UHPC Joint Fill Construction Problems and Solutions on the Pulaski Skyway

Author(s) & Affiliation:

Michael D. McDonagh, P.E., P.Eng., WSP USA
Andrew J. Foden, Ph.D., P.E., WSP USA

Abstract:

The redecking of the Pulaski Skyway is the largest implementation of ultra-high performance concrete (UHPC) in North America to date. Approximately 90,000 m² (1 million ft²) of deck was replaced with precast concrete panels connected with field-placed UHPC, using a total volume of more than 5,000 cubic yards (3,800 cubic meters) of UHPC. The construction of the new deck took place over the course of four years in a temperate climate with hot summers and cold winters. The very large quantity of deck, the large volumes of field-placed UHPC, and multiple years of construction with all possible weather and temperature conditions created challenges to successful UHPC placement.

This paper discusses the types of problems that arose and the solutions that were developed during the course of the redecking construction project. The problems included placement issues related to pumping, fiber segregation issues deriving from low ambient temperature, cracking due to early age loading, and underfilled pockets and joints due to leaking or blown-out forms. The distinct issues encountered are set out in detail, along with the solutions and the methods that were employed to find the solutions, with a discussion on the reasoning behind the selection made in each case.

The information presented is intended to serve as a resource for engineers and construction inspectors undertaking UHPC joint fill projects, providing substantive explanations of the sort of UHPC construction problems that can arise and examples of means utilized to address them.

Keywords: *UHPC, Construction, Inspection, Deck, Repair*

1. Introduction

The Pulaski Skyway is a three and one-half mile (5.6 km) long viaduct located in northern New Jersey that serves as a direct link to New York City via the Holland Tunnel. Between 2014 and 2018, the entire mainline deck of the Pulaski Skyway was replaced. Because the Skyway is such a critical part of the greater New York City transportation network, the New Jersey Department of Transportation (NJDOT) wanted to minimize traffic disruptions during the redecking and design the new deck to eliminate any significant deck maintenance for the next 75 years. Consequently, the NJDOT replaced the majority of the nearly 1 million square feet (93,000 square meters) of deck with precast concrete deck panels connected with ultra-high performance concrete (UHPC). Using UHPC with precast concrete deck panels enabled the project to benefit from the higher quality and faster installation of precast concrete panels compared to a conventional cast-in-place concrete deck, while not sacrificing any durability at the connections as is often seen with conventional connection materials.

Figure 1. Partial Elevated View of the Pulaski Skyway

The key properties of UHPC that make it ideal for connecting precast bridge elements include its high tensile and compressive strengths, which lead to short rebar lap splices and thus narrow connections; a fast cure time relative to conventional concrete; a highly flowable, self-consolidating consistency before curing to completely fill connections even if they are congested; and extreme durability represented by very low permeability. The purpose of this paper is not to present the advantages of UHPC in detail, however, as this has been done previously by the authors for the Pulaski Skyway and by others more generally.

The large amount of deck that was replaced resulted in the use of over 5,000 cubic yards (3,800 cubic meters) of UHPC, making it the largest use of field-cast UHPC on a single project in North America to date. The construction duration spanned several years and multiple seasons, and construction work continued regardless of the weather or temperature. Actual temperatures during the construction period dropped to as low as 0°F (-18°C) and rose to as high as 99°F (37°C).

Problems were encountered with UHPC placement, and solutions to those problems were developed through collaboration with the owner, contractor, design engineer, and UHPC material supplier. This paper makes no assertion as to liability by any party for any issues that arose during construction. The sole purpose of this paper is to describe the problems that were encountered with UHPC and the solutions that were developed, so that this information can benefit future UHPC joint fill projects.

2. Deck Replacement Strategy

The majority of the Pulaski Skyway deck was replaced with 8-inch (200-mm) thick lightweight precast concrete deck panels. One section of the Skyway deck was widened, and to avoid adding dead load to the existing steel structure due to the extra deck area, unfilled steel grid deck panels composite with 4-inch (100 mm) thick precast concrete on top were used. These panels are commercially known as Exodermic deck panels. To maximize the durability of the deck, stainless steel rebar was used in the full-depth precast concrete deck panels, and galvanized rebar was used in the Exodermic deck panels (to be consistent with the galvanized steel grid). A 1-inch (25-mm) thick polyester polymer concrete (PPC) overlay was placed on top of the deck.

The northbound deck was replaced first while the southbound deck remained open to traffic. After completion of the northbound deck, traffic was switched to the new northbound deck while the southbound deck was replaced.

3. UHPC Usage on the Pulaski Skyway

The Pulaski Skyway redecking used UHPC primarily in the following three locations. The first location is the narrow transverse connections between adjacent precast deck panels. The connections between full-depth precast concrete deck panels are 8 inches (200 mm) wide and the connections between the Exodermic deck panels are 10 inches (250 mm) wide.

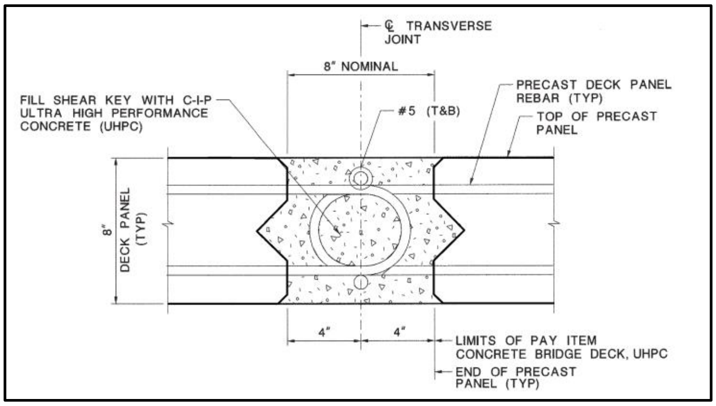

Figure 2. Typical Transverse Panel Connection

The second location where UHPC was placed is in the deck panel shear connections and haunches that connect the deck panels to the steel framing. Shear studs are welded to the steel framing and extend into the pockets or reserves of the deck panels that are then filled with UHPC. The full-depth precast concrete deck panels had discrete pockets in which shear studs were grouped. The Exodermic deck panels had reserves where the precast concrete was blocked out over the entire length of the underlying steel framing, to facilitate shear stud placement which also had to avoid the deck steel grid. Because the shear pockets and reserves are located over the steel framing, the haunches between the bottoms of the deck panels and the tops of the steel framing were poured monolithically with the shear pockets and reserves.

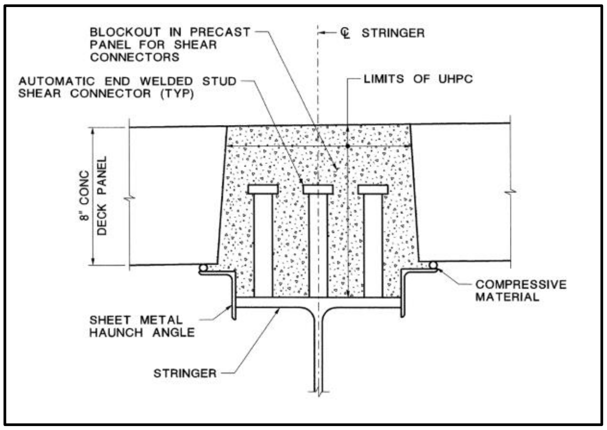

Figure 3. Typical Shear Pocket Detail, As Constructed

The third UHPC location is the longitudinal connection between the northbound deck panels and the southbound deck panels under the median barrier. The two new halves of the deck were connected with UHPC in a full-depth pour that was typically 3-feet (0.9 m) wide.

4. UHPC Joint Fill Construction Problems

This section details the various problems that were encountered with using UHPC to connect deck panels on the Pulaski Skyway, with a description of solutions that were developed.

4.1 Problems Caused by Pumping UHPC

To the authors' knowledge as well as that of Lafarge, the UHPC material supplier, the Pulaski Skyway project was the first time that UHPC was placed using a concrete pump. The contractor asserted that there would be efficiency gains due to the ease of transporting the UHPC between the mixers and the placement locations, as well as improved site safety compared to using motorized buggies or wheel barrows to move the fresh UHPC. As a result, Lafarge's on-site technician worked with the contractor and adjusted the properties of the fresh UHPC exiting the mixer.

Typically, every batch of fresh UHPC is tested using a flow test, as defined by ASTM C1856, which in turn references ASTM C1437 with modifications. In order to be acceptable for placement, at the end of the flow test the fresh UHPC should spread to a diameter of between 8 inches (200 mm) and 10 inches (250 mm).

However, when UHPC meeting this specification was put into the pump, the energy imparted by the pump would increase the workability of the UHPC, while the friction of the UHPC passing through the pipe and hose and the exposure of the pipe and hose to the sun increased the temperature of the UHPC, which tends to reduce workability. Thus, it was very difficult to predict the flow of the UHPC out of the pump hose and difficult to know how to adjust the properties of the UHPC coming out of the mixer to compensate. Nonetheless, when the use of a concrete pump began in late fall of 2014, the technician was able to successfully adjust the UHPC properties over multiple batches and pours such that the UHPC exiting the pump hose met the workability criteria for placement.

Figure 4. UHPC Being Successfully Placed with a Pump in Late Autumn of 2014

Figure 5. Long Pump Pipe in Spring of 2015

As the following spring arrived, however, the ambient temperatures and the prevalence of sunny days increased, resulting in problems ranging from plugged pumps to voids in the cured UHPC due to a lack of material workability, when the contractor was using over 300 feet of pipe and hose. The solution to the problems caused by pumping was simple – the contractor stopped using a concrete pump and instead started using motorized buggies to transport the fresh UHPC between the mixer and the pour locations. In fact, after temporarily switching to buggies when the NJDOT put a temporary halt on pumping to investigate the situation, it became evident that there was a significant increase in efficiency with no safety issues and the contractor never sought to use the concrete pump again. Solutions for the voids that resulted when the UHPC lost workability due to pumping will be discussed in the section on repair of deficient UHPC pours.

Figure 6. Partially Removed Form Revealing Underfilled Haunch due to Loss of Workability

4.2 Problems Caused by Leaking or Blown-Out Forms

Another problem that arose during some of the earlier UHPC placements was that, after stripping the top forms, the UHPC pours were not completely filled. Recommended practice by FHWA and Lafarge is to install chimneys at key locations and to monitor and keep the chimneys at least partially full of UHPC during the hours after the pour. The chimney is just a box or bucket sitting on the deck above a UHPC pour location with a hole in the bottom to provide head pressure for the fluid UHPC to ensure that the pours will be completely full.

However, chimneys will not be enough to keep the pours full if there are form leaks or blowouts. Simply making formwork stronger becomes impractical if the pressure demand exceeds the capacity of typical formwork, as was the case for some of the early UHPC pours.

The contractor chose to pour the deck panel connections simultaneously with the haunches and shear connections, leaving them all interconnected. In addition, in attempts to reduce the number of bulkheads, the contractor initially poured the UHPC continuously over many panels, leading to very high head pressures on the downslope formwork. This, in turn, led to a series of leaks and form blowouts.

Figure 7. Underfilled UHPC Panel Connection and Shear Pocket Due to Leaking Forms

The solution was to limit the length of UHPC pours on the Pulaski Skyway by limiting the number of panels whose connections and haunches were poured simultaneously, in particular in the areas with higher profile grades. This was accomplished by placing plywood bulkheads at the intersection of the haunches and the transverse panel connections at the limits of the pour. A rule of thumb employed was to limit the number of panels whose haunches and connections were poured simultaneously to three, which spans a bridge length of approximately 75 feet. The repair to underfilled pours will be discussed in the section on repair of deficient UHPC pours.

4.3 Problems Caused by Not Waterproofing Formwork

UHPC has a very low water-to-cementitious materials ratio, typically on the order of 0.25 or less. As a result, the fresh UHPC must be protected to prevent moisture from being drawn out, either by dry adjoining precast concrete or by plywood forms. For this reason, adjoining precast concrete surfaces should be in a saturated-surface-dry condition just prior to pouring UHPC, and formwork should not be able to absorb water. Formwork can be made of plastic or other non-absorbent materials, or more commonly is made of plywood with non-absorbent resin coatings.

On one occasion, the contractor used bare plywood for top forms of the deck panel connections. It resulted in cracking of the UHPC that was still present even after the overfilled UHPC was ground away. The cracking was determined to be mostly superficial. Because the PPC overlay placed on top of the deck is applied with a high molecular weight methacrylate primer, the NJDOT did not require any remedial action. Otherwise, it would be prudent to seal the cracked UHPC with a methacrylate sealer as a minimum course of action.

4.4 Problems Caused by Waterproofing Detaching from Formwork

For some of the deck panel connection top forms, the contractor attached polyethylene sheeting to the underside of plywood top forms as a means of waterproofing the forms. Unfortunately, in one series of panel connection pours the fresh UHPC managed to flow in between the polyethylene sheeting and the plywood, and the weight of the UHPC and the force of the flow pulled the sheeting downward and into the UHPC connection by as much as several inches. As a result, the polyethylene sheeting acted as a bond breaker within the mass of the UHPC connection, while the top of the UHPC was negatively affected by moisture loss due to contact with the uncoated plywood form which led to shrinkage cracking of the UHPC.

The long-term solution for this problem was to exercise greater care in attaching the polyethylene sheeting to the formwork and to use prefabricated forms with a non-absorbent coating, with the latter being the preferred method. The affected UHPC pours had to have the UHPC completely removed and replaced where the sheeting was more than 0.5-inch (13-mm) deep. The details of how this was performed are discussed in the section on repair of deficient UHPC pours.

4.5 Problems Caused by Low Ambient Temperature

Because of the project schedule and the very large number of UHPC connections, UHPC pours continued year-round for several years, including during the winter. Fresh UHPC needs to be kept at a minimum temperature of 50° F (10° C) in order to achieve its expected qualities and material properties. If the temperature of the fresh UHPC drops below 50° F (10° C), the rate of curing slows down significantly, and it takes much longer to achieve initial material setup. The steel fibers that are suspended in the fluid UHPC, therefore, have much more time to drift downward due to gravity, and the fibers can segregate at the bottom of the UHPC. The result is a lack of fiber in the top half of the UHPC which can lead to cracking and insufficient capacity to development rebar and resist tension forces.

When pouring UHPC in temperatures that are below 50° F (10° C), or that are expected to drop below that temperature over the three days following the pour, measures must be taken to ensure that the UHPC and the surrounding structure are kept at a temperature of 50° F (10° C) or higher. This can be accomplished by a combination of heaters and insulating blankets. However, for various reasons, the required minimum temperature was not maintained on a handful of UHPC pours on the Pulaski Skyway. In all cases, subsequent cylinder testing showed that the UHPC still met the minimum required 28-day compressive strength.

Questions remained, however, as to whether the field-placed UHPC had experienced any fiber segregation. The NJDOT required the contractor to take 2-inch (50-cm) diameter cores of the field-placed UHPC to check for fiber segregation. While some of the cores exhibited signs of minor segregation, Lafarge certified to the NJDOT that the UHPC met the design criteria. As a result, no corrective action was taken.

4.6 Problems Caused by Early-Age Loading

On multiple different occasions, the contractor loaded previously poured UHPC connections before the UHPC had achieved the 14 ksi (96.5 MPa) minimum strength required for loading. The contractor drove motorized buggies across precast deck panels and over their recently poured UHPC connections, by either driving over the top forms or by prematurely removing the top forms. In at least two cases, the UHPC connecting the precast panels had only been poured the previous day. The gross weight of each motorized buggy was similar to the average weight of an automobile but with a much smaller width and wheel base. At least one of those locations was also a cold weather pour with insulating blankets on top that were removed over a width of about 8 feet (2.5 meters). In the case of the cold weather pour, the concerns were not just about early age loading but also about the minimum temperature not being maintained on the previously poured UHPC in the area where the insulating blankets were removed.

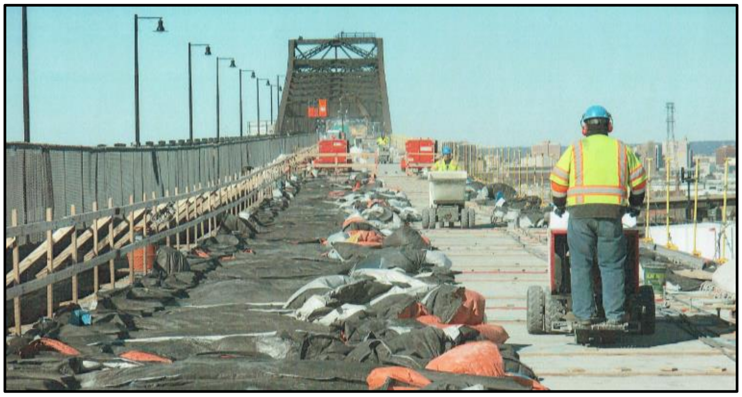

Figure 8. Insulating Blankets Removed and UHPC Connections Loaded Prematurely

One of the first steps that the NJDOT required was for the contractor to take a 2-inch (50-mm) diameter core from each prematurely loaded connection to check for indications of fiber segregation. A number of those cores showed indications of fiber segregation and some also had cracks. These results led to a more rigorous sampling and testing program. NJDOT, in coordination with the design engineers, WSP USA, implemented a program of testing twenty-four 2-inch (50-mm) diameter cores taken from previously cast UHPC deck panel connections that were considered acceptable in order to establish baseline properties. A diameter of 2 inches (50 mm) was used in order to reduce the likelihood of hitting reinforcing steel during the coring operation, and therefore to minimize the damage to the in-place UHPC. The main goals of the testing program were to determine an acceptable tensile capacity of the UHPC and, relatedly, to determine acceptable fiber distribution.

Due to the small sizes of the samples, it was not practical to perform direct-tension tests on the cores. Therefore, the cores were tested using ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. Several prior studies, including one by Dr. Benjamin Graybeal indicated that there was a direct correlation between the splitting tensile strength of UHPC cylinders and the direct tension capacity.

Each core was divided in half, so that each half core could be tested separately as a means to identify any performance reductions between the two halves due to possible fiber segregation where the fibers would settle towards the bottom. Several additional control cores were created from two newly cast UHPC samples, one containing 2% steel fiber as per the project specifications and one without any steel fibers to serve as a lower bound sample. The control samples were thermally treated to accelerate their curing to approximate the age of the cast in-place UHPC baseline samples. Prior to execution of the testing, a tensile strength of 725 psi (5 MPa) was established as a preliminary acceptance threshold, based on the published tensile design strength of Ductal®, Lafarge's UHPC being used on the project.

Each half-core and control sample was measured, weighed, and then subjected to a splitting tensile strength test. The measured splitting tensile strength of all of the half-cores and control samples greatly exceeded 725 psi (5 MPa), being nearly 3 times to nearly 10 times greater, including cores with cracks in them and including the control sample with no steel fiber. Furthermore, almost all test results were within two standard deviations of the mean with no extreme outliers.

It was clear that the data could not be correlated to the actual tensile capacity of the UHPC. As Dr. Graybeal states in his paper, "Practical Means for Determination of the Tensile Behavior of Ultra-High Performance Concrete," the ASTM C496 test, unmodified, overestimates the capacity of fiber reinforced concretes, which include UHPC, since the concretes do not fail immediately after cracking and they exhibit significant reserve capacity. To correlate with direct tension capacity, Dr. Graybeal proposes several modifications to the ASTM C496 methodology, the most significant one being the implementation of a crack detection method to detect when the first crack appears. Proposed crack detection methods include LVDTs, combined video and audio recordings, and ultrasonic testing during the split cylinder test. Unfortunately, the testing lab relied only on visual crack identification, and thus likely missed the actual first crack and greatly overestimated the tensile capacity. Furthermore, the ASTM C496 methodology involves testing 6-inch (152-mm) diameter cylinders which raises questions about geometric compatibility.

Despite the inability to correlate the test data to direct tension capacity, the baseline samples could still be compared to the control samples with 2% steel fiber. However, even this left some doubt about the results, as three of the 0% fiber control samples had higher test results than three of the half-cores including a bottom half-core sample.

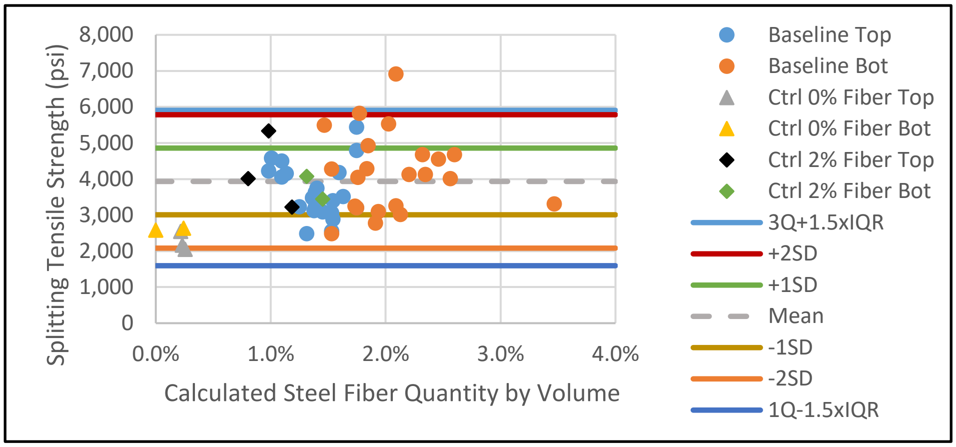

Figure 9. Calculated Steel Fiber Quantity by Volume vs. Splitting Tensile Strength Test Results of Baseline Samples

The density of the baseline samples was also calculated as an attempt to quantify fiber content and to identify changes in fiber content due to segregation. This, too, was determined to be an unreliable indicator, as the calculation for steel fiber quantity is highly dependent on the assumed density of the UHPC without steel fiber.

After all of this testing and analysis of baseline samples, it was determined that there were too many uncontrollable or unknown variables and it was impossible to determine actual fiber content or to establish actual tensile capacity of 2-inch (50-mm) diameter UHPC cores. As a result, an acceptance criterion was agreed upon by the NJDOT based on the splitting tensile strength only, using 1.71 standard deviations below the mean as the minimum based on a t-distribution analysis of the 24 baseline samples.

Following the establishment of this criterion, core samples were taken from the UHPC connections that had been loaded prematurely, and they were subjected to the same splitting tensile strength testing as the baseline cores. All of the samples from the prematurely loaded areas had a splitting tensile strength result above the established minimum value with only one exception that was only slightly below the limit. Furthermore, the distribution of the splitting tensile strength values was very similar to that of the baseline samples. While a small number of samples had cracks and apparent fiber segregation, their test results were consistent with the other samples with no reduction in capacity. Consequently, none of the UHPC pours in question were removed.

One lesson learned from this experience is that measuring the tensile capacity and fiber content of UHPC cores from splitting tensile strength tests is very difficult. In order to accurately measure the tensile capacity of the UHPC cores, additional work would have been required to refine the methodology to strictly follow Dr. Ben Graybeal's recommended modifications for detecting the first crack. Furthermore, based on the existing available information, it would have been necessary to take 6-inch (152-mm) diameter cores which would have caused more damage to the bridge deck and would have required additional repair work. Rather than spending additional time and effort to refine the methodology to establish a better scientific means to evaluate the cores, the owner ultimately decided to rely on the testing results that indicated there was no significant difference in the tensile capacity of the prematurely loaded UHPC pours versus previous UHPC pours that were accepted.

5. Repair of Deficient UHPC Pours

After the initial problems with form leaks that were not detected until after the UHPC had cured, the NJDOT undertook a testing program to see if topping off the low UHPC pours with fresh UHPC would be an acceptable solution. The owner wanted to make sure that the repaired UHPC deck panel connections and shear pockets had the same capacity as monolithic UHPC, including tensile capacity. The tests were carried out using the steel framing from the full-scale deck panel and UHPC connection mockup that had been required prior to initial UHPC placement activities earlier in the project.

Several repair methods were considered, including simply placing a bonding agent between the previously cast UHPC and the freshly placed UHPC. The method that was finally tested on the mockup involved coring 1 7/8-inch (48-mm) diameter holes into the previously cast UHPC panel connections and 1-inch (25-mm) diameter holes into the previously cast shear pockets as a way to increase the contact surface area between the two UHPC pours, with an epoxy bonding agent applied to the exposed surface of the hardened UHPC.

A series of pull-off tests were required in accordance with ASTM C1583, *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)*. The NJDOT required a minimum pull-off capacity of 725 psi (5 MPa), based on the direct tension design strength of the UHPC published in the product data sheet, which also includes a mean direct tension strength of 1,160 psi (8 MPa). Unfortunately, none of the pull-off tests met the 725 psi (5 MPa) threshold. As a result, for the entire project, the NJDOT disallowed topping off or otherwise repairing any cured UHPC pours that were cast low or that had any voids or other deficiencies, and required that they be completely removed and recast, with a few minor exceptions.

Figure 10. Pull-Off Test Setup

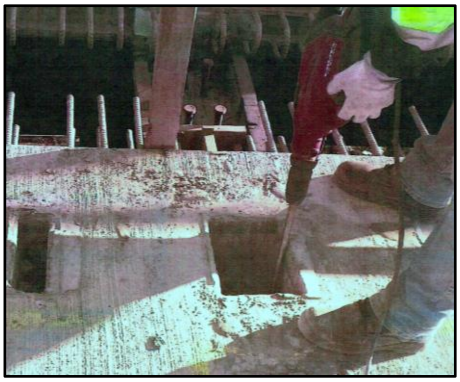

Figure 11. Removing Cured UHPC from Underfilled Shear Pockets

Despite the fact that some of the cured UHPC that needed to be removed was many months old by the time removal efforts began, and thus would have reached the 28-day compressive strength of 22,000 psi (150 MPa) or higher, it was successfully removed with small jackhammers (typically 20 lb [9 kg] maximum size to minimize collateral damage), albeit at a slower pace than what would be expected for removing conventional concrete.

6. Conclusion

The new Pulaski Skyway deck was completed in 2018, with final punch list and project closeout activities extending into 2019. While there were some problems with UHPC placement, the vast majority of the more than 5,000 cubic yards (3,800 cubic meters) of UHPC were placed without any problems. Where problems did arise, the combined efforts of the owner, the designer, the contractor, and the UHPC supplier resulted in solutions that are anticipated to maintain the long service life of UHPC connections.

It is hoped that other designers, owners, construction engineers, and contractors can benefit from the experience gained on the Pulaski Skyway. This information can help others anticipate and therefore avoid potential problems and provides some guidance on solutions that were employed should similar problems arise on other projects.

7. References

ASTM Standard C496, 2017, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,” ASTM International, West Conshohocken, PA, 2017, DOI: 10.1520/C0496-17, www.astm.org.

ASTM Standard C1437, 2015, “Standard Test Method for Flow of Hydraulic Cement Mortar,” ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C1437-15, www.astm.org.

ASTM Standard C1583, 2013, “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength of Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),” ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/C1583-13, www.astm.org.

ASTM Standard C1856, 2017, “Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete,” ASTM International, West Conshohocken, PA, 2017, DOI: 10.1520/C1856-17, www.astm.org.

Graybeal, B., "Design and Construction of Field-Cast UHPC Connections," FHWA, U.S. Department of Transportation, Report No. FHWA-HRT-14-084, Available at http://www.fhwa.dot.gov/publications/research/infrastructure/structures/14084/ [Cited Feb. 20, 2019].

Graybeal, B., "Practical Means for Determination of the Tensile Behavior of Ultra-High Performance Concrete," Journal of ASTM International, Vol. 3, No. 8, September, 2006, DOI: 10.1520/JAI100387, www.astm.org.

McDonagh, M.D. and Foden, A.J., “Benefits of Ultra-High Performance Concrete for the Rehabilitation of the Pulaski Skyway,” Proceedings of the First International Interactive Symposium on UHPC, Des Moines, IA, July 18-20, 2016, DOI: 10.21838/uhpc.2016.91.