduct projects involving UHPC smoothly in the future. These objectives were:

1) Provide technical input to USACE and contractor personnel during the planning and construction process,
2) Monitor the UHPC mock-up to identify any possible problems that should be addressed during deck placement,
3) Provide UHPC material testing support as required,
4) Document lessons learned that can successfully be used on subsequent ODOT construction projects utilizing UHPC.

This report is intended to provide information and guidance ODOT can use to implement UHPC bridge connections and repairs.

1.4 Ultra-High Performance Concrete (UHPC)

1.4.1 Overview

Ultra-High Performance Concrete (UHPC) is a cementitious composite material with increased durability and strength properties compared to NSC. UHPC was first developed in the late 20th century and is a product of advancements in superplasticizers, fiber reinforcement, supplementary cementitious materials, and optimized gradation of dry materials (Graybeal 2014). Its properties differ from those of typical portland cement concrete, so many of the methods for casting UHPC and determining its fresh and hardened material properties have been modified from the methods used for conventional concrete. UHPC has been successfully used in multiple applications related to connection of precast concrete bridge components due to its superior bond development characteristics with steel reinforcement, ease of placement, and long-term durability compared to conventional concrete. The long-term benefits of using UHPC in many applications are evident, but commercially available proprietary mixture formulations are very expensive and mix design using local materials is much more complicated than for conventional concrete.

The superior mechanical properties of UHPC allow for the optimization of structural elements, including bridge girders, where the enhanced tensile strength can lead to the elimination of mild steel shear reinforcement (Graybeal 2006). It can also be used to construct relatively lightweight deck systems (Aaleti et al. 2014). The cost of commercially available UHPC is often approximately 10-20 times that of conventional concrete due to the high cementitious materials content and fiber reinforcement, but the superior mechanical properties and durability have led to much recent interest in applications where small amounts can be used for long-term gain (Graybeal 2011). Such applications include connections between precast bridge components such as deck panels, deck bulb-tee girders, and adjacent box girders. Other applications of UHPC include precast piles, seismic retrofits, thin-bonded overlays for deteriorated decks, and blast mitigation (Graybeal 2011). UHPC formulations can also be made with local materials (e.g. Wille et al. 2011) in order to reduce costs.

Connections cast using UHPC can extend the life of a structure and allow for less maintenance over time. Joints replaced or connections made using this material will have better durability, better resistance to impacts and abrasion, and will allow for a smaller quantity of material to be used while still obtaining adequate load transfer between connected components. Using UHPC allows for small, simple connections without the need for post-tensioning (when connecting precast elements) or large amounts of field-cast concrete (Graybeal 2010). Joints cast using UHPC also tend to behave more like monolithic construction than typical field-cast connections. The use of UHPC for connecting precast elements has been the focus of many cases studies and research projects. It has also been studied as an overlay material to repair and/or extend the life of existing bridges. However, the use of UHPC as a repair material for existing joints in bridges has not been extensively studied.

1.4.2 Material Properties

The Federal Highway Administration (FHWA) has performed extensive investigation of the properties of UHPC for use in bridge and other infrastructure components (Graybeal 2011, Graybeal 2014). FHWA defines UHPC as “a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking tensile strength greater than 0.72 ksi (5 MPa). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability as compared to conventional and high-performance concretes" (Graybeal 2011). The post-cracking tensile strength is such that it can be included in design of structural elements.

In order for UHPC to be a more valid material for everyday practice in the bridge community, several studies funded by FHWA have extensively examined UHPC material properties (Graybeal 2006, Graybeal and Stone 2012, Graybeal and Baby 2013, Swenty and Graybeal 2013). The authors followed the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) recommended procedures for the material characterization tests that would typically be done on conventional concrete. In some cases, the authors had to modify or develop new tests to adequately test specimens to get useful information due to the vast differences in material properties. These studies found the tested formulations to have the typical material properties shown in Table 1 if cured in field conditions and deployed with 2% steel fibers by volume.

Table 1. Typical material properties of field-cast UHPC (taken from Graybeal 2014)

Characteristic	Average Result
Density	155 lb/ft^3 (2,480 kg/m^3)
Compressive Strength (ASTM C39, 28-Days)	24 ksi (165 MPa)
Modulus of Elasticity (ASTM C469, 28-Days)	7,000 ksi (48 GPa)
Direct Tension Cracking Strength	1.2 ksi (8.5 MPa)
Split Cylinder Cracking Strength (ASTM C496)	1.3 ksi (9.0 MPa)
Prism Flexure Cracking Strength (ASTM C1018)	1.3 ksi (9.0 MPa)
Long-Term Creep Coefficient (ASTM C 512,11.2 ksi (77MPa) Stress)	0.78
Long-Term Shrinkage (ASTM C 157, initial reading after set)	555 με
Total Shrinkage (embedded vibrating wire strain gage)	790 με
Coefficient of Thermal Expansion (AASHTO TP60-00)	8.2 x 10^{-6} in./in./°F (14.7 x 10^{-6} in./in./°C)
Chloride Ion Permeability (ASTM C1202, 28-day test)	360 coulombs
Chloride Ion Permeability (AASHTO T259, 0.5 in. (12.7 mm) depth)	<0.10 lb/yd^3 (<0.06 kg/m^3)
Scaling Resistance (ASTM C672)	No scaling
Abrasion Resistance (ASTM C944 2x Weight, ground surface)	0.026 oz. (0.73 g) lost
Freeze-Thaw Resistance (ASTM C666A, 600 cycles)	RDM = 99%
Alkali-Silica Reaction (ASTM C1260, tested for 28 days)	Innocuous

Note: RDM = relative dynamic modulus

2.0 Mock-up Construction and Performance

2.1 Overview

The mock-up section consisted of two representative girders and three full-depth precast panels matching the design for the bridge. This configuration resulted in two full-width joints, twenty shear pockets, and the haunches over each girder to be placed with UHPC. An overall view of the completed mockup with the joints and shear pockets visible is shown in Figure 2. The bridge deck will be covered with an overlay, so the mockup panels were also roughened to the proper surface condition. As with the final bridge construction the panels were cast with an exposed aggregate surface in the area of the UHPC joints and the connection was made with a non-contact lap splice of epoxy coated reinforcing bars, as shown in Figure 3. Each shear pocked contained four steel shear studs as shown in Figure 4. Shear studs were welded in place after placement of the deck panels to a steel plate embedded in the girder top flange (Figure 5). The configuration of the shear studs led to no connecting steel reinforcement in the panels along the girder lines.

Figure 2. Overall view of the bridge deck mock-up

Figure 3. Close up of joint exposed aggregate surface and epoxy coated bars

Figure 4. Shear studs visible in one of the mock-up shear pockets

Figure 5. Steel plate embedded in the prestressed girder top flange for placement of steel shear studs

2.2 Planning

Dr. Floyd reviewed plans for the proposed joint mock-up and provided input by email to USACE personnel in advance of a project meeting held on October 26, 2020. The primary point of discussion was whether the mock-up joint placement planned for November 2020 should be postponed to April 2021 if the construction schedule was revised such that slab joints in the bridge would not be placed until May 2021. Dr. Floyd attended the project meeting between the contractor, USACE, and LafargeHolcim (the UHPC manufacturer) representatives on October 26, 2020 to provide the same input to the contractor. The revised construction timeline and plans for the mock-up to be placed in November 2020 were discussed along with expected UHPC mixing and placement procedures. Dr. Floyd, USACE personnel, and the LafargeHolcim representatives recommended that the mock-up should be placed within one month of the actual joint placement so that the contractor could have a better assessment of the placement methods in similar temperature and weather conditions. The outcome of the meeting was to postpone mock-up placement to April 2021 (later revised to May 2021) to better match with the revised bridge construction schedule.

In advance of the mock-up placement several emails were exchanged with USACE personnel during the months of March and April 2021 to discuss plans for both for mock-up and bridge joint placement and to plan for an inspection of the bridge site and mock-up and for in-person meeting with USACE and contractor personnel in advance of mock-up placement. Dr. Floyd compiled materials related to material and construction specifications for UHPC identified during previous projects (Floyd et al. 2021a, Floyd et al. 2021b). This information was then provided to USACE personnel working on the project to aid their planning.

An onsite pre-placement meeting with USACE and contractor personnel attended by Dr. Floyd was held on May 18, 2021, where the formwork, mixing process, placement process, curing, and grinding for the mock-up UHPC were described by the contractor. Dr. Floyd provided input as requested relative to formwork construction and placement methods. Dr. Floyd examined the prepared mock-up after this meeting and pointed out some concerns about sealing of the formwork to USACE personnel that were addressed with the contractor.

Dr. Floyd and the student working on the project attended an additional onsite meeting immediately prior to mock-up placement on May 26, 2021. At this meeting the contractor described the plans for mixing and placement of the UHPC for the mock-up and the different joint end types and bottom formwork that would be examined in the mock-up. Joint end details examined included chamfers around the edge of the joint end, a form insert into the end of the joint, and flat formwork flush with the slab. A small galvanized angle and foam insulation board cut to a V-shape were examined as alternatives for sealing the bottom of the joint during UHPC placement to determine which was most efficient for adequately sealing the joint and providing proper UHPC cover on the joint reinforcement. The two options are shown in Figure 6. Additional items addressed at this meeting included discussion of approximately 1.5 hours of material workability after discharge from the mixer, need to keep mix temperature between 50 °F and 90 °F, flow between 8.5 in. and 9.25 in. for the mock-up, and ice requirements. Formwork preparation was also discussed, and it was indicated that small water leaks (small drips) during the required water tightness test were not of consequence, while a steady flow of water out of the formwork was unacceptable. Dr. Floyd provided input as requested on formwork, placement methods, curing, and strength testing. It was agreed that OU personnel would conduct the 1-day compressive strength tests on the UHPC material for the mock-up and the bridge placements. Testing at other ages would be conducted by a commercial testing laboratory in Kansas City, MO.

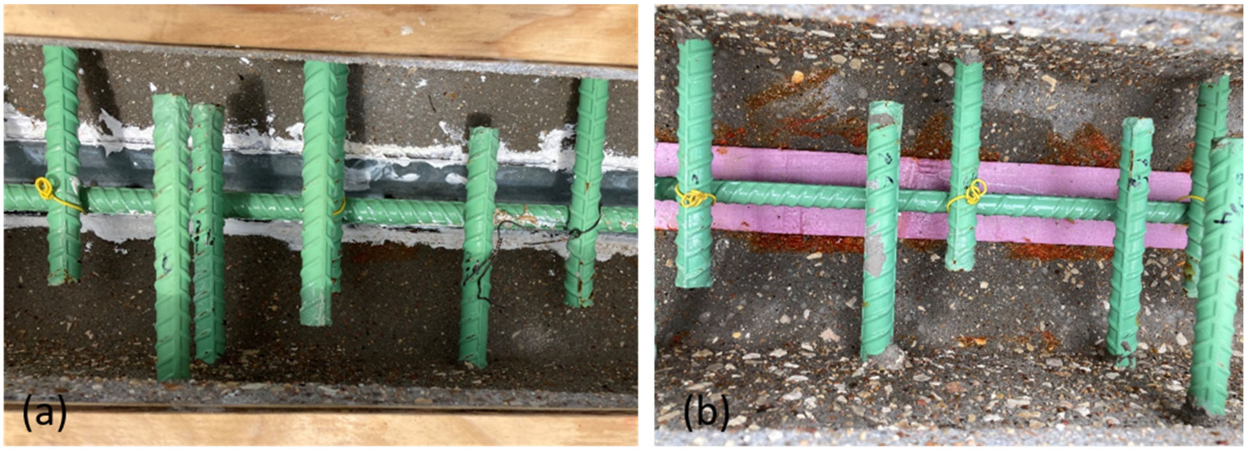

Figure 6. (a) Galvanized angle and (b) insulation foam investigated as possibilities for forming the bottom of the UHPC joints

2.3 Mock-up Placement

Dr. Floyd and the student working on the project were present during mock-up placement on May 26, 2021. They took photos of the placement process and answered questions posed by the USACE personnel as requested.

The joint formwork was tested for watertightness by filling with water in advance of the UHPC placement. Substantial leaks were observed that were filled with caulk before a subsequent water test. The final water test resulted in only very small water leaks. Care was taken to ensure the exposed concrete surfaces were prewetted to a saturated surface dry condition by filling the joints with water, draining, and vacuuming out any excess water.

UHPC placement for the mock-up began at approximately 1:00 pm on May 26, 2021. The UHPC material utilized for this project was Ductal® JS1000 which included premix in pre-weighed supersacks of 2400 lb each, steel fibers included at 2% by volume, and a high range water reducing admixture (HRWR). Approximately 25% of the required mixing water was added as ice for the mockup in order to control temperature of the UHPC material since the ambient temperature that day was in excess of 80 °F.

There were two stationary mixers on-site, shown in Figure 7, and batches were offset between the two mixers to ensure a near continuous flow of material. Each batch was approximately 0.66 yd^3 in volume and consisted of one supersack of premix, approximately 34 lb of HRWR, approximately 122 lb of water, and 4 bags of steel fibers. The premix was first placed into the mixer using a construction forklift (Figure 8), then the water and HRWR were added by members of the construction crew. The steel fibers were added last, once the UHPC material reached a fluid consistency. Each UHPC batch took approximately 20 minutes to mix before pouring it into the joint. There was a delay in pouring the UHPC for some batches due to issues with adding the steel fibers to the mixers. The steel fibers were blocked from going down into the mixer due to small openings in the grates on the top of the mixers, so contractor personnel manually stirred the fibers to get them to pass through the grates into the batch while the mixer was still operating. The increased time required for mixing affected the workability of the UHPC as it increased the temperature of the concrete and slowed down the placement process of the UHPC joint which allowed the workability of the material already in the joints to decrease. Flow and temperature were measured by the UHPC manufacturer's representative after each batch, and while the OU team did not take additional measurements, they did observe visually adequate flows.

Upon reaching adequate combination of the steel fibers with the other materials, the UHPC was discharged from the mixers into wheelbarrows and transported to the joint locations (Figure 9). Material was discharged directly into the joints using a piece of plywood to help direct material into the joint as shown in Figure 9. Placement was begun near the lowest point of the cross slope and material was allowed to fill the joint

Figure 7. High shear mixers used for mixing UHPC for the full-scale mock-up

Figure 8. Placement of the UHPC premix into one of the stationary mixers

Figure 9. Placement of UHPC into transverse deck joints of the mock-up

and flow “uphill” under the head pressure of the material. Once the joint was nearly full a form top was placed on a section of the joint and attached to the deck using concrete screw anchors. The placement point was then moved along the joint. Buckets with holes in their bottoms were connected to holes in the top form at approximately 8 ft intervals along the joint length and UHPC was added to these buckets to maintain head pressure on the UHPC in the formwork (Figure 10). The material was allowed to flow along the joint and through the haunch into the shear stud pockets, but new material was always placed into already placed material. Any point where two flows combined, external consolidation using steel rods was utilized to ensure adequate combination of the material. In some cases, the shear pockets were topped up to ensure they were completely filled. Most of the shear pockets had formwork tops in place before placement of the UHPC, but many of these had to be removed to ensure proper filling with material. A hammer was used to sound formwork tops to ensure each section was filled with material.

Figure 10. Top formwork placed on completed UHPC placement and head buckets in place

During the UHPC pouring process, leaks were observed in a few locations of the connection. The nature of the UHPC is more complex than other kinds of concrete; it has a very high flowability and it produces a higher hydrostatic pressure on the formwork. Thus, the UHPC can cause expansion to small leaks and create more substantial leaks, potentially blowing out the formwork. Some locations in the connection experienced a significant leak, especially at locations where the panel joint intersected the girder or at the end of a haunch were an end of span bulkhead might be placed on the actual bridge (Figure 11). This was due to filling a larger volume of UHPC that created more pressure on the formwork along with little vertical pressure at the gap between panels. The side forms of the haunch along the girders were pieces of pink foam insulation held in place by the weight of the panels on top of the insulation. It was also noted that some of the silicone caulking used to seal the joints had not set by the time of UHPC placement. The leak issue was solved by the contractor applying additional spray foam and formwork bracing as shown in Figure 11, and contractor personnel kept monitoring the connection for any potential leaks while pouring the UHPC. They successfully managed to stop all leaks, but this process did require accessing the forms from the underside, which could be problematic during placement on the bridge.

Figure 11. Bracing and spray foam utilized to stop a leak at a (a) deck joint to girder intersection and (b) end of the haunch

As UHPC placement progressed, it was noticed that the exposed deck panel surfaces within the joints had begun to dry out. A water hose was utilized to provide a directed misting spray to these surfaces to return them to a prewetted condition. Top forms were removed from some of the shear pockets that had remained covered throughout UHPC placement to observe the concrete surfaces in these areas. It was noted that the covered sections had remained damp throughout the placement.

At the end of the pouring process, external vibration methods, like rodding and tapping with a hammer, were used to ensure filling the voids in the panel connection.

The high ambient temperature on that day had decreased the fluidity of the UHPC and caused a skin to begin to form on the top of the UHPC placements. Additionally, the buckets attached to the top of the form were not continually filled with UHPC. That means as the UHPC started to settle more, the joint would have an empty area at the top, potentially affecting the performance of the connection. This can be avoided by overfilling the connection by pouring UHPC in the buckets as they serve as an overpressure source for this kind of connection.

Dr. Floyd and the student working on the project attended an onsite post-placement meeting with USACE and contractor personnel on June 3, 2021, to discuss lessons learned from the mock-up placement and plans for remediation of any issues observed. Dr. Floyd provided input as requested relative to issues observed during mock-up placement. He also provided input directly to USACE personnel before the meeting to allow them to be prepared with questions for the contractor.

2.4 Mock-up Monitoring Over Time

2.4.1 Overview

It was decided by the USACE personnel that no instruments would be installed in the mock-up, and the instruments that had been prepared for this purpose were not put into place. The mock-up was instead monitored with visual inspections and cores taken from the joint locations. Photos were taken of the mock-up before and after UHPC placement for use in continued monitoring.

2.4.2 General Observations

The completed mock-up was examined after the lessons learned meeting on June 3, 2021 and all visible joint locations were carefully documented with photographs and handwritten observations to provide a baseline for follow-up inspections. In general, the mock-up joints looked very good, with very little observed cracking between the joint material and base concrete. An overall view of the mock-up joints and a close-up view of one location are shown in Figure 12. Note that all joints had not been ground to allow for examination of multiple grinding methods. A close-up view of the completed ground surface for one of the shear pockets is presented in Figure 13 to show the texture.

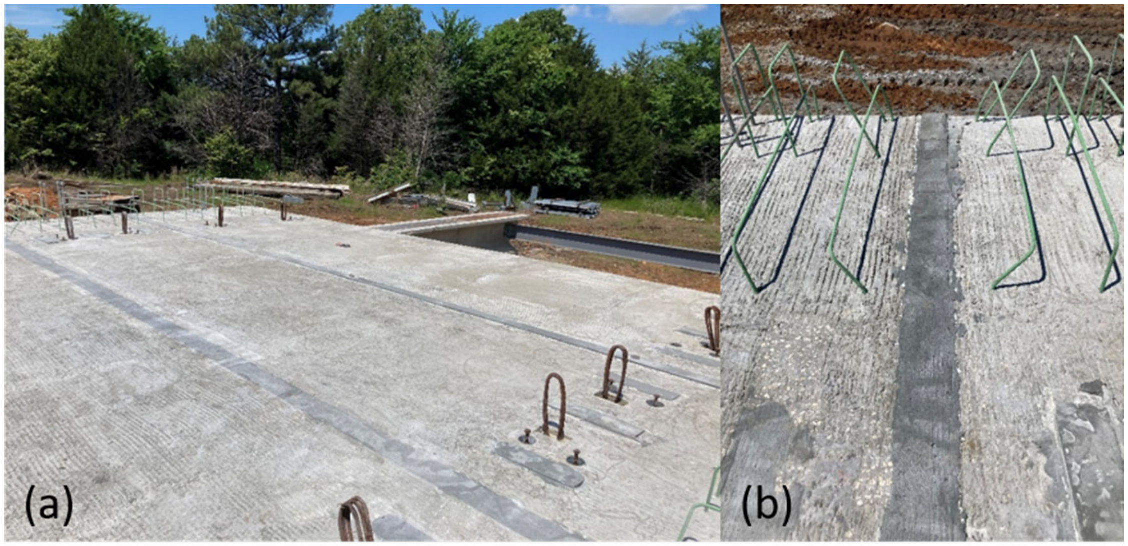

Figure 12. (a) Overall view of the mock-up joints and (b) close-up view of one joint and two shear pockets near the sidewalk and guardrail location

Figure 13. Close-up view of ground UHPC shear pocket to show texture after grinding

There were a few cracks observed in the mock-up bridge deck after seven days of placement. There was a crack in one of the deck panels near the joint caused by placement of anchors to attach the formwork top to the panel too near the joint location (Figure 14). Based on these observations, the contractor planned to place anchors further away from the joints to reduce the possibility of similar cracking in the bridge placements. Another crack was noticed at the interface between the deck panel and one of the connections. This crack could be due to shrinkage in the UHPC or poor bonding at the interface due to inadequate surface prewetting.

Figure 14. Crack alongside UHPC joint caused by formwork anchors

It was noted that several of the shear pockets were not filled to the top during placement of the UHPC and in these cases the formwork tops were removed, and the shear pockets filled directly with UHPC to complete the placement. However, several of the shear pockets were not filled above the level of the deck when the formwork was removed (Figure 15). This effect was likely caused by a combination of lost flowability over time, the overall thickness of the slab, and the limited amount of UHPC placed in the head buckets. The accessible end of the girder haunch was examined and appeared to be completely filled and have adequate consolidation, as shown in Figure 16.

The OU research team performed a detailed examination and took detailed photos of the mock-up on August 17, 2021, but no changes from the original inspection in June or additional items of interest were noted.

Figure 15. Close-up view of a shear pocket where the UHPC did not extend above the top of the slab as intended

Figure 16. Photo of the end of the UHPC haunch showing that the forms were filled at the farthest location from the placement points

2.4.3 Lessons Learned

The lessons learned meeting addressed the improvements to the mixing and placement process that could help in the actual placement of UHPC on the bridge, which was at the time anticipated for the beginning of August. Forming methods, the mixing process, placement of the UHPC, and grinding methods were all discussed in the meeting. In terms of forming, using foam board instead of galvanized steel on the bottom of the joint was determined to be the best option as it provided the better seal and reduced water evaporation. Pictures of the two joint fill materials taken from below after joint placement are shown in Figure 17. More spray foam is visible for the steel angle location indicating that more leaks had to be sealed for this detail. However, the contractor also planned to investigate using a plastic angle since the angle provided less intrusion of the formwork bottom into the joint and ensured the desired 2 in. to 3 in. bottom cover on the joint reinforcement. Joint end formwork options examined in the mock-up included chamfers around the edge of the joint end, a form insert into the end of the joint, and flat formwork flush with the slab. The joint end with a formwork insert provided the best performance, as shown in Figure 18. Leakage to the sides of the joint end was observed when using a flat surface and leakage at the bottom resulted in a fiber ball where the paste leaked out from around the fibers (Figure 18a).

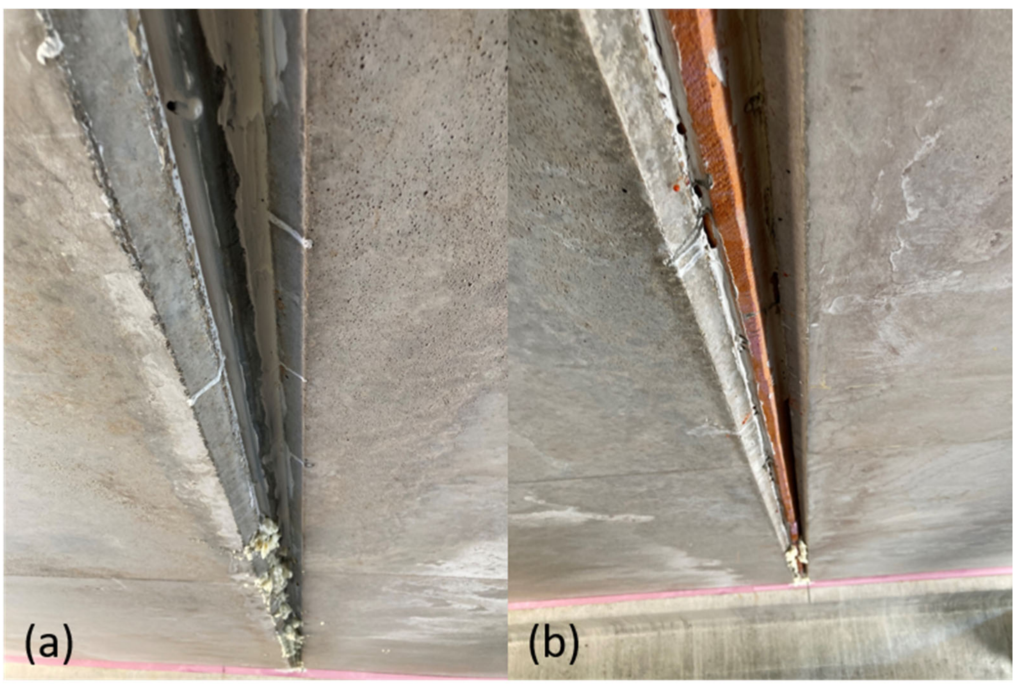

Figure 17. Of joint formwork bottom materials used in the mockup (a) steel angle and (b) pink insulation foam cut into a wedge shape

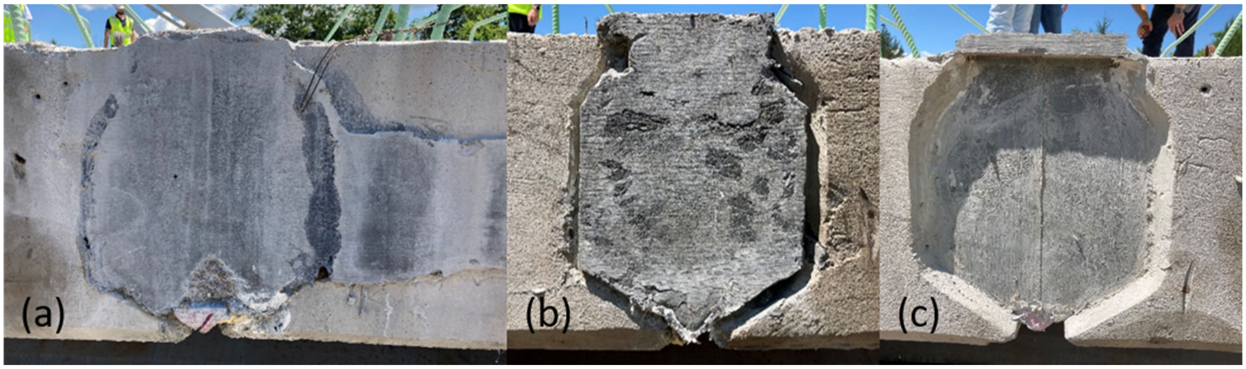

Figure 18. Joint ends examined in deck joint mock-up (a) flush end, (b) chamfered edges, and (c) formwork insert

The contractor expressed a plan to utilize Sika high grade caulk instead of typical caulking materials to provide a better seal at the formwork joints and intent to limit the amount of caulking as much as possible to avoid contamination of the deck panel surface in the joint. It was also discussed how to maximize the bond of the UHPC to the deck panel concrete using proper surface wetting, which included keeping the joints covered with formwork until the UHPC is brought to the joint to reduce evaporation. Covering the joint with a form after placing UHPC and between placements would help reduce exposure of the UHPC to direct sunlight and resulting dehydration that may occur if the ambient temperature exceeds 80 ºF during actual placement.

Other solutions identified during the meeting included modifying the mixer to allow for faster charging with steel fibers, increasing the crew on each mixer from one to two individuals, and preweighing all materials. An additional solution suggested was to use motorized buggies with a larger capacity for transporting the materials from the mixer to the joints and manual wheelbarrows with a designated individual to maintain material in the head bucket chimneys. However, mixer placement on the bridge had not been determined at this point pending analysis of the panels to support the mixer loads before the joints were placed. The two options considered were to place material beginning at the south end of the bridge always supporting the mixers on completed panels, or to place the joints beginning at the north end of the bridge and to locate the mixers on panels supported only by the leveling bolts.

A walk-behind grinder was used for removing the sacrificial top surface of the joints, which produced a good surface as shown in Figure 12. Use of this grinder required bending of the reinforcing bars to be used for the sidewalk and guardrail, so it was discussed that the sections in the sidewalk area do not need to be ground since they will be covered with the sidewalk concrete. Additional discussion on the grinding requirements in the sidewalk locations was held by email after the meeting. A hydrojet was also considered for removing the sacrificial portions of the joints but was ultimately not used.

2.4.4 Mock-up Core Samples

Plans were made for taking cores from the mock-up joints to evaluate bond of the UHPC to the slab concrete and consolidation of the UHPC. It was decided that at least one of these cores should be taken at the interface of the joint and slab concrete to capture the interface behavior and at least one from one of the shear pockets to obtain a sample of the UHPC with no reinforcing bars or base concrete.

The OU research team cut three cores from the mock-up joints on August 17, 2021, to evaluate bond of the UHPC to the slab concrete and consolidation of the UHPC. Two cores were taken at the interface of the UHPC joint and slab concrete to capture the interface behavior and one was taken from the UHPC in one of the shear pockets. The coring operation is shown in Figure 19. One of the cores taken from the joint interface purposefully included a reinforcing bar to see consolidation around the bar and a core was taken from a shear pocket to obtain a sample of the UHPC with no reinforcing bars or base concrete. Photos of the cores are shown in Figures 20-22.

Figure 19. Coring of the bridge mock-up at the joint interface

A crack or interface was visible between the deck concrete and UHPC in Core 1, as shown in Figure 20. Core 1 was taken from a slab joint section placed near the end of the mock-up placement sequence. At that point in the placement the material had begun to stiffen up. However, it is not entirely clear whether the observed crack was present in the mock-up or was a result of the coring process. The core was taken very close to the edge of the slab panel and the core broke while it was being cut. A section was cut through the core to see how far the crack propagated along the interface, which is also shown in Figure 20. This interface would not affect the development of the reinforcement in the joint but could potentially allow water into the joint and cause deterioration of the deck concrete.

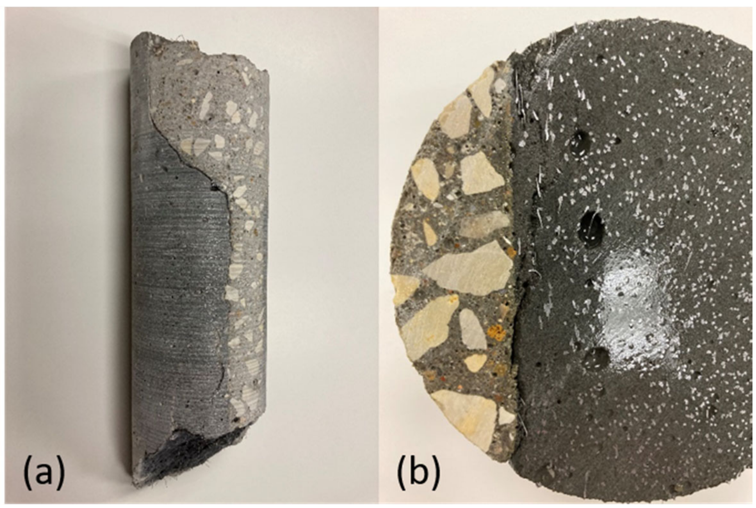

Figure 20. Core 1 taken from the UHPC to deck concrete interface showing (a) the separation at the UHPC to deck concrete interface and (b) a section through that interface (right)

Core 2 (Figure 21) was taken from a shear pocket near the end of the mock-up placement and exhibited excellent consolidation with only minor air pockets visible. Fibers were clearly distributed throughout the core as well. Core 3 (Figure 22) was located such that it would include one of the reinforcing bars being spliced within the joint and to ensure the core was approximately half in the UHPC and half in the deck slab concrete for the majority of the core length. This core was taken from a joint near the middle of the mockup width and middle of the mock-up placement. The interface between the UHPC and slab concrete appeared to be flawless, and the reinforcing bar was completely encapsulated by the UHPC.

Figure 21. Core 2 taken from a shear pocket showing UHPC consolidation and fiber distribution

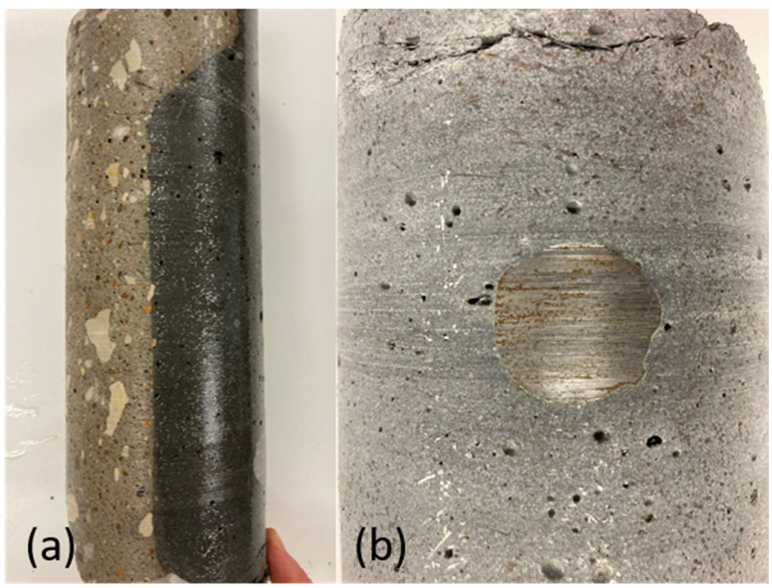

Figure 22. Core 3 taken from a shear pocket showing UHPC consolidation and fiber distribution

Core 3 was cut to length and tested as a splitting tensile strength cylinder using the methods of ASTM C496 to assess the bond between the UHPC and conventional concrete. The prepared core had an average diameter of 3.72 in. and length of 3.99 in. The interface of the conventional concrete and UHPC was nearly centered within diameter of the core and the cylinder was loaded along this interface as shown in Figure

23. The specimen failed along the interface, as shown in Figure 23, at a load of 19,800 lb resulting in a tensile stress of 850 psi. However, since the interface was not perfectly centered within the core the UHPC portion was still able to sustain load after failure and before the machine could be stopped which means that the actual failure strength may have been closer to 800 psi. This is still greater than the 500 to 600 psi that would be expected for the conventional concrete used in the deck panels indicating that the interface bond was better than the base concrete strength. Figure 24 shows a picture of the core after testing and the UHPC that was still bonded to the conventional concrete.

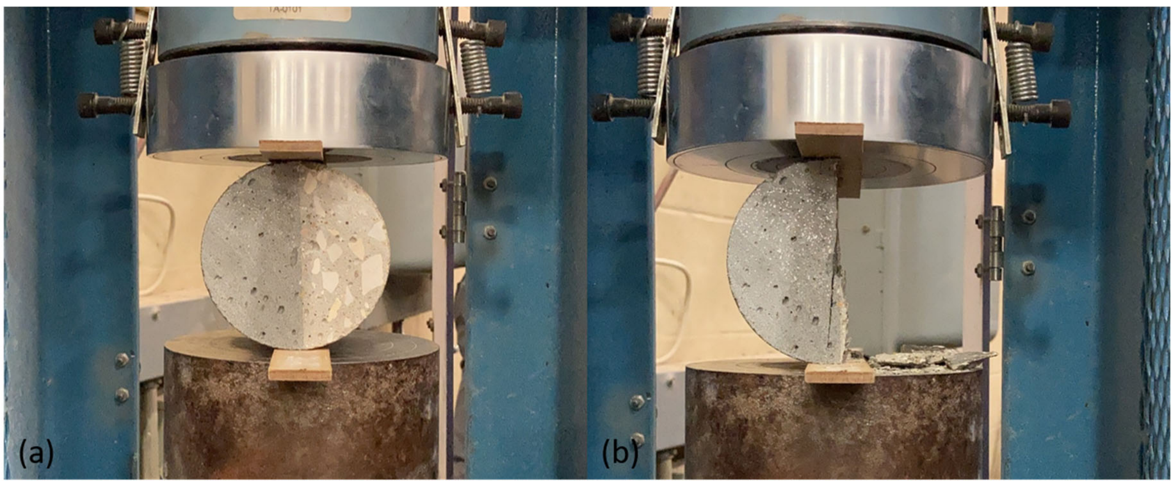

Figure 23. Interface core (Core 3) splitting tensile strength specimen (a) during test and (b) at failure

Figure 24. Core used to test strength of the conventional concrete to UHPC interface after testing

2.5 Compressive Strength Testing

All compressive strength cylinders were cast from the last batches of UHPC used for the mock-up completed at approximately 4:00 pm on May 26. Three of the cylinders taken at the end of the day were transported to Fears Structural Engineering Laboratory on the OU campus by contractor personnel and were tested after 24 hours (on May 27) using the methods of ASTM C1856 and C39. Ends of the cylinders were ground plane to the requirements of ASTM C1856 before testing. The average compressive strength of the cylinders tested at the OU research facility was approximately 8 ksi, which was more than the expected value of 6 ksi. The transport of the cylinders and placing them at a warm temperature may have accelerated the compressive strength gain of the UHPC.

2.6 Summary

In general, the mock-up was placed successfully, and the resulting joints were of very good quality in spite of the issues encountered during placement. However, the purpose of the mock-up construction was to allow the contractor time to become familiar working with the material in a situation with limited consequences and to identify any issues in methods that needed to be corrected. Several items were identified that allowed for solutions to be formulated before placements on the actual bridge commenced.

3.0 Deck Joint Placement

3.1 Overview

UHPC joint placement was conducted beginning with the southwest end of the bridge proceeding northeast. This allowed for the mixers to be situated at first on the bridge approach and then subsequently on completed spans while still allowing for short transport distances from the mixers to the joints. After placement of the mock-up it was decided that the joints for the first few spans would be placed as individual spans instead of the original plan of placing two spans at a time. A bulkhead was placed at each continuous deck pier location to allow for stopping the UHPC flow in the haunch at that point. The first three spans were placed individually. It was also decided that placements would initially be at night due to high daytime temperatures and to reduce drying effects from the sun observed during the mock-up placement. Approximately 11 yd^3 of UHPC was required for the joints in each span and the material was mixed in 16 to 17, 0.75 yd^3 batches. Joints for Span 1 were cast overnight beginning on August 19, 2021, joints for Span 2 on September 7, 2021, and joints for Span 3 on September 8, 2021. After the first three spans the contractor felt comfortable enough with the material to cast joints for two spans at a time for the rest of the bridge. Joints for Spans 4 and 5 were cast overnight on September 27, 2021, joints for Spans 6 and 7 overnight on September 29, 2021, and joints for Spans 8 and 9 during the day on October 25, 2021. By late October daytime temperatures had reduced to the point that no detrimental effects were expected from daytime placement. A manufacturing issue for some of the panels on Spans 10 and 11 led to a delay in those joints being placed and at the time of this report those joints had not yet been placed.

3.2 Initial Joint Placement

Dr. Floyd and the student working on this project attended an onsite meeting with USACE and contractor personnel on August 17, 2021 held to discuss preparations for the first span UHPC joint placement. Dr. Floyd provided input as requested relative to mixing and placement. He also provided input directly to USACE personnel before the meeting to allow them to be prepared with questions for the contractor. One item in question was whether it would be appropriate to switch from the wheelbarrows used for placement of the UHPC during the mock-up construction to a concrete bucket moved using the overhead gantry crane in place on the bridge for girder and panel placement. This placement method had been used successfully at Fears Lab and the OU team recommended allowing the change. It was decided to use pink insulation foam board as the material to seal the bottom of the joints as this material produced the tightest seal and provided adequate concrete cover below the joint reinforcement during mock-up placement.

The joints for bridge Span 1 were cast on the night of August 19, 2021 with Dr. Floyd and the student working on the project in attendance. The joints prepared for UHPC placement are shown in Figures 25 and 26. Plywood strips were placed on the deck between the deck and the form top to create a 0.25 in. UHPC height above the deck for later grinding. Figure 27 shows the foam insulation and high grade caulking used to seal the bottom of the joint. The joint formwork had been water tested to ensure that it did not leak and to saturate the concrete surfaces in the joints. The water was drained and suctioned with a shop vacuum before UHPC placement began.

Figure 25. Bridge deck immediately before Span 1 joint placement

Figure 26. Joint prepared for casting and showing splice reinforcement

Figure 27. Foam insulation and caulk used to seal the bottom of the joint

The placement was started at approximately 7:50 pm and the anticipated 11 yd^3 of UHPC was to be mixed in 16, 0.75 yd^3 batches. Two mixers were used to mix the UHPC material (Figure 28) as done in the mock-up placement and the batches were spaced out by approximately 5 minutes to allow for near continuous mixing. The mixers utilized on the bridge were vertical axis high shear mixers rather than the horizontal axis mixers used in the mock-up but had the same mixing capacity. The change was made to allow for faster placement of the steel fibers in order to reduce overall mixing time. No difference was observed in the quality of the material coming out of the mixers relative to those used in the mock-up. The mixers were charged using methods very similar to the mock-up, where the dry material was placed in the mixer from a supersack hoisted into place with a construction forklift as shown in Figure 28. Water, ice, and HRWR were then added from buckets by contractor personnel on the mixers, and finally the steel fibers were added after the mix had become fluid. The UHPC material was mixed at a rate of approximately 4-5 batches per hour during the first placement. Approximately 40% of the mixing water was replaced with ice to reduce the concrete temperature to a manageable level since the starting ambient temperature was in the low to mid-80s Fahrenheit. The UHPC supplier representative directed the mixing process, identified any needed changes in water or ice content, took flow measurements for each batch, and made necessary compressive strength cylinders.

Figure 28. Mixers used on bridge deck placements being charged with dry materials

Material was discharged directly from the mixers into a Garbro concrete transfer bucket (Figure 29) and the bucket was transported to the joint location using the overhead gantry crane where material was placed directly in the joint opening (Figures 30 and 31). Plastic sheeting was placed in strips along the deck (Figures 29 and 30) to catch UHPC that dripped from the bottom of the transfer bucket and simplify cleanup. The placement was begun at the southwest corner of Span 1 and placement proceeded along the joint to the southeast and then to the north. After each section of joint was placed to near the top, the formwork top was put in place and secured to the deck using screw type concrete anchors. Shear pockets were covered at the beginning of the placement and left covered throughout. One worker was tasked with staying ahead of the UHPC placement with a hand pump sprayer (Figure 30) to ensure all concrete surfaces remained saturated during placement. The hand pump sprayer had been identified as a better alternative to the water hose sprayer used for the mock-up as it could be better controlled. Other workers were tasked with following behind the joint placement and keeping head buckets spaced at 8 ft along the form tops approximately half full (Figure 32). This placement pattern continued until all of the joints were complete. Compressive strength cylinders were cast from batches taken from each of the two mixers and spaced throughout the placement. All joints were successfully in place by approximately 1:00 am on August 20, 2021, for a total time of approximately 5 hours.

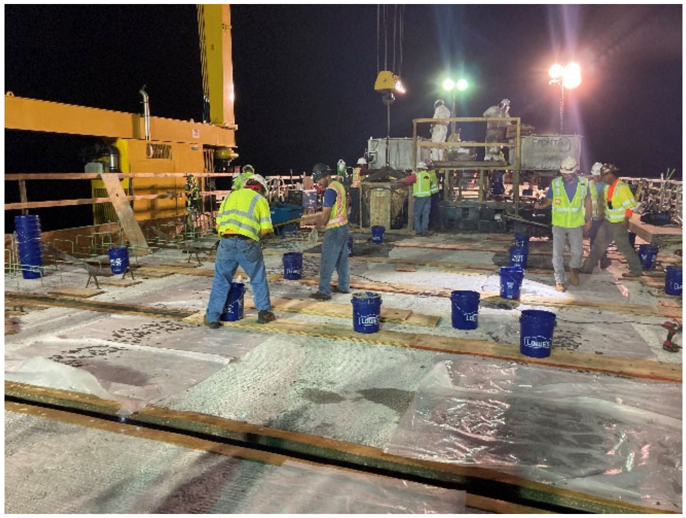

Figure 29. Concrete mixers used on the bridge placements with one mixer being discharged into the concrete transfer bucket. Head buckets in place on the joint top forms are also visible

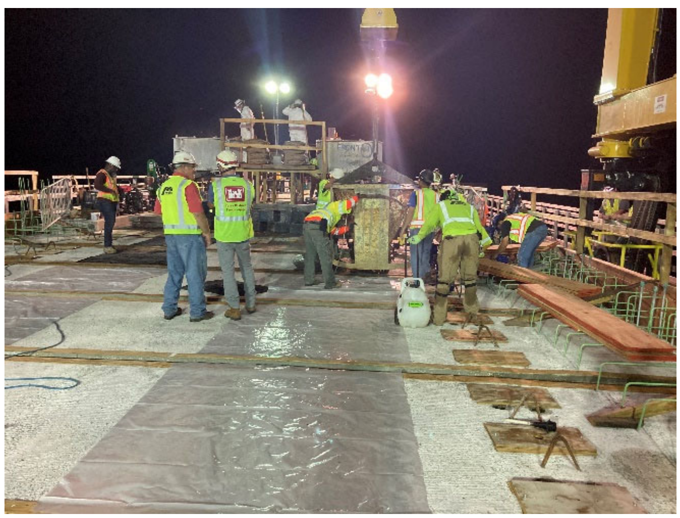

Figure 30. UHPC placement into the joint formwork

Figure 31. Discharge of UHPC from the transfer bucket into a joint

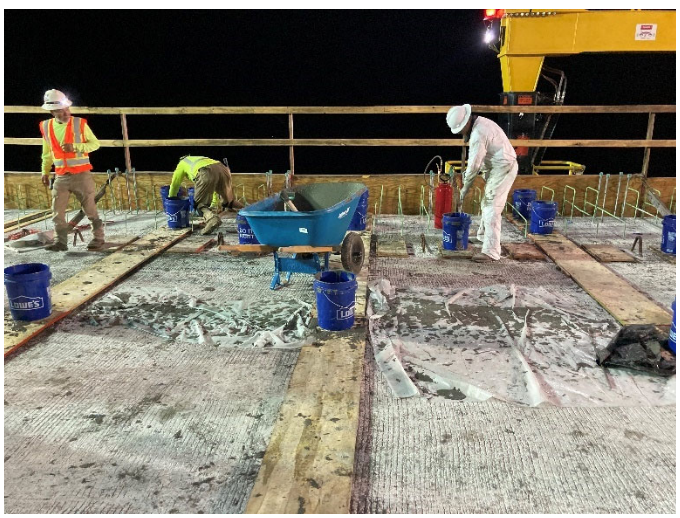

Figure 32. Placement of UHPC into the head buckets on the joint top formwork

The formwork had been water tested to ensure that it did not leak and to saturate the concrete surfaces in the joints before placement began. The water had been drained and suctioned with a shop vacuum, but a substantial quantity of water was observed in the northwest side haunch after the first UHPC placement. The water was pushed forward by the UHPC mass and was removed from the forms using a shop vacuum. In addition to the water test before placement, two individuals were stationed below the bridge deck on the access catwalks to watch for leaks during placement. No significant leaks were observed.

The material flowed very well out of the concrete bucket and flowed very well into the formwork until near the end of the span placement, at which point workability was noticeably reduced. A picture of UHPC in one of the joints is shown in Figure 33. Flow tests taken after each batch were consistently 8.5 in. to 9 in., but the high concrete temperature and time required for placement led to the reduced workability. Also, the placement took more than the anticipated sixteen batches and the contractor briefly stopped mixing after the sixteenth batch, which led to a delay of approximately 45 minutes between batches. The UHPC had already began to lose some workability at that point which led to needing to open many of the shear pockets, fill them individually, and agitate the material with pieces of rebar to ensure proper mixing, which can be seen in Figure 32. Discussions between USACE, UHPC supplier, and OU personnel concluded that these procedures would result in satisfactory performance.

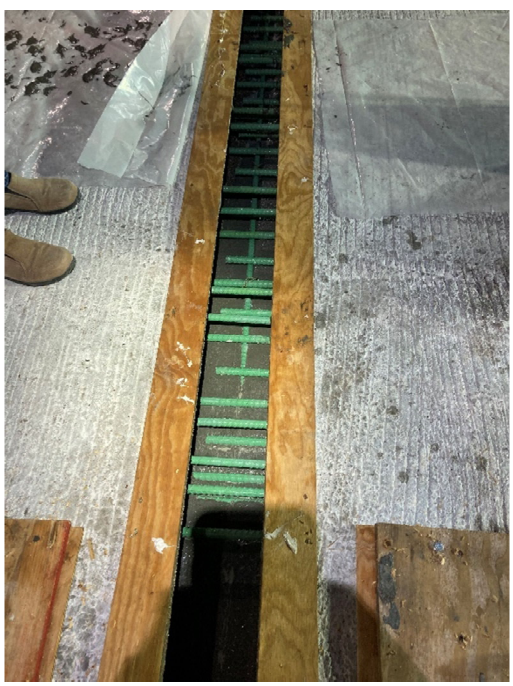

Figure 33. UHPC in one of the joints on Span 1

3.3 Subsequent Joint Placements

Joint placements on the subsequent spans were conducted using the same general procedures as used for Span 1. Some minor modifications to forming and placement methods were made as better methods were identified. A cementitious grout material was used to seal along the sides of the insulation foam used to seal the bottom of the joint as it was determined to work better than the caulking material on the joint side (Figure 34). This method was changed for the placements of Span 3 and after. In all cases silicone caulk was still used on the underside of the joint. Heavy duty sealant tape was also used along the side of the haunch to help support the insulation foam used for the haunch forms that was only held in place by the weight of the panels. Modification to placement methods included placing enough plastic on the deck to cover most of the panels between joints (Figure 35) adding a short rubber sleeve to the bottom of the transfer bucket to help direct flow of the UHPC into the joint (Figure 36), covering the joints with the top forms between batches of the UHPC to reduce evaporation and a skin forming on the top of the material before casting was complete, and placing batches south to north along the western girder line first before moving west to east.

Figure 34. Insulation foam and cementitious grout used to seal the bottom of the joint

Figure 35. Spans 8 and 9 ready for UHPC joint placement

Figure 36. Placement of UHPC using the concrete transfer bucket and rubber sleeve

Three formwork blowouts occurred during placement of Spans 4 and 5. The OU team was not present during these blowouts but received a description of what happened from USACE personnel and were able to take pictures of the results. The first blowout occurred on the downstream side of the eastern girder on Span 4 within the girder span. This blowout resulted in approximately 1 yd^3 leaking onto the spillway. The dam gates were opened to clean the UHPC from the concrete spillway, but some material remained (Figure 37) The blowout occurred in a section of the haunch were the compressed pink foam and sealant tape was used as a side form with no other lateral support. This became an emergency situation due to it being a large leak and due the lack of access on the downstream side of the bridge. Holes had to be drilled into the girder to install concrete anchors to seal the formwork, which was an outcome that the USACE had hoped to avoid. However, the leak was stopped and placement could continue. The other blowouts were smaller, occurred over the piers where they could be easily accessed, and were sealed by wedging 2x4 lumber into the gap to stop the leaks. These leaks occurred at the corner of the span end plywood bulkhead and the haunch side forms came together.

Figure 37. UHPC material from formwork blowout remaining on concrete spillway channel

In general, subsequent placements went very well. By the placement for Spans 8 and 9 the contractor was able to mix and place the 17 batches required for one span in approximately 4 hours and to complete the two-span placement in a single 10 hour shift.

3.4 Completed Joints

Completed deck panel joints were examined during placement of Spans 8 and 9, and overall appeared to be excellent (Figure 38). All joints had been ground using a walk behind grinder (Figure 39) except in the locations that would be covered by the sidewalk. No cracking due to formwork anchor placement was observed. There did appear to be a slight visible separation between the UHPC joint and deck panel concrete on the first joint on Span 2 at the southeast edge starting approximately one-quarter of the joint length from the edge of the deck and extending to approximately the middle of the deck (Figure 40). This crack appeared to be very tightly held together, is not expected to compromise the strength of the connection, and since it will be covered by an overlay is not expected to significantly compromise joint durability. This crack is similar to one that was observed on the mock-up specimen and may have been caused by inadequate prewetting of the deck panel surface, which could have compromised the bond strength between the panel and the joint.

Figure 38. Example completed UHPC joint

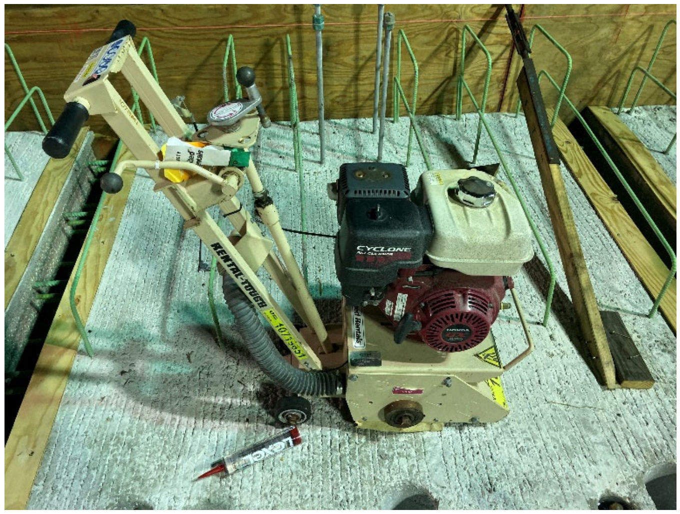

Figure 39. Grinder used for grinding UHPC joints

Figure 40. Crack at interface of UHPC joint and precast deck panel on Span 2 (quarter provided for scale)

A limited number of shear pockets were observed that had not been filled to the top similar to what was observed in the mock-up (Figure 41). One pocket in this condition was observed on Span 1, one on Span 3, and one on Span 7.

Figure 41. Shear pocket that was not filled above the level of the top of the deck

3.5 Compressive Strength Testing

One day compressive strength cylinders for each span were transported to Fears Lab by contractor personnel during the day following placement. For all spans cast overnight, specimens were tested the morning after reaching 24 hours of age in the night, at approximately 30-32 hours of age to match with the working hours of Fears Structural Engineering Laboratory. Compressive tests were performed using the methods of ASTM C1856 and ASTM C39 with the ends ground as specified in ASTM C1856. The compressive strength results are presented in Table 2. Span 1 exhibited a 32-hour compressive strength of 11,120 psi, which was significantly higher than the anticipated 6000 psi at 1 day of age. Spans 2 and 3 exhibited 32-hour compressive strengths near the desired 6000 psi at one day. The difference in compressive strength was attributed to significant lower ambient temperatures at the time of placement for Spans 2 and 3. Spans 4-5 exhibited a compressive strength of only 2020 psi for the first cylinder tested at approximately 32 hours of age, so the remaining cylinders were held until later that day and tested at approximately 40 hours of age at which time the compressive strength was 5790 psi. Due to the results observed for spans 4 and 5 the cylinders for Spans 6 and 7 were held until approximately 40 hours of age, at which time they exhibited compressive strengths of 11,700 psi and 11,800 psi, respectively. Since the cylinders for Spans 8 and 9 were cast in mid-morning they could be tested at 24 hours of age, but they were held until the same time as the other cylinders were tested (approximately 30 hours), at which time the compressive strengths were 2020 psi and 2570 psi. Additional cylinders were tested the next morning, at approximately 46 hours of age, which exhibited strengths of 9900 psi and 9830 psi. While the later age compressive strengths were not always provided to the OU team, it was indicated by USACE that later age breaks were more consistent and always met the required strengths at 7 and 28 days of age. The inconsistency in the early age strengths was attributed to temperature at the time of casting and a resulting delay in set and compressive strength gain. Since the cylinders tested at later ages met the required strengths and the spans could not be loaded until required compressive strengths were met, no detrimental effects of low early strengths are anticipated.

Table 2. Compressive Strength Results (psi) for Bridge Spans

Age	Span 1	Span 2	Span 3	Spans 4,5	Span 6	Span 7	Span 8	Span 9
1 day (~30-32 hours)	11,120	6410	5680	2020	nd	nd	2020	2570
~40 hours	nd	nd	nd	5790	11,700	11,800	nd	nd
~46 hours	nd	nd	nd	nd	nd	nd	9900	9830

Note: nd indicates no data were collected for that combination of span and age

4.0 Summary and Lessons Learned

4.1 Summary

The project described in this report was part of an implementation of ultra-high performance concrete (UHPC) during replacement of the S.H. 71 over Eufaula Spillway Bridge by the U.S. Army Corps of Engineers (USACE) with the Oklahoma Department of Transportation (ODOT) as an interested party. Precast, prestressed beams were utilized for the primary girders and full depth precast, prestressed deck panels were designed to span between the two girders. The panels and girders were connected with UHPC to create a composite system. The primary contractor on this project also had no previous experience using and placing UHPC and this Task Order allowed for an expert from the University of Oklahoma to provide input on the required mock-up test, be on site to observe during UHPC placement, provide input during the process, and monitor performance of both the mock-up and bridge joints.

Several issues were identified during mock-up construction that could be corrected before placement on the bridge. This included procedures used for charging the mixers, transport from the mixers to the formwork, and materials used to form the joints. Several lessons learned were identified during the process of casting the mock-up and bridge joints that are documented in the report. In general, the UHPC joints performed very well, and cores taken from the deck mock-up indicated excellent bond between the UHPC and deck panel concrete.

4.2 Lessons Learned

4.2.1 Formwork

- Water tests of the joint formwork were an effective method to determine if the formwork would leak during UHPC placement.
- Pink insulation foam formed into a wedge and sealed with cementitious grout on the joint side and silicone caulk on the back side was the most effective method for sealing the bottom of the joint of those examined.
- Compressed foam board insulation held in place by the weight of the slab panels and sealant tape was an effective method for forming the sides of the girder haunch, but in some cases needed additional side support, such as at the intersection of the joints and haunch. Care must also be taken to ensure the foam is not compressed and then the panel lifted off of the material creating a gap.
- Adequate time must be allowed between placement of joint sealant materials such as silicone caulk or cementitious grout and UHPC placement to allow the sealant materials to cure.
- It is best practice to keep the formwork tops loosely in place on top of the joints except during active placement of UHPC to reduce evaporation from the joint concrete and UHPC surfaces and then to attach the formwork tops securely once the joint is filled.
- Concrete surfaces should be kept saturated surface dry by first thoroughly prewetting during the water test or using wet burlap and then by a designated

crew member working in advance of the UHPC placement with a sprayer to keep the surfaces wet.

4.2.2 UHPC Placement

- The proprietary UHPC material Ductal® was used throughout this project and it performed very well under the direction of a manufacturer's representative.
- Use of a concrete transfer bucket and overhead crane allowed for efficient placement of UHPC into the joints as it allowed for discharge of an entire batch of material from the mixer at once and easy placement of the material into the joints. Wheelbarrows were an effective means for transporting material to fill the head buckets.
- Alternating mixes between two mixers was an efficient method for increasing the speed of UHPC production, but care must be taken to ensure materials are properly weighed out and staged in advance to reduce the time required to charge the mixer.
- Care should be taken to ensure that the head buckets or chimneys placed in the formwork tops are kept charged with UHPC once the formwork tops are put in place.
- Proper consideration of mix temperature is a critical consideration to ensure proper workability throughout the UHPC placement. Use of ice and placing material at night are possible ways to maintain mix temperature.

4.2.4 Compressive Strength Testing

- Compressive strength testing at one day of age led to inconsistent results due to the effects of temperature and required transport to the testing lab. These results did not correlate with later age strengths, which were in the expected range. This indicates that initial testing should be specified at a later age than one day unless high early strength is a project necessity.
- Due to the late set time for some of the specimens, care should be taken to ensure specimens are completely set before they are moved from the project site.

4.3 Recommendations

- The results of this project indicate that a contractor with limited experience placing UHPC can quickly learn to work efficiently with the material. It is recommended that a mock-up be required for large UHPC projects to ensure that the contractor is familiar with the material and to verify that planned placement methods will work for the specific situation.
- It is recommended that early age compressive strength tests be specified at a later age than one day unless high early strength is a critical project requirement. Two to four days is a more reasonable age to obtain consistent results.
- Thorough evaluation of the UHPC formwork is needed to ensure that it is watertight and that no weak points will lead to formwork blowouts during testing. The individual inspecting the formwork should have prior experience with UHPC, potentially from a mock-up or previous projects.
- Care should be taken to ensure that concrete surfaces to be bonded to UHPC are adequately prewetted and protected from evaporation. UHPC placed in the joint should also be carefully protected from evaporation.
- A training course on UHPC would be a helpful requirement for supervisory personnel and inspectors working on a project, especially if the parties involved have limited experience with UHPC.

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