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Bonding of Overlays to Ultra High Performance Concrete

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EXECUTIVE SUMMARY

This study evaluated the bond performance of overlays bonded to ultra-high performance concrete (UHPC) within the context of Delaware Department of Transportation (DelDOT) bridge applications. Polyester polymer concrete (PPC), latex modified concrete (LMC), and modified class D concrete (MCD) are applied as overlays on UHPC components to protect the bridge deck from deicing salts and provide a smooth riding surface. These overlays differ in composition, bonding agents used, mechanical and physical properties. The difference in properties between these materials results in distinct bond performance on the UHPC substrate. It is critical for an overlay to develop good bonding with the substrate to maximize overlay durability and minimize maintenance.

UHPC is a cementitious composite material with optimized particle packing, internal steel fiber reinforcement, and a low water-to-cement ratio, resulting in superior mechanical properties. UHPC has high compressive strength (at least 22 ksi) and sustained post-cracking tensile strength (of at least 0.72 ksi). Compared to conventional and high-performance concretes, UHPC is nearly impermeable (owing to its discontinuous pore structure), resulting in considerably improved durability. Transportation agencies are using UHPC in bridges for link slabs, connections between precast components, and entirely UHPC structural members. To ensure adequate bonding of overlays to the UHPC substrate, minimum pull-off bond strengths of 250 psi and 200 psi are recommended for PPC and LMC overlays by AASHTO T-34 and ACI 548.4M-11, respectively. In addition, DelDOT specifies a minimum pull-off bond strength of 250 psi for PPC and MCD overlays; the DelDOT specification does not have an explicit bond strength requirement for LMC.

Current literature addressed the bond performance of overlays bonded to conventional concrete substrates. However, when it comes to UHPC substrate, the literature is limited to investigating LMC and UHPC as overlay materials on UHPC, while considering only scarification and hydrodemolition as surface preparation methods. The lack of knowledge regarding the bond performance of other overlays (PPC and MCD) on UHPC as well as the influence of additional surface preparation methods was addressed in this work. The study evaluated the effects of cording depth, overlay age and substrate preparation method, specifically, grinding and sandblasting (GSB), hydrodemolition (HD), surface retarder (SR), and control “non-prepared” (NP) surface on the bond strength. Furthermore, the efficacy of different roughness measurement methods in quantifying the roughness of prepared UHPC substrate was investigated. The three roughness measuring techniques utilized include ICRI concrete surface profile (ICRI CSP) chips, sand patching, and surface profile gauge.

The sensitivity study looking at the effects of coring depth on bond strength concluded that the coring depth of 0.5 in. was the most appropriate for pull-off bond tests on UHPC. Results indicated that surface prepared by GSB performs better than NP substrate surface. However, HD and SR increased surface tortuosity beyond GSB and exposed steel fibers, which further promoted mechanical interlocking across the overlay-UHPC interface. For MCD overlays, it was determined that the substrate hygric state (dry versus saturated surface dry) does not have a statistically significant effect on the bond strength. Bond strength of PPC and LMC plateaued within 7 and 14 days of placement, respectively. Bond strength of MCD decreased by approximately 48% (from 338 to 175 psi) following 14-day moist curing. This reduction in bond strength of MCD was accredited to the effects of restrained drying shrinkage. Finally, in terms of roughness measuring methods, the surface profile gauge was deemed more effective in quantifying the roughness of prepared UHPC surfaces compared to sandpatch method (which could only be applied to NP and GSB surfaces because SR and HD exposed steel fibers in UHPC limiting the spread of sand). ICRI CSP chips could not be successfully used to qualitatively assess the texture of the UHPC substrate because they were created for normal concrete, which has significantly different microstructure compared to UHPC.

Chapter 1

INTRODUCTION

1.1 Background information

Since 2000, the commercialization of proprietary Ultra-High Performance Concrete (UHPC) introduced this advanced construction material to the United States market (Graybeal, 2011). UHPC is used in a variety of applications in the bridge industry such as precast, prestressed girders, waffle panels for bridge decks, and bridge connections between precast concrete deck panels and girders (Russell and Graybeal, 2013) as shown in Figure 1. While the tensile strength of conventional concrete is assumed as $7.5\sqrt{f_c'}$ in reinforced and prestressed concrete, it remains significantly lower than the tensile strength of UHPC that reaches 2000 psi as stated by (Kusumawardaningsih et al., 2015). Furthermore, compared to conventional and high-performance concretes, UHPC is nearly impermeable (owing to its discontinuous pore structure), resulting in considerably improved durability.

Figure 1. UHPC placement in the connection region between deck-bulb-tee girders (Graybeal, 2010).

Overlays are materials used to provide a smooth riding surface and protect the bridge decks by preventing infiltrations of deicing salts and other aggressive chemicals. In Delaware, the three types of overlays used by the Delaware Department of Transportation (DelDOT) are Polyester Polymer Concrete (PPC), Latex Modified Concrete (LMC), and Modified Class Concrete (MCD). Details of these overlay systems are defined by DelDOT's Standard Specifications for Road and Bridge Construction (Majeski and Hastings, 2022). These overlays differ in constitutive raw ingredients, the used bonding agents, permeability, curing time, and shrinkage. The difference in properties between these materials results in distinct bond performance on the UHPC substrate. One of the key parameters to assess the performance of an overlay is its bonding quality to the substrate. An overlay with sound bond maximizes the structure's durability and minimizes maintenance. To ensure adequate bonding, a minimum pull-off bond strength of 250 psi and 200 psi is recommended for PPC and LMC overlays by AASHTO T-34 and ACI 548.4M-11, respectively. DelDOT specifies a minimum pull-off bond strength of 250 psi for MCD.

According to Silfwerbrand (1990) the bond strength of overlays to the substrate is affected by the substrate properties (strength, aggregate gradation, and age), overlay properties (water to cement ratio, thickness, age, and curing time), interface characteristics (roughness, microcracks, surface moisture at time of placing the overlay, and the use of bonding agents). That study also highlighted that ambient conditions are also among the factors associated with bond quality. Roughness and microcracks depend on the surface preparation method used before applying the overlay. A variety of surface preparation methods are discussed in the literature, such as grinding and sandblasting (GSB), surface retarder (SR), hydrodemolition (HD) (Figure 2), explosive blasting, shot blasting (Silfwerbrand, 2003; Courard et al., 2018). To classify the roughness of the prepared concrete surface, several measurement methods are discussed in the literature, like ICRI CSP chips, sand patch method, and profilometer (Garbacz et al., 2013).

Figure 2. HD process in the field. Source: North Carolina Department Of Transportation (2013).

To assess the bond strength at the interface, numerous test methods been established (J. Silfwerbrand, 2003). The two most-commonly used test methods are bond pull-off test ASTM C1583 (ASTM, 2020) and slant shear testing ASTM C0882 (ASTM, 2020). Specifically for overlays, the bond pull-off test is more often used because of its simplicity and ease of use in the field.

1.2 Objectives and scope

Current literature (Haber et al., 2018) addresses the bond performance of overlays bonded to conventional concrete substrate. However, when it comes to UHPC substrate, the literature is limited to the investigation of LMC and UHPC as an overlay while considering only scarification and hydrodemolition as surface preparation methods. The study reported that while both overlays exceed the minimum required bond strength, UHPC overlay had comparable and, at times, higher bond strength than LMC overlay depending on the surface preparation method. The lack of knowledge regarding the bond performance of other overlays (PPC and MCD) on UHPC as well as the influence of additional surface preparation methods need to be addressed. Furthermore, the optimal coring depth specified—a parameter of the pull-off bond test used to assess the bond performance—must be examined. This study investigated the sensitivity of coring depth (0, 0.5, 1, and 1.5 inches) on the pull-off bond strength to determine the most appropriate test parameter for overlays bonded to UHPC. Furthermore, the effect of UHPC surface preparation method (specifically, GSB, SR, and HD) will be evaluated for PPC, LMC, and MCD and compared to a control non-prepared surface. In addition, this study evaluated the effect of overlay age (7, 14, 28, and 56 days) on pull-off bond strength. The substrate hygric state was also considered for the case of MCD.

Chapter 2

LITERATURE REVIEW

This review introduces UHPC, its benefits, applications, and a summary of overlay materials and their advantages. Test methods typically used for laboratory and field testing of the bond strength of overlays on concrete were presented, followed by a review of past studies that focused on the bond strength of overlay materials to concrete. The reviewed literature provides information on variables that influence the bond strength. The primary variables discussed include substrate surface preparation method, test method, and substrate strength. The reported bond strengths in the reviewed literature were compared to the minimum strength requirements stated in ACI specifications.

2.1 UHPC

Ultra-high-performance cement (UHPC) is a cementitious composite comprising discontinuous internal fibers, low water-cement ratio, and optimized gradation of granular material (Graybeal, 2011; Aaleti and Sritharan, 2019). The utilization of ultra-high-performance concrete (UHPC) in bridges is projected to continue growing due to its superior mechanical and durability properties in addition to its practicality in accelerating construction. UHPC has high compressive and tensile strength (Graybeal, 2013). The common UHPC-class materials are generally defined as having a compressive strength of at least 22 ksi and sustained post-cracking tensile strength of 0.72 ksi. The discontinuous pore structure of UHPC reduces the ingress of aggressive chemicals, resulting in good durability performance. Owing to its self-consolidating property and excellent mechanical and durability performance, typical applications of UHPC in the United States included deck-to-girder, girder-to-girder and connections between adjacent deck panels, link slabs, bridge deck overlays, and more. In addition, some states have utilized UHPC in prestressed concrete girders to eliminate some of the mild steel reinforcement and reduce cross-sectional dimensions (Graybeal, 2011).

2.2 Overlays

Overlays are utilized to prevent water, deicing salts, and other aggressive chemicals from infiltrating the bridge decks. Overlays provide a smooth riding surface for traffic in addition to serving as a protective layer (Haber et al., 2018). The necessary protective properties of an overlay material are the resistance to abrasion and skidding, thermal expansion coefficient that is comparable to that of the substrate, resistance to Portland cement's alkalinity, high flexibility, and resistance to aggressive chemicals, deicing salts, and free-thaw cycles (Gama, 1999). Common overlay materials used by DelDOT include low-slump Portland cement concrete, Polymer Modified Concrete (PMC), Latex Modified Concrete (LMC), and asphalt.

LMC contains latex rubber as a secondary binding phase. Latexes are formed by dispersing polymer particles—mostly acrylics, styrene-butadiene rubbers (SBR), and polyvinyl acetates (PVA)—in water to form emulsions that can be seamlessly dispersed into a concrete mix (Kardon, 1997). The water content in the latex must be taken into consideration in the mix design of the concrete (Lane, 2017). The addition of latex to concrete provides a continuous impermeable film in the hardened concrete that reduces its permeability. Latex was also found to promote the bond of overlay to a concrete substrate (Gama, 1999). One major drawbacks to the use of LMC is the relatively long curing time, which increases the time to reopening a bridge to traffic. Moist-curing of LMC of at least 48 hours with an allowance of about 72 hours for drying is recommended prior to opening the traffic (Gama, 1999; Lane, 2017). An additional disadvantage of LMC is that it cannot be placed in freezing conditions; the material must be placed at ambient temperatures ranging from 45 °F to 86 °F. Although admixtures can be reduce the curing time of

LMC, this modification increases the cost of LMC. Per ACI 548.4M, an LMC overlay should have a minimum thickness of 1 in. Because LMC should not be mixed for more than 5 minutes, it is recommended that mixing is done onsite as recommended by the manufacturer. Most latex manufacturers recommend a continuous mobile batch mixer for bridge and parking deck applications (Wallace, 1987).

PPC, on the other hand, does not contain cement and the primary binding phase is polyester. The primary benefit of PPC over LMC is its rapid curing at ambient temperature as well as superior bonding to substrate concrete. Curing of polyester is controlled by an initiator. The initiator content can be varied to improve the working life of PPC and its curing kinetics. PPC should not be mixed at ambient temperatures below 50 °F (Lane, 2017), making it difficult to apply in field conditions during the colder months of the year. Mixing of PPC should be done with care as polyester resin and initiator are both flammable, although inert filler is often recommended by the manufacturers to reduce explosion hazards (Gama, 1999). In addition to rapid curing, PPC is also characterized with improved fracture toughness, tensile strength and durability when compared to PMCs. However, PPC undergoes shrinkage during curing, necessitating application of primer prior to placement to mitigate the negative effects of shrinkage on the bond performance (Gama, 1999).

Asphalt can also be used as an overlay, both with and without a membrane (which is primarily used for waterproofing and is applied as either a sheet or a liquid). The advantages of asphalt overlays are simplicity of application, relatively low cost, and enhanced rideability (Haynes et al., 2020) . The drawback of utilizing asphalt overlays is the fact that they collect water and/or chlorides underneath them (Krauss et al., 2009). According to Haynes et al. (2020), water accumulation ultimately leads to cracking and debonding of the overlay due to freeze-thaw cycles. Various types of fractures and pitting are common in asphalt. Fissures can develop for a variety of other causes, including uneven pavement surfaces, poor mixing, and paving over existing cracks. If the substrate is weak or deteriorated, an asphalt overlay is not typically a good choice since it will not last for a long time and a total replacement is more economically effective.

2.3 Factors Influencing Overlay-Substrate Bond

The bond strength between the overlay and substrate is influenced firstly by the cleanness of the substrate's surface. The bond surface between the overlay and substrate needs to be clear of debris, contaminants, and grease as they significantly impact the bond strength by forming a layer that prevents interlocking between the substrate and overlay (Silfwerbrand, 1990; Austin et al., 1995). Impurities are typically removed by pressure air, but removing oil or grease from a surface can be challenging.

To create an appropriate substrate surface by removing the laitance and increasing the roughness, the surface must be prepared before placing the overlay. In case the substrate is old, and the overlay is used for repair, surface preparation removes deteriorated material. While some techniques, such as wire brushing, can only remove a thin layer of concrete, other techniques, (e.g., hydrodemolition) can remove material down to a considerable depth. According to Silfwerbrand (1990), some of the more vigorous surface treatments effectively increase surface roughness but also introduce microcracks in the surface concrete. Surface preparation methods that result in microcracks adversely affect the top layer of the substrate and can significantly diminish bond strength.

Properties of the overlay also play a role in the bond performance. For instance, implementation of effective overlay curing protocols is important to limit shrinkage and the associated overlay cracking. Curing procedures differ by overlay type. For example, overlays incorporating Portland cement are moist-cured, while PPC is protected from moisture during its curing, per DelDOT (2022). Another factor related to the overlay curing is the ambient temperature. For example, hydration reaction is an exothermic reaction, so the reaction kinetics correlate with an ambient temperature. Fladr et al. (2019) showed that if the curing temperature is high, the thermal contrast between the overlay material and ambient temperature can lead to overlay cracking and reduced strength. In addition, at high ambient temperatures, the hydration reaction advances rapidly leading to reduced concrete strength compared to curing under more optimal conditions (Figure 3).

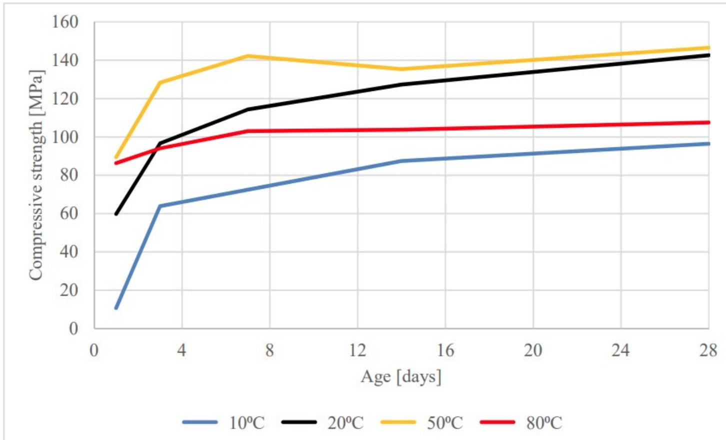


Figure 3. Development of concrete compressive strength at different ambient temperatures (Fladr et al., 2019).

The influence of age on the overlay-substrate bond strength can be considered over short and long term. The short term begins with casting the overlay including the curing period. The bond strength is expected to increase rapidly during this phase as the overlay material is gaining strength. A study conducted on the early-age bond strength of concrete overlays (Bissonnette et al., 2011) revealed that the bond strength development was faster than the compressive strength development—bond strength plateaued in 14 days compared to 28 days for compressive strength as shown in Figure 4). The long-term performance of overlay-substrate bonds will depend on several factors, primarily the loading history and environmental effects (e.g., temperature swings, exposure to aggressive chemicals and moisture, etc.)

Adequate compaction of the overlay is needed to ensure overlay material homogeneity and to minimize the presence of air voids. Good compaction also reduces the occurrence of air voids along the interface, thus increasing the contact area between the overlay and substrate. This is particularly important in surfaces with high surface roughness amplitude (Silfwerbrand, 1990).

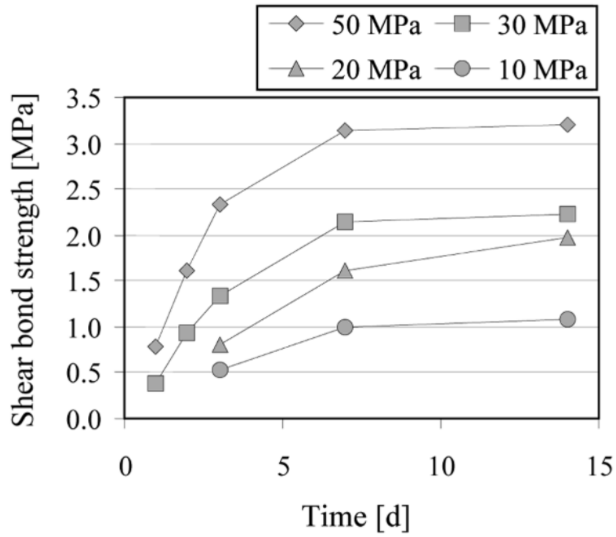


Figure 4. Interface shear bond strength development for overlays of different compressive strengths (Bissonnette et al., 2011).

2.4 Bond Test Methods

Methods for testing the bond strength of interfaces between cementitious can be divided into shear and tension tests. The tensile bond strength can be measured using a bond pull-off test ASTM C1583 (ASTM, 2020), direct tension test, and split cylinder test (ASTM C496), while a slant-shear test ASTM C0882 (ASTM, 2020) is used to measure shear bond strength. The typical test values for different tests are summarized in Table 1. The test methods presented in Table 1 are not universally applicable to all overlay applications. For instance, the slant shear test is not recommended by ACI 546.3R, primarily because it does not capture bond strength adequately owing to its dependence on the compressive strength of the substrate. The following subsections provide an overview of the most commonly utilized test methods.

Table 1. Available bond test methods and typical test values for Portland-cement concrete overlays ACI 546.3R.

Description	Test method	Typical value
Direct tensile bond	ASTM C1404 CSA A23.2-6B ASTM C1583 ICRI 210.3	1 day – 70 to 150 psi (0.48 to 1.0 MPa) 7 days – 150 to 250 psi (1.0 to 1.7 MPa) 28 days – 250 to 300 psi (1.7 to 2.1 MPa)
Slant shear bond	ASTM C1042 ASTM C882	1 day – 400 to 1000 psi (2.8 to 6.9 MPa) 7 days – 1000 to 1800 psi (6.9 to 12 MPa) 28 days – 2000 to 3000 psi (14 to 21 MPa)

2.4.1 Bond Pull-off Test

ASTM C1583 (ASTM, 2020) bond pull-off test measures the tensile bond strength between an overlay material and a substrate. The test is performed by drilling a core into the substrate to a minimum depth of 0.5 in. into the substrate. A metallic puck is then glued to the top of the specimen and the load is then applied at a rate of 5 psi/s, using an apparatus shown in Figure 5. At the conclusion of the test, the maximum load and the failure mode are recorded. Failure will occur either at the overlay-substrate interface, in the overlay, in the substrate, or at the puck-overlay interface. Only the overlay-substrate interface failure mode is indicative of overlay bond strength, while the cohesive failure of the substrate/overlay indicate the lower bound on the bond strength. Tests that result in puck-overlay interface failure are not considered valid. The test, unlike the other bond tests to be discussed, can be used for both field and laboratory measurement of bond strength.

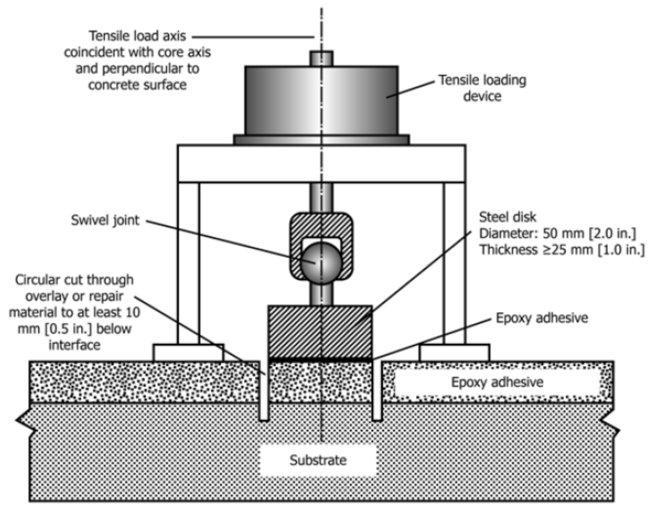


Figure 5. Schematic of the bond pull-off test setup ASTM C1583 (ASTM, 2020).

2.4.2 Direct Tension Test

Direct tension test is another method employed to obtain the bond strength of bonded cementitious materials. The test is conducted by subjecting the test specimen to direct tension, as shown in Figure 6. The test specimen comprises a bonded substrate and overlay material. ASTM C1404 recommends each half (substrate and overlay) to be made with half of a 3 in. by 6 in. cylindrical mold, placed in a steel-pipe nipple separated by 0.2 in. The steel pipe nipple and O-ring, shown in Figure 6, promote the occurrence of interface failure mode, thus, allowing to directly measure bond strength (Semendary et al., 2019). It should be noted that ASTM C1401 standard was withdrawn in 2010 due to the introduction of ASTM C1583 (ASTM, 2020). However, the ability of the test methods to promote interfacial failure makes it favorable for capturing bond strength. Furthermore, the test can capture the direct tension that occurs in bridge deck overlays when the overlays experience shrinkage-induced curling (Newtson et al., 2018).

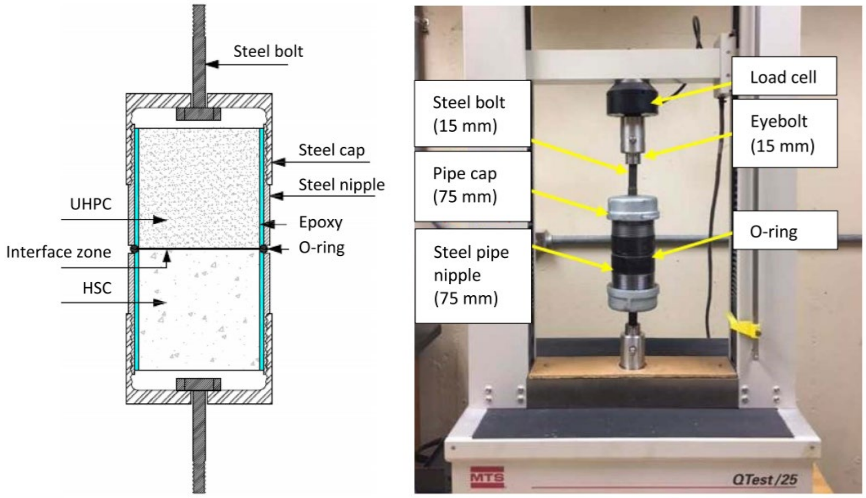


Figure 6. Example specimen for direct tension bond tests (Semendary et al., 2019).

2.4.3 Splitting Tensile Test

Splitting tensile test involves indirectly subjecting overlay-substrate interface to tensile stresses, analogous to ASTM C496. The test specimen comprises two bonded half-cylindrical samples, tested in a setup shown in Figure 7. The bond strength is computed as:

$$F_n = \frac{2P}{\pi d h} \tag{1}$$

Where:

F_n: Bond strength

P: Ultimate load

d: Specimen diameter

h: Specimen height

Figure 7. Splitting tensile bond test setup (Newtson et al., 2018).

2.4.4 Slant Shear Test

Slant shear test is conducted by applying a compression force to a cylindrical test specimen. The test specimen is made up of two halves of 3 in. by a 6 in. cylinder with a 30-degree-angle interface (Figure 8). The experimental setup is simple to conduct and the test simulates real-life conditions where combined compression and shear forces are imposed on structures. Júlio et al., (2004) reported that this test method is more sensitive to the effect of surface roughness than other test methods, making it appropriate for investigating the effect of surface roughness on the bond strength. The bond strength is computed as follows:

$$\tau_n = \frac{P}{A}\sin\theta\cos\theta \qquad (2)$$

τ_n: Shear stress

P: Ultimate load

A: Cross sectional area

θ: Angle of bonded interface with the horizontal plane

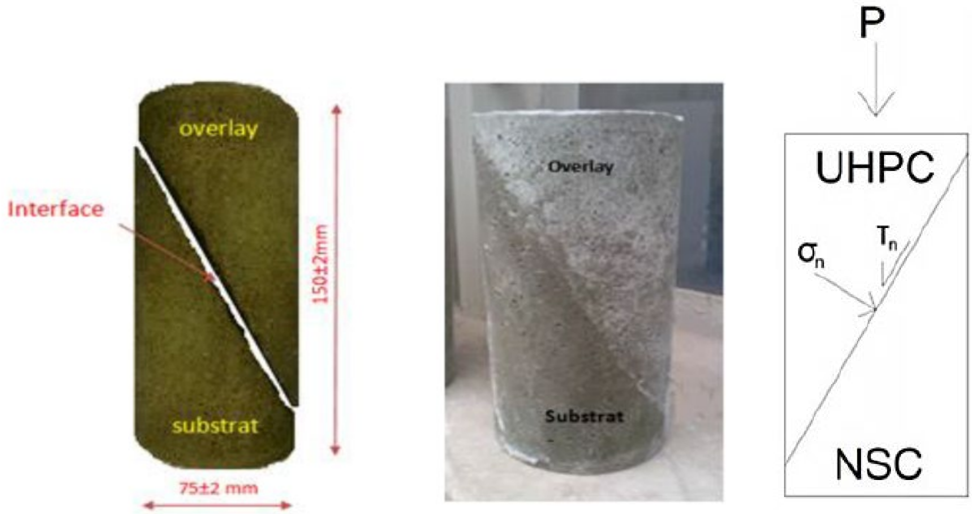


Figure 8. Slant shear bond test specimen (Dawood et al., 2017).

2.5 Construction guidelines

According to AASHTO T-34 (Guide Specifications for Polymer Concrete Bridge Deck Overlays) and ACI 548.4M-11 (Specification for LMC Overlays), a minimum pull-off bond strength of 250 psi and 200 psi is recommended for PPC and LMC overlays, respectively. ACI 548.5R (Guide for Polymer Concrete Overlays) specified that acceptable tensile bond strength is achieved when either:

a) the minimum pull-off strength of 250 psi from an average of three tests regardless of the depth of failure plane; or

b) failure occurs in the substrate at a depth of at least 1/4 in. over more than 50% of the test area for three of four tests.

If (a) or (b) are not satisfied, the surface preparation should be adjusted. The manufacturer's batching, mixing, placing, and curing requirements should also be modified until the desired strength is obtained. For a normal concrete substrate, the (b) requirement can be satisfied if the tensile strength of the overlay is higher than the bond strength or the cohesive strength of the substrate. However, in the case of a UHPC substrate (which has high tensile strength compared to most overlays), this condition may not be satisfied despite the bond strength being high enough.

DelDOT standard specifications for road and bridge construction (Majeski et al., 2022) also recommend a minimum pull-off bond strength of 250 psi for PPC and MCD overlays. However, DelDOT does not have an explicit bond strength requirement for LMC overlays. For the construction phase, ensuring the quality of the overlay and satisfactory bond strength is achieved by following guidelines on substrate surface evaluation and preparation, overlay material selection, finishing and curing.

2.5.1 Substrate Evaluation and Preparation

The guide for polymer concrete overlays (ACI 548.5R) recommends evaluating and preparing the substrate surface prior to applying the overlay. Visual inspection and acoustic sounding are conducted to confirm that the entire substrate surface is free of delaminations. In addition, copper sulfate electrode tests may be conducted to locate areas of active reinforcing steel corrosion that could contribute to delaminated concrete in the future. Concrete that is delaminated, containing chlorides that cause reinforcing bar corrosion, or has a compressive strength less than 2000 psi should be removed and replaced with higher-quality concrete. If reinforcing bar corrosion is present, a corrosion protection system should be considered. The age of the concrete surface should also be considered, as newly cast decks should be cured for at least 28 days and existing decks should be dry before the overlay is applied. If necessary, substrate repairs may be required, including the repair of defects such as delaminations, spalls, cracks, and improper drainage. Damaged sections should be removed with tools such as chipping hammers, bush hammers, and scarifiers, that do not further damage the surrounding areas. Other acceptable removal methods include dry or wet sandblasting, airless blasting using steel shot, and high-pressure water blasting (8 to 23 Ksi). In addition, the substrate surface should also be free of stagnant water, oil, dirt, grease, curing agent, and laitance.

AC I548.4M provides specifications for the use of LMC overlays. The specification recommends that the substrate should be blasted clean and saturated surface dry (SSD) for 1 hour before placement of LMC overlay. Similar to substrate preparation for PPC, standing water and other surface impurities should be removed. The concrete substrate surface should have a minimum profile of CSP 5 as described by ICRI R310.2. The substrate preparation should be done to achieve the minimum bond strength as specified in the contract document, or the tensile strength of the substrate if it is greater. DelDOT's surface preparation specifications (Majeski et al., 2022) for PPC and LMC align with AASHTO T34 and AC I548.4M. For MCD, DelDOT's specifications provide the same surface evaluation and preparation as for LMC including the SSD condition.

2.5.2 Mixing Equipment and Materials

According to DelDOT's specifications (Majeski et al., 2022), the mix composition of PPC should contain approximately 12% polyester resin by weight of dry aggregate, with the percentage adjusted during placement to enable proper finishing and texturing of the overlay surface. The amount of polyester concrete initiator should be used to produce an initial set time between 30 and 90 minutes. Accelerators or inhibitors recommended by the resin supplier should be used to achieve proper set times. Continuous automated mixers should be used that produce a satisfactory mix consistently throughout the application process. The mixers should be portable mechanical mixers of appropriate design and size as recommended by the PPC system provider.

Mixing LMC must be in a self-contained, mobile, continuous mixing-type equipment. Mixers should be self-propelled and capable of carrying sufficient unmixed dry bulk cement, sand, coarse aggregate, latex modifier, and water to produce the needed batch volume of LMC. The mixers should be equipped with visible recording meters for measuring cement and adjustable flow meters for controlling the flow of water and latex emulsion into the mixing chamber. The mixers need to be clean and calibrated to automatically proportion and blend all components of the indicated composition on a continuous or intermittent basis. The mixers should have enough capacity to allow placement and finishing operations to proceed at a steady pace. LMC is mixed on-site and the ingredients should be added in accordance with the recommendations of the latex modifier manufacturer. The slump of LMC must be between 4 and 6 in. at the point of discharge and should meet the latex manufacturer's minimum mixing time recommendations to ensure the correct air content and slump. When discharged, LMC must remain uniform in composition. The maximum time allowed between the start of mixing and the completion of discharge at the worksite is 60 minutes.

Finally, MCD is mixed like any Portland cement concrete with care to use Delaware #8 aggregates and shrinkage reduction admixtures capable of reducing 80% of the shrinkage in addition to Synthetic fibers conforming to the requirements of ASTM C1116, Type III. The bond agent used for MCD should conform to AASHTO M235 Type V or ASTM C1059 type II

2.5.3 Finishing and Curing

The thickness of PPC should be checked with a ruler before its initial set, and if the minimum thickness was not achieved, an additional layer with a minimum thickness of 1/4 in. should be added after the overlay hardens. The finished PPC surface should be free of any smooth or glassy areas. Any surface defects should be repaired in the manner recommended by the manufacturer. Per the DelDOT's specifications, PPC should be protected from moisture for a minimum of 4 hours after finishing. In addition, the traffic can be opened after PPC overlay reaches full cure (a minimum of 4 hours after finishing).

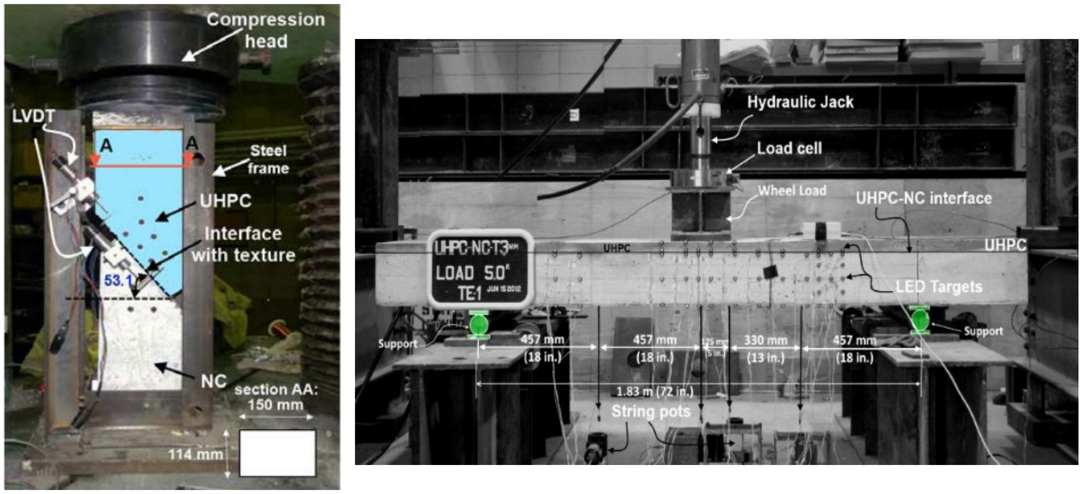
LMC is to be consolidated especially around the edges and areas around the joints using vibrating machines. LMC must be finished before a plastic film forms on the surface. For curing, LMC must be covered with wet burlap and polyethylene film withing 20 min since the overlay application. Burlap is kept wet for 48 hours and removed after to let LMC to air cure for an additional 72 hours. During the curing period the temperature should not fall below 45 °F.

For MCD, curing is done by covering the finished overlay surface with wet burlap and a layer of white opaque polyethylene sheeting. The polyethylene sheet material is secured to prevent displacement. The curing temperature should not drop below 45 °F. Moist curing should be implemented until MCD reaches the full design compressive strength (4500 psi), or for a minimum of 14 days.

2.6 Bonding of Cementitious Materials

Several studies were conducted to capture the factors affecting the bond strength between concrete materials. This section provides a brief overview of some of the relevant studies. Factors such as substrate surface roughness, substrate hygric state, substrate strength, and test method are presented.

Aaleti et al. (2019) studied the bond strength between UHPC overlay and normal-strength concrete (NC). The effects of substrate roughness, concrete strength, and curing condition on shear transfer at the UHPC-NC interface were investigated. The surface roughness of the substrate was varied and categorized as low roughness (<0.059 in.), medium roughness (0.118 in.), and high roughness (>0.197 in.). A slant shear test was employed to simulate the combined compression and shear effect (Figure 9a). Findings showed that the shear strength of 3162 psi (21.8 MPa) obtained with a surface roughness depth of 0.063 in (1.6 mm) was slightly higher than the 28 days interface shear strength of 3045 psi (21 MPa) recommended by (ACI 2006). An increase in texture depth from 0.05 in. (1.26 mm) to 0.063 in. (1.59 mm) increased interface shear capacity by 812 psi (5.6 MPa). Based on the result from the slant shear test, which shows a positive correlation between surface roughness and bond strength, three-point bending tests were conducted on UHPC bonded to NC composite to replicate bridge deck condition (Figure 9 b). The same range of interface texture depth was adopted. The composite deck with a 0.197 in. texture depth resulted in a 7% higher load capacity compared to a0.118 in. texture depth. Thus, surface roughness is important in promoting shear strength at the overlay-deck interface.



(a) (b)

Figure 9. Test specimens: (a) slant shear bond test; and (b) flexural test on a precast concrete deck with UHPC overlay (Aaleti et al., 2019).

Several studies recommend SSD condition in the substrate prior to overlay placement. As noted by Omar (2010), if the surface is dry, the water in overlay materials will be absorbed by the substrate which can lead to incomplete hydration of the cement and reduce flexural strength from 363 psi to 261 psi. However, if the substrate is wet with the presence of free water, the pores can be inaccessible, impacting the ability of the overlay material to penetrate the substrate and establish proper adhesion (Júlio et al., 2004). Beushausen (2010) and Beushausen et al. (2017) further suggested that the presence of moisture could negatively impact the bond strength. A direct comparison of the effect of surface moisture on bond strength was reported (Austin et al., 1995)—a slight increase of 6.4% was observed in adopting an SSD surface in place of a wet surface. The authors, however, acknowledge that bond strength is dependent on numerous interrelated factors such as repair material properties and substrate surface roughness. Hence, it is recommended that pre-wetting to achieve SSD can increase tensile bond strength (De la Varga et al., 2018). Overall, the literature contains conflicting evidence as to the effects of substrate hygric state on the bond strength. Additional work is needed to clarify the hygric state effects for a wider range of materials, surface preparation methods, and bond test methods.

Júlio et al. (2004) studied the effect of bond strength between two bonded concrete materials, by adopting slant shear and bond pull-off tests. The surface of the substrates was prepared using five approaches, (1) cast against steel formwork, (2) surface prepared with a steel brush, (3) partly chipped surface (4) partly chipped surface plus water saturation 24 h before concrete cast, and (5) sandblasted surface. Bond pull-off test was conducted on 0.2 m. cube, a core of 3 in. (75 mm) diameter was drilled into the samples, extending 0.6in. (15 mm) beyond the interface into the substrate. Using epoxy, a circular steel disc was bonded to the top of the sample and pulled at a rate of 7.25 psi/s (0.05 MPa/s) until debonding occurred. Preliminary tests conducted by the authors suggested that the compressive strength of the overlay must be less than that of the substrate to avoid cohesive failure of the substrate when using the slant shear test.

Results from pull-off tests (Figure 10) revealed that with no surface preparation, the bond strength of overlay to substrates can be low such that debonding occurred during core drilling. Sandblasting gave the highest bond strength for bond pull-off and shear tests. A respective increase from 0 psi to 384 psi in pull off bond strength and from 189 psi to 1860 psi in shear strength was reported with sandblasted surfaces. While the effect of pre-wetting was stated to be insignificant to bond strength, the authors did not provide data to support this conclusion. Furthermore, the relationship between the slant shear test and bond pull-off test was presented as shown in Figure 11. A positive correlation between the two tests was noted. Thus, it might be possible to adopt slant shear tests to evaluate in situ bond strength.

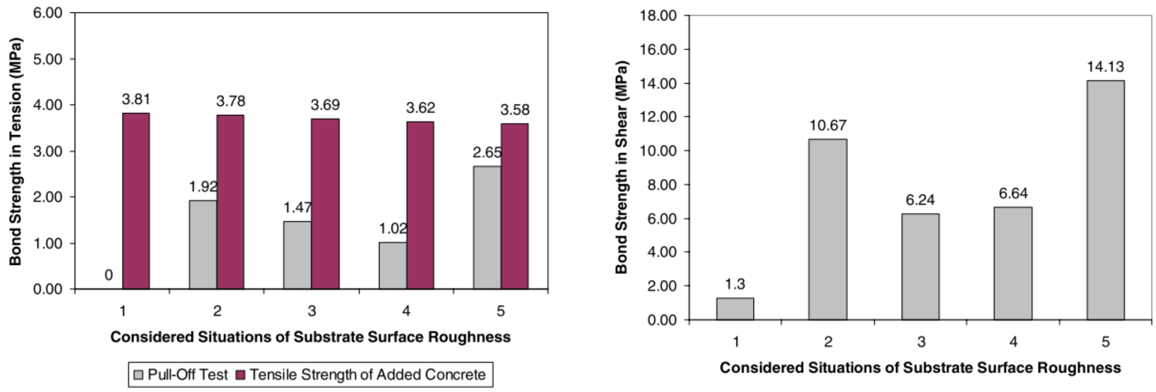


Figure 10. Tensile bond strength of concrete-to-concrete bonds (Júlio et al., 2004).

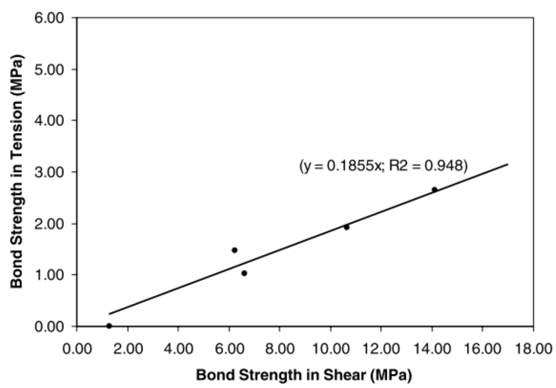


Figure 11. Correlation between bond shear tests and bond pull-off tests concrete (Júlio et al., 2004).

Haber et al. (2018) characterized the behavior of UHPC as an overlay material on bridge decks. The surface of the substrate was prepared using HD and scarification. Field tests on the Laporte Road bridge in Iowa and laboratory tests were reported. In addition, microstructural analysis using Scanning Electron Microscopy (SEM) was used to evaluate the consolidation of UHPC and the porosity of the interface. Bond strength was measured using ASTM C1583 (ASTM, 2020). As shown in Figure 12, the bond strength of UHPC overlay with surface prepared using scarification was low (0.78 MPa) in comparison to 496 psi achieved when HD was employed. The higher strength can be attributed to higher surface roughness achieved using HD. The HD surface was classified as having surface texture consistent with ICRI CSP 10 as compared to CSP 7 which was obtained using scarification. A change in failure mode can also be observed in the laboratory data presented in Figure 12. While overlays placed on scarified concrete surface failed at the interface, the failure occurred in the substrate for HD specimens.

Table 2 summarizes field pull-off bond tests. The field bond strength values from locations without delaminated or distressed concrete were within the range of laboratory values; two locations exhibited the puck-overlay interface failure and thus represent the lower bound on the bond strength. The tests performed at locations suspected to have damaged concrete substrate exhibited significantly lower bond strength values accompanied with cohesive failure of the concrete substrate (Figure 12).

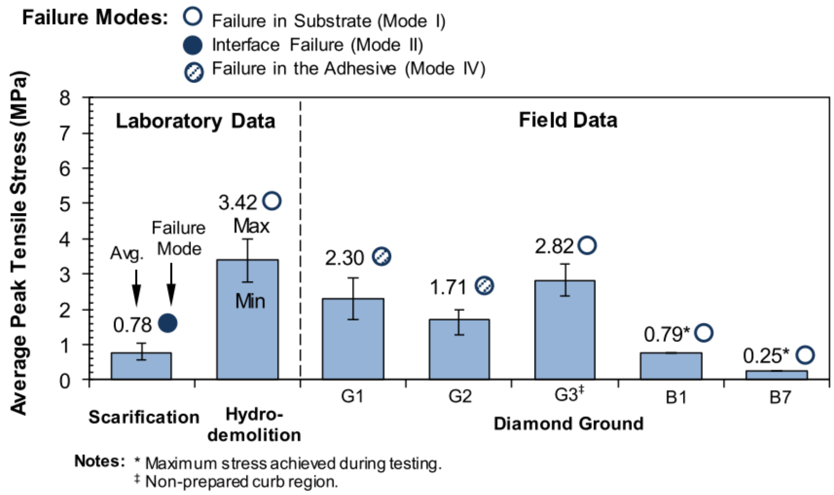


Figure 12. Tensile bond strength of UHPC overlays on concrete (Haber et al., 2018).

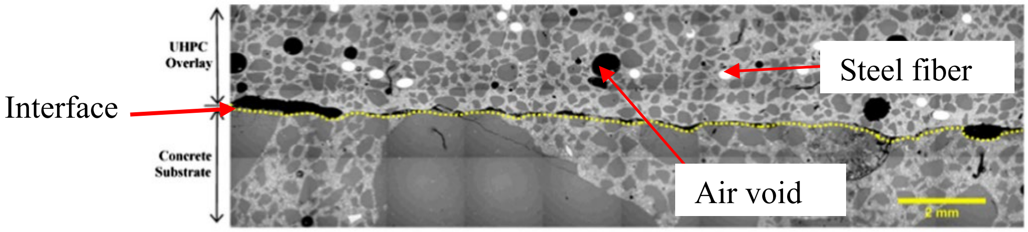
Table 2. Test matrix for the field tests (Haber et al., 2018).

Location ID	Lane (Construction Stage)	Potential Delamination*	Diamond Ground Substrate	Existing Distressed Concrete
G1	West-Bound (1)	No	Yes	No
G2	East-Bound (2)	No	Yes	No
G3	East-Bound (2)	No	No	No
B1	West-Bound (1)	Yes	Yes	Yes**
B7	East-Bound (2)	Yes	Yes	No

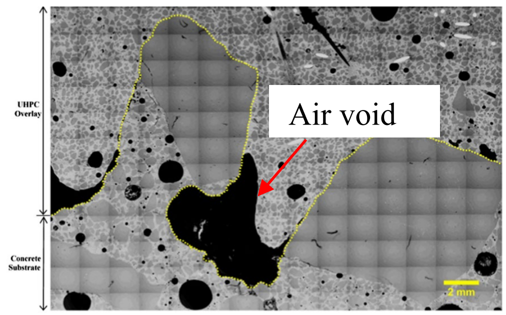
Notes:
*As determined by chain drag.
**As determined by photographic evidence.

To investigate the effect of consolidation, microstructural analysis was conducted on UHPC-concrete interfaces using a sample area of 45 mm by 25 mm. SEM backscattered images with a magnification of 150X were collected to analyze the interface properties, and evaluate the interfacial region for presence of fibers and entrapped air. As shown in Figure 13 a, the interfacial region has no steel fibers; therefore, steel fibers did not contribute to the adhesion along the bondline. Next, consolidation of the interface was quantified by measuring the area of air voids at the interface. From Figure 13, the surface prepared with HD was found to have more air voids than scarified surface due to the increased macro-texture of the concrete substrate. In addition, the samples from the laboratory were observed to have more voids than field samples. The difference was associated with poor consolidation in the lab samples—the researchers used a low-power motorized hand trowel device whereas a lane-width vibratory screed was used in the field.

The authors concluded that an interface void content of less than 10% results in adequate tensile bond strength at the interface. HD surface preparation was recommended because, unlike scarification, and despite the higher possibility to result in air voids, it has a low tendency to introduce microcracks in the substrate. Its other benefit is the higher degree of macrotexture roughness for improved mechanical interlock.



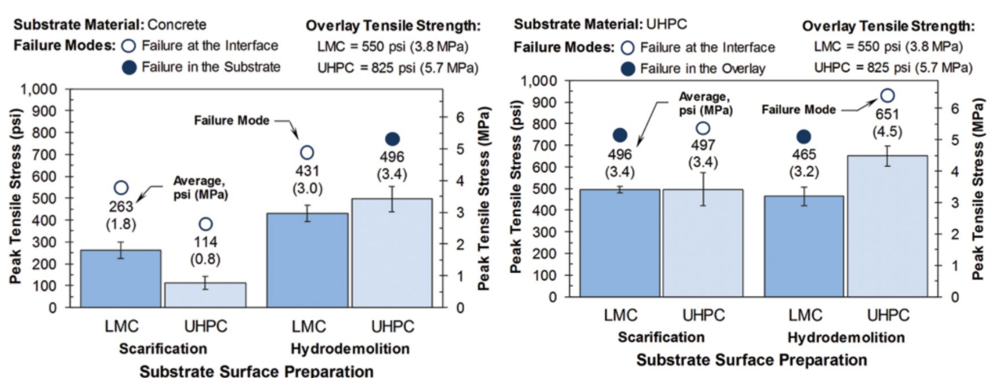
(a)



(b)

Figure 13. Microstructure of the interface region for specimens prepared via (a) scarification and (b) hydrodemolition (Haber et al., 2018).

Haber et al. (2017) compared the use of LMC and UHPC as overlays on normal concrete and UHPC substrates. For each of the overlays, the concrete surfaces were prepared with scarification and HD, and bond pull-off tests were conducted to assess the bond strength. Figure 14 shows the peak tensile stresses of LMC and UHPC overlays on concrete and UHPC substrates. Comparatively, the bond strength of UHPC was higher on both substrates except for the instance where scarification was adopted for overlay on the concrete substrate. Overall, authors concluded that hydrodemolition is more desirable than scarification. In addition, it was observed that the measured bond strengths on UHPC were higher than those on the concrete substrates.



(a) (b)

Figure 14. Peak stresses recorded from direct tension bond tests on (a) a concrete substrate, and (b) UHPC substrate (Haber et al., 2017).

Newtson et al. (2018) investigated the performance of a locally produced UHPC as a repair material for normal strength concrete. The authors conducted slant-shear, splitting tension, and direct tension tests to measure the bond strength between UHPC and the substrate. The surface of NSC was prepared using mechanical hand-held grinders. The macrotexture depth on the test specimens was measured per ASTM E965 and classified in Figure 15 as (1) lightly ground with a depth of 0.002 in. (0.05 mm), (2) horizontal grooves with a depth of 0.035 in. (0.9 mm), (3) cross-hatched with a depth of 0.063 in. (1.6 mm), and (4) rough with a depth of 0.11 in. (2.8 mm). The average slant-shear bond strengths measured at 7 days are presented in Figure 16. The highest shear stress of 2610 psi (18 MPa) was obtained on the roughest concrete surface, which was 1523 psi higher than the shear strength of the lightly ground surface. The minimum bond strength obtained of 1088 psi (7.5 MPa) was higher than the minimum 1000 psi (7 MPa) recommended by ACI 546.04 for slant shear, showing that all the surface preparation methods adopted provided adequate shear strength.

(a) (b) (c) (d)

Figure 15. Surface texture of the substrate: (a) lightly ground with a depth of 0.002 in. (0.05 mm); (b) horizontal grooves with a depth of 0.035 in. (0.9 mm); (c) cross-hatched with a depth of 0.063 in. (1.6 mm); and (d) rough with a depth of 0.11 in. (2.8 mm) (Newtson et al., 2018).

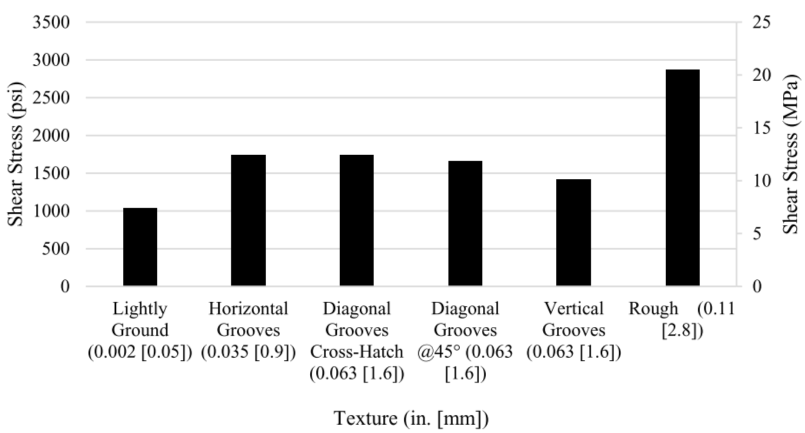


Figure 16. Slant-shear bond strengths (Newtson et al., 2018).

The tensile bond strengths are shown Figure 17. As the texture depth increases, the tensile strength of the prism specimen also increased. The authors attributed this increase to the greater surface area of the more textured surfaces. For cylindrical specimens, a relationship between tensile strength and texture could not be established from the data. Despite the differences between the two test methods, the minimum recorded tensile strength of 232 psi (1.6 MPa) was higher than the minimum recommended strength of 150 psi (1 MPa) recommended by ACI 546.04 for direct tension.

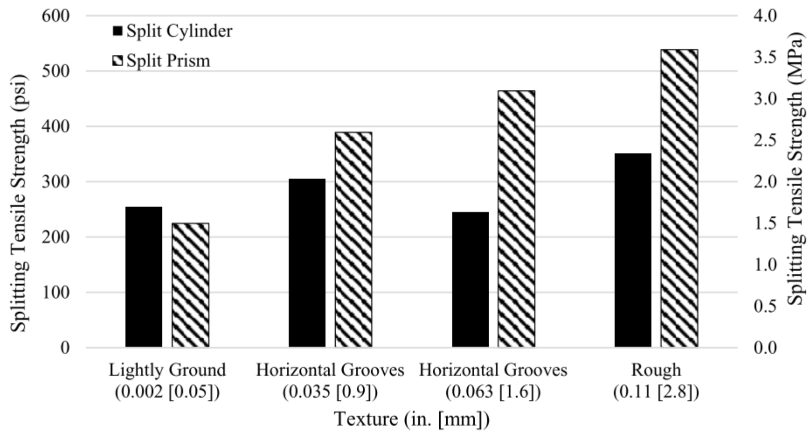


Figure 17. Split cylinder and split prism bond test results (Newtson et al., 2018).

The result from the direct tension test is shown in Figure 18. ACI 546.04 recommends a tensile strength of 150 psi (1 MPa) for concrete repair material. Tensile strength on the concrete chipped surface resulted in a bond strength of 154 psi (1.06 MPa), this value is slightly greater than the minimum tensile bond strength of 150 psi (1 MPa) recommended for concrete repair by ACI 546.04. The higher tensile strength on the rough and chipped surfaces in comparison to horizontal grooves was attributed to the greater surface area and exposed aggregate that allows UHPC to bond better to the concrete surface.

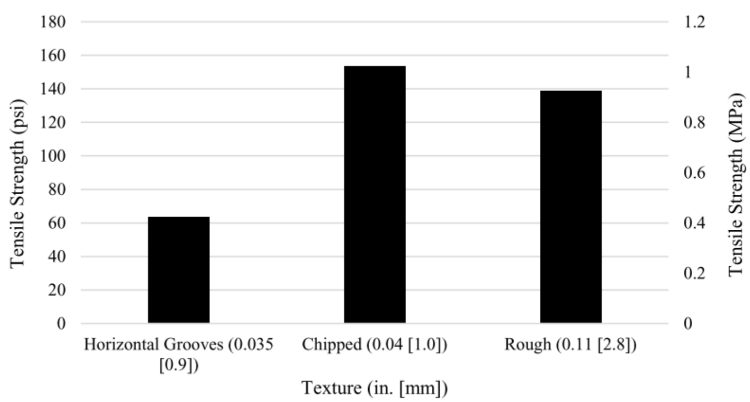
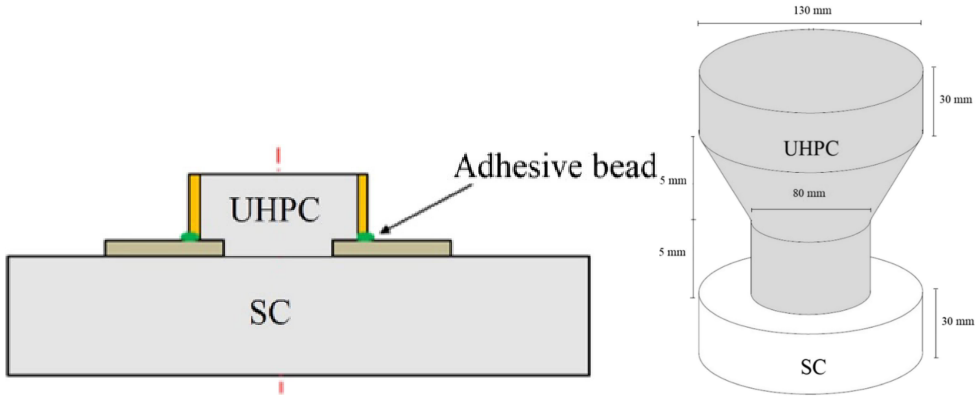


Figure 18. Direct tensiion bond strength of UHPC overlays on concrete (Newtson et al., 2018).

Valipour et al. (2020) identified some of the challenges with bond pull-off tests. One is the need to core the overlay which can damage the bond and introduce variability in the data if the ends of the drill are not sharp. The other issue is the tendency to have an undesired failure mode at the puck-overlay interface. Additionally, for UHPC overlays on NC, the likely failure mode is cohesive failure of the substrate considering the significantly higher tensile strength of UHPC. To address these concerns, Valipour et al. (2020) modified the test setup recommended by ASTM C1583 (ASTM, 2020) (Figure 19a). A PVC tube was positioned on the substrate before placing the UHPC overlay to eliminate the need for coring. A thin metal washer was also introduced at the interface to reduce the contact area and force the failure at the interface. The authors also proposed a laboratory-targeted bond test method modification to obtain bond strength. The test setup involves having a conical-shaped overlay material cast on the concrete substrate. The shape can be achieved by casting the base and inserting a cylindrical PVC in the cylinder before placing the overlay material as shown in Figure 19b. SC is first cast into a cylindrical mold measuring 5.12

in (130 mm) in diameter and 3 in (75 mm) in height. The first layer of concrete is 1.2 in (30 mm) while the top layer is 3.15 in (80 mm) of UHPC with an intermediate width of 3.15 in (80 mm).



(a) (b)

Figure 19. Schematic illustration of (a) the modified bond pull-off test (b) debonding test method (Valipour et al., 2020).

The results of the bond pull-off test on concrete slabs showed that irrespective of the overlay thickness of UHPC, failure occurred in the substrate (Table 3), suggesting good bonding between the substrate and UHPC. No relationship can be established between bond strength and overlay thickness in the study. However, the coefficient of variation (COV) increased with overlay thickness, likely because of a strength mismatch between the substrate concrete and UHPC. The authors attribute the high COV to spatial variability in the substrate (e.g., shape, diameter, and strength of the coarse aggregate) and effects of test parameters such as the coring process, load eccentricity, and variation in the loading rate.

Table 3. Bond strength and failure modes (Valipour et al., 2020).

Samples	Number of samples	Bond strength (MPa)	C.O.V. (%)	Fracture mode
UHPC-1 (6 mm)	5	0.45	27.5	A
UHPC-1 (12 mm)	5	0.5	41.6	A
UHPC-1 (19 mm)	5	0.45	44.8	A
UHPC-1 (25 mm)	5	0.52	67.4	A

The modification of the bond pull-off test did not address the limitations of the test. Cohesive failure of the substrate was still the dominant failure mode. However, several failures at the UHPC-substrate interface were observed demonstrating that interface failure is possible. The bond strengths obtained using the modified test method of 65.3 psi (0.45 MPa) was observed to be lower than that obtained using a bond pull-off test, making it difficult to verify if the values from the established pull-off strength were estimated using the modified tensile test.

Curing time is crucial for the development of bond strength, the tendency of premature bond failure exists if the composite material is loaded beyond the bond strength due to incomplete curing of the overlay material. As presented in Figure 20 longer curing time results in higher bonding of UHPC overlay on concrete substrate.

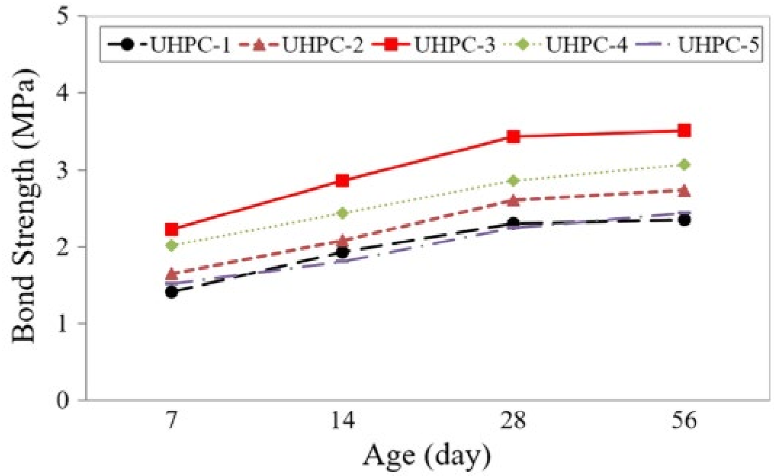


Figure 20. Effect of curing of UHPC overlay on bond strength (UHPC 1,2,3,4, and 5 represent different mix ratios) (Valipour et al., 2020).

2.7 Summary

From the literature reviewed, factors affecting bond strength have been identified, and different overlay materials and their benefits for bridge deck application have also been outlined. Common overlay materials include asphalt and low-slump Portland cement, such as modified Class D concrete, polymer modified concrete, and latex modified concrete were introduced. The literature highlighted that LMC and PPC have superior bond strength and improved durability compared to other types of overlays; however, LMC and PPC are more expensive. Several factors that influence overlay-substrate bond strength were identified, most importantly surface preparation and hygric state. However, only one small-scale study evaluated the performance of LMC and UHPC overlays on a UHPC substrate prepared by scarification and hydrodemolition; UHPC substrate hygric state effects were not evaluated. This clearly indicates a need for additional work to elucidate the performance of various overlay materials, surface preparation methods, and substrate hygric states on the overlay-UHPC bond performance.

Test methods (including bond pull-off test, the three-point bending test, and the beam-on-ring test) and respective standards used for field and laboratory testing were also presented. While some of the other test methods may be more favorable for laboratory investigations, bond pull-off test was identified as the most suitable for larger scale studies as well as field assessment of bond strength. ASTM C1583 (ASTM, 2020) specifies a minimum core depth of 0.5 in. for bond pull-off test. However, this requirement applies to conventional concrete substrates and are currently no studies that evaluated the sensitivity coring depth on the bond pull-off strength of overlays on UHPC. Furthermore, one of the acceptance criteria for polymer concrete overlays in ACI 548.5R requires a minimum of 50% of the specimens failing within substrate material, which is unlikely to be accomplished on UHPC substrate due to its high tensile strength.

In summary, despite the numerous studies conducted to evaluate bond of overlays on conventional concrete, there is a general lack of understanding of overlay performance on a UHPC substrate. This study aims to address this gap by testing the bond strength of PPC, LMC, and MCD overlays on UHPC substrate. The test variables included overlay age, surface preparation method, and hygric state of the substrate. In addition, a sensitivity study was conducted to evaluate the effect of coring depth on the bond pull-off strength. Recommendations were made based on the findings.

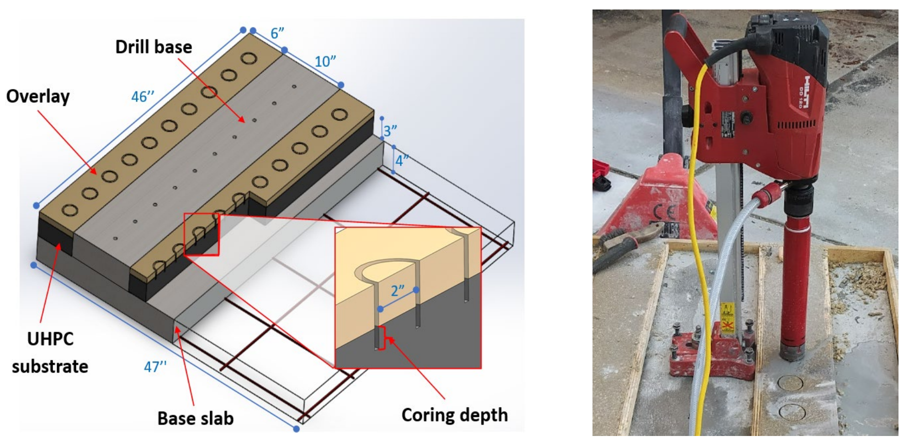
Chapter 3

EXPERIMENTAL PROGRAM

The primary objectives of the study were to:

1. Evaluate the sensitivity of bond pull-off test to coring depth;
2. Investigate the effect of PPC, LMC, and MCD overlay age on bond pull-off strength;
3. Evaluate the effect of UHPC substrate surface preparation on bond pull-off strength of PPC, LMC, and MCD overlays; and
4. Develop metrology for UHPC surface roughness measurements.

To achieve the objective of the study, multi-layer slabs measuring 46x47x8 in. were utilized (Figure 21). The 3,500-psi-concrete base slab served as a support for test strips (consisting of UHPC substrate and PPC, LMC, or MCD overlay) and normal-concrete strips (used to anchor and support the core drill rig).



(a) (b)

Figure 21. (a) Illustration of the slab components and substrate details; and (b) drill anchored to the drill base.

Bond pull-off test matrix (Table 4) was developed to evaluate the effect of several variables on the UHPC/overlay bond performance. The study first investigated the effect of coring depth on the bond pull-off strength to identify optimal coring depth for the following tests. Ten cores were tested for each depth (0, 0.5, 1, and 1.5 in.). GSB was the considered surface preparation for testing the coring depth with a PPC overlay. Considering that PPC is a fast-curing material (two-hour traffic return according to PPC manufacturer), the age of the overlay used for studying the effect of the coring depth was 14 days.

The effect of the overlay age to the bond quality was then evaluated. The coring depth was decided from the previous tests and the same surface preparation (GSB) was again considered. To investigate the change in bond quality over time, PPC, MCD, and LMC overlays of age varying from 7 to 56 days were tested. Since MCD is a portland cement concrete, the right quantity of water used is important and should not be absorbed by the substrate right after placing the overlay. Based on DelDOT’s specifications, it is compulsory to achieve a SSD hygric state of the substrate surface prior to casting the overlay. However, due to having a discontinuous pore structure, liquid absorption of UHPC is significantly reduced compared to the other types of concrete (Ben Graybeal, 2011), hence, the importance of the SSD hygric condition was addressed by testing both SSD and dry surfaces with different overlay ages and surface preparation methods.

The roughness of the substrate, which depends on the surface preparation technique used, was hypothesized as a key factor influencing the bond between the substrate and the overlay. Three methods were considered, GSB, HD, and SR. All the overlays were tested with each one of the surface preparation methods in addition to a non-prepared (NP) surface. The hygric condition of the UHPC surface was again considered when testing MCD.

At least ten bond pull-off tests were conducted to evaluate each variable for statistical significance. It is a well-known fact that bond pull-off tests are variable because of several possible failure modes and the difficulty of conducting the specimen preparation and test consistently (e.g., coring, adhering the pucks, applying the load at a perfect 90 deg. Angle). Using ten replicate tests was decided based on (1) Tatar Research Group's experience with conducting these tests on other projects (Tatar et al., 2016; Tatar et al., 2021); (2) reported variability from other similar studies from the literature; and (3) the desire to make meaningful statistical comparisons between the test groups (by reducing uncertainty). So far, the observed variability from the present study indicated that 10 tests were sufficient.

Table 4. Bond pull-off test matrix.

Research Objective	Overlay	Surface Preparation	Coring Depth (in.)	Overlay age (days)	Surface hygric state	Number of specimens
1. Coring depth	PPC	GSB	0	14	Dry	10
			0.5			10*
			1.0			10
			1.5			10
2. Overlay age	PPC, MCD	GSB	0.5	7	Dry	10
				14		10*
				28		10**
				56		10
	LMC, MCD			7	SSD	10
				14		10
				28		10***
				56		10
3. Surface Preparation	PPC, MCD	NP	0.5	28	Dry	10
		GS				10**
		HD				10
		SR				10
	LMC, MCD	NP			SSD	10
		GSB				10***
		HD				10
		SR				10

*,**,***: tests of the same conditions were conducted once and considered for each case.

Chapter 4

MATERIALS

Four materials are used for this project as previously stated (UHPC, PPC, MCD, and LMC). This section discusses the properties of each material, mixture components, and testing according to requirements specific to each material. More details about each material are available in the appendix.

4.1 Ultra High Performance Concrete

A proprietary UHPC commonly specified for link slabs and bridge connections was used. UHPC ingredients were stored in the Structural Engineering Laboratory, in a dry environment while thoroughly covered to prevent moisture ingress or steel fiber corrosion. The environment temperature was maintained between 40-95ºF (4-35ºC).

Dry ingredients (a combination of cement, ground quartz, silica fume, and sand), admixtures (water reducer), water, and steel fibers were mixed in IMER 750 mixer (Figure 22) following the UHPC manufacturer’s recommendations. Fresh mix temperature was recorded for each batch prior to placing. Ice or cold water was used on warm days to ensure that the temperature of fresh UHPC remains below 85 ºF (29 ºC). Similarly, at low ambient temperatures, warm water was used to avoid slow early strength gain. The recorded temperature for all mixes was below 85 °F.

The flow of freshly mixed UHPC was measured as per ASTM C1437. The mold and flow table conforming to ASTM C230 were leveled before starting the test. The mold was filled in a single layer with the fresh UHPC and was not tapped. After 2 min. of lifting the mold, the maximum and minimum diameters of the UHPC were measured using a tape measure; the average of the two diameters was reported as the flow value. The manufacturer-reported typical flow value was between 7 and 10 in. Results of this test varied based on weather conditions but were all acceptable in a range of 8 to 9.4 in. To ensure consistency between the mixes, the flow test was conducted for each batch of UHPC.

(a) (b)

Figure 22. (a) IMER 750 mixer used to mix UHPC; and (b) typical consistency of fresh UHPC.

Figure 23. UHPC flow test.

For each batch of UHPC, three 3 x 6 in. cylindrical specimens were prepared per ASTM C1856. The cylinders were cured in the same conditions next to the slabs (at room temperature and covered with a plastic tarp for 48 hours according to the manufacturer's recommendations). After unmolding the specimens, the top surface of each cylinder was cut with a diamond blade saw to ensure a smooth top surface. The specimens were tested at 28 days.

Based on the manufacturer's reports, the compressive strength should reach a minimum of 14 ksi at 4 days and 21ksi at 28 days. To evaluate this, the 3 in x 6 in. cylindrical specimens were used for compressive strength testing per ASTM C1856. At least 3 samples were prepared for each testing age. The ends of the cylinders were ground and loaded at 145±7 psi/s up to failure. Compressive strength evolution with time is shown in Figure 24 recorded compressive strengths exceeded both the 14 and 28-day values specified by the manufacturer.

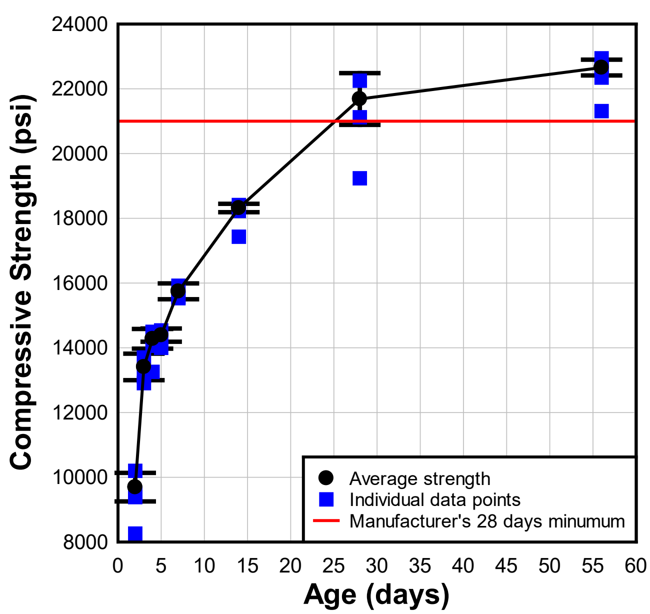


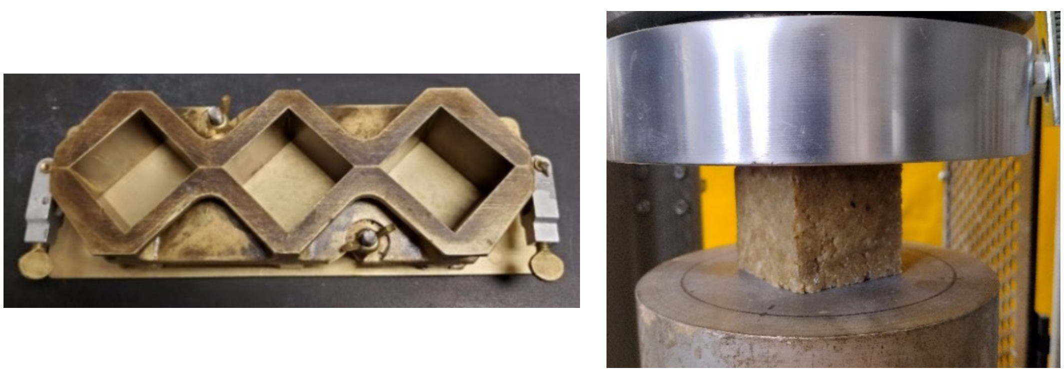
Figure 24. UHPC strength gain over time. Error bars indicate one standard deviation.

4.2 Polyester Polymer Concrete

KwikBond PPC 1121 Polyester Polymer Concrete, made from a polyester resin, curing agent, and aggregate, was used. PPC cures rapidly and can achieve a compressive strength of over 4000 psi in 24 hours. It also has higher flexural strength compared to conventional concrete. KwikBond supplied the polyester-based polymer overlay materials for this project. After the UHPC surface was prepared and blasted dry and clean using high-pressure air, the primer composed of High Molecular Weight Methacrylate (HMWM), Cumene Hydro Peroxide (CHP) Initiator, and Zcure accelerator, was mixed in a bucket, and applied evenly on the prepared surface. The bond agent mix proportions can vary based on the temperature (see Appendix A).

To combine the polyester polymer, aggregates (45 to 67% passing the #8 sieve according to AASHTO T335), and Methyl Ethyl Ketone Peroxide (MEKP) initiator, a mobile mixer is employed. PPC was applied on the prime coat after this latter has been painted on the substrate. DelDOT standard specifications require PPC containing approximately 12% polyester resin by weight of dry aggregate, which is the graded silica and quartz aggregates. Due to the equipment used in the lab which only allowed the mix of small batches, unlike UHPC mixing, PPC is mixed for each strip separately, with attention to keeping the consistency by following the same mix design for one strip of 46x6x1 in. repeatedly. During bridge construction, an abrasive sand top dressing is applied to the fresh overlay, however, to have a strong bond between the testing equipment through epoxy and the overlay, this step is not conducted.

The specimens were protected against moisture for at least 4 hours with a plastic cover. PPC was tested for compressive strength using 2 by 2 in. (Figure 25) cube specimens made in brass or steel cube molds per ASTM C109. According to AASHTO-T34, polymer overlay materials should have a minimum compressive strength of 5000 psi. The 3-day compressive strength of PPC specified by the manufacturer is 6400 psi. To ensure that the PPC specimens prepared in the laboratory meet this requirement, for each slab, three cubes were tested following ASTM C109. The measured average compressive strength at 7 days of PPC was 7013 psi, and the minimum compressive strength recorded was 5714 psi which exceeded the 5000 psi requirement.



(a) (b)

Figure 25. (a) 2-in. brass cube mold; and (b) compressive test on a 2-in. PPC cube.

4.3 Modified Class D Concrete

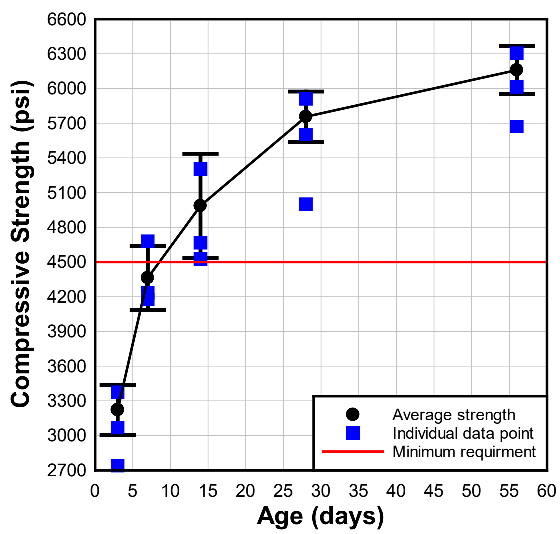
DelDOT specifies modifications to the Class D Portland cement concrete when used as an overlay. Class D Portland cement concrete contains fine aggregates with a fineness modulus of 2.3 to 3.2 and conforms to AASHTO M6. Synthetic fibers conforming to the requirements of ASTM C1116, Type III are required (0.5 pounds per cubic yard with a minimum length of 0.5 in. and a maximum length of 1.5 in.). The maximum water-to-cement ratio is 0.4. The modifications made include the use of Delaware #8 coarse aggregate and shrink-reducing admixture providing 80% or greater shrinkage reduction. The admixture must contain no more than 0.1% chloride by weight (SikaControl®-75 was used which does not contain intentionally added chlorides). For this project, MCD was supplied by a ready-mix plant certified by DelDOT.

For MCD overlays, a bond agent conforming to AASHTO M235 Type V or ASTM C1059 type II must be used. L&M™ EVERBOND™ was selected for this project for being the one used by DelDOT. The bond agent is a milky white acrylic liquid that is painted on the surface prior to applying the overlay. The bonding adhesive becomes an integral part of the interface between the substrate's (UHPC) surface and the MCD overlay.

Figure 26. Bonding agent used for MCD (image from manufacturer's product datasheet).

Curing in compliance with DelDOT specifications started immediately after completing leveling and finishing. Wet burlap was placed atop the overlay throughout the 14-day curing period. The burlap was covered tightly with a 4 mil thick white opaque polyethylene sheeting to prevent moisture loss.

In addition to the overlay specimens (1 in. thick slab strips), cylinders measuring 3 x 6 in. were tested in accordance with AASHTO T22 as specified by DelDOT's specifications. The compressive strength test was conducted at different ages (3, 7, 14, 28, and 56 days). Class D Portland cement concrete is expected to have a minimum 28 day compressive strength of 4500 psi according to DelDOT's specifications.



(a)

(b)

Figure 27. (a) MCD compressive strength gain over time, error bars indicate one standard deviation; and (b) example of a tested MCD cylinder.

4.4 Latex Modified Concrete

LMC combines cement, water, and a polymer called styrene-butadiene latex modifier. Trinseo modifier A latex was used by the manufacturer for the overlay in this study. Coarse aggregates of Delaware #8 are among the materials used for this concrete along with fine aggregates. The fine aggregates with a fineness modulus between 2.3 to 3.2 make 50 to 60% of the total aggregate by weight. The mix used in this study had a water-to-cement ratio of 0.38 while DelDOT specifies a maximum of 0.4.

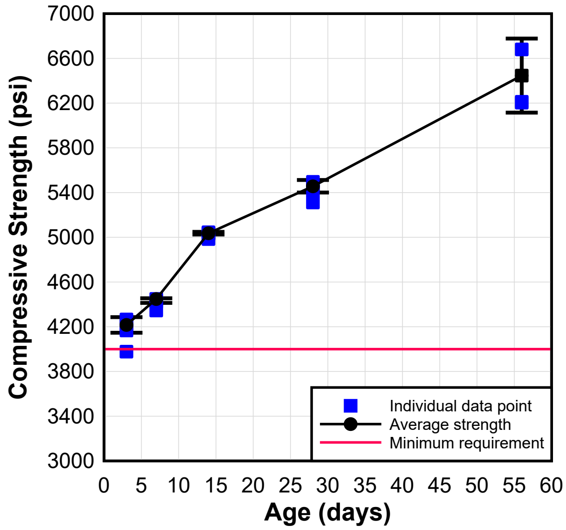
Based on the LMC contractor data, LMC is expected to have an acceptable bond strength, low permeability, modulus of elasticity, improved freeze-thaw, good flexural strength, and improved tensile strength. To achieve overlay properties comparable to the industrial overlay used in the field, LMC was mixed in the Structural Engineering Laboratory in a mobile mixing unit regularly used by a certified contractor in projects involving LMC overlays. Unlike PPC and MCD, the use of a bond agent is not needed for LMC, before pouring this latter, a small quantity of the same concrete was brushed on UHPC, and aggregates were removed. The film of the paste was meant to improve the adhesion to the substrate.

(a) (b)

Figure 28. (a) Delaware #8 aggregate used for LMC; and (b) freshly mixed LMC.

The slump test was conducted according to DelDOT's specifications (per AASHTO T119) with an acceptable range of 4 in. to 6 in. Air content of 3.5% was measured on fresh LMC samples, per AASHTO T152. For curing, the newly installed LMC strips were promptly covered with wet burlap within 30 minutes of placing the overlay. To keep the burlap from drying out quickly, the covered test specimens were sealed with plastic sheeting. The wet burlap and plastic were kept for 48 hours. After removing the wet burlap, LMC was then allowed to dry-cure for at least 72 hours as advised by the manufacturer.

As required by DelDOT's specifications, LMC was tested in compliance with AASHTO T22. Cylinders measuring 3 x 6 in. were subjected to the same curing protocol as the overlay. Compressive strength test was performed at 7, 14, 28, and 56 days. Cylinders were loaded at a rate of 35.7 psi/s until failure. According to DelDOT's specifications, the minimum compressive strength of LMC at 28 days should be 4000 psi. Properties of both the fresh and hard LMC met DelDOT's requirements.



(a)

(b)

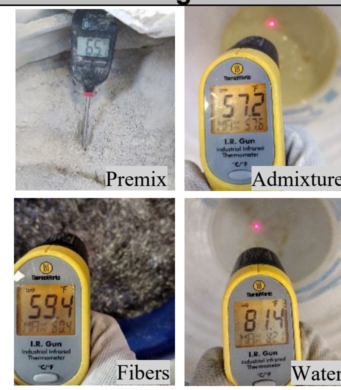
Figure 29. (a) LMC compressive strength gain over time; (b) typical failure mode of an LMC cylinder. Error bars indicate one standard deviation.

Chapter 5

SPECIMEN PREPARATION

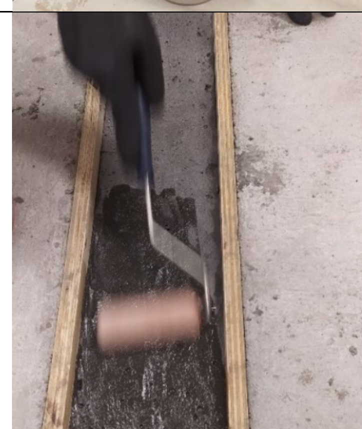
UHPC test strips (6 in. wide) were separated by 10 in. wide normal concrete strips used for mounting the coring drill (Figure 21). At the bottom, the purpose of the base slab, made of 3,500 psi ready-mix concrete, was to support the UHPC and overlays and facilitate the transportation of test specimens for surface preparation. On top of the 4 in. deep base slab, a 3 in. thick UHPC interlayers were placed using proprietary UHPC, commonly specified by U.S. transportation agencies for link slabs and bridge connections. To limit the effect of the autogenous shrinkage of UHPC on the overlay-UHPC bond strength, UHPC was left to cure for at least 28 days. During the curing period, the surface preparations and roughness measurements were processed. On top of the UHPC substrate, 1 in. thick overlays were placed following both the manufacturer guidelines and DelDOT's specifications. The production of the UHPC substrate and the mixing and placement of PPC, MCD and LMC overlays are described in Table 5, Table 6, Table 7 ,and Table 8 respectively.

Table 5. UHPC strips production procedure.

Step	Description	Figure
1	The mix components were measured into clean buckets and the temperature of each material is assessed to ensure being in the appropriate range. Warm water was used during cold mixing temperatures.	
2	Dry ingredients were mixed until a uniform homogenous mix was achieved.	
3	Water and admixtures were added following manufacturer's guidelines, with care to use the entire quantity with no waste (considering the very low water to cement ratio in UHPC).	
3	After achieving a fluid mix, fibers were added gradually to the mix ensuring uniform distribution in the mix.	

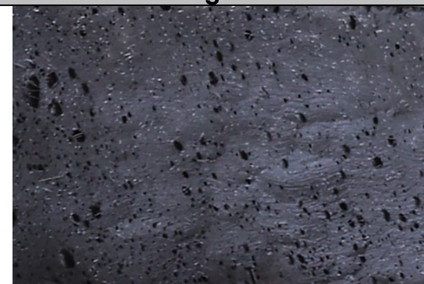
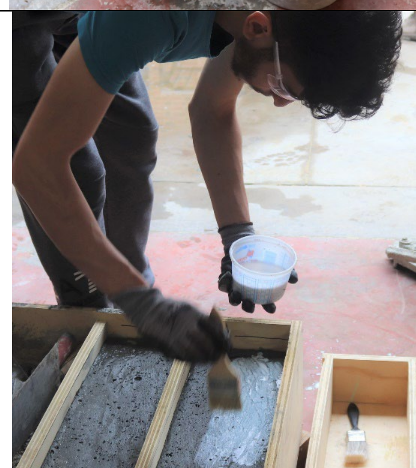
Step	Description	Figure
4	After a consistent homogenous mix with uniformly distributed fibers was achieved, UHPC was discharged into buckets, then to the slab strips and cylindrical molds.	
5	The slabs were covered with a plastic sheet for curing and to prevent moisture loss for at least 48 hours at an ambient temperature above 40° F.	

Table 6. PPC overlay mixing and placement.

Step	Description	Figure
1	The surface was cleaned by blowing the UHPC strips with compressed air.	
2	The primer was mixed following the manufacturer's guidelines, see Appendix A.	
3	The primer was painted on the UHPC surface to complete refusal, leaving a thick coat of saturated primed surface (100 square foot/gal). The ambient temperature of the lab at the time of primer application was between 65 and 85 °F. In case of a surface with exposed fibers, the primer was applied in stippling motion to avoid tearing up the roller with the steel fibers.	
4	PPC constituents (polyester binder resin, graded silica, quartz aggregates, and methyl ethyl ketone peroxide initiator) were proportioned and mixed following the manufacturer's recommendations (Appendix A).	

Step	Description	Figure
5	PPC was applied withing 15 min of priming. The thickness of the overlay was kept at 1 in. PPC was finished to yield a well-compacted material with a slight glossy sheen surface without excessive resin bleed. The slabs were then covered with plastic sheets to protect PPC from moisture.	

Table 7. MCD overlay mixing and placement.

Step	Description	Figure
1	The UHPC surface was cleaned of any contaminants, loose particles, or dust as described in Table 6, step 1. For the SSD group, the surface was sprayed with tap water approximately 1 hour prior to overlay placement.	
2	Upon the arrival of the ready-mix concrete, the air content was measured to verify it conforms with DelDOT's specifications. The measured value was 3.5%.	
3	L&M™ EVERBOND™ was applied by brush to create a thin continuous layer following the manufacturer's recommendations (Appendix B) prior to installing the overlay. In case of a surface with exposed fibers, the bond agent was applied in stippling motion to ensure uniform spread.	
4	MCD was placed into the strips before the bond agent dried. The overlay was manually distributed along the UHPC strip ensuring adequate compaction.	

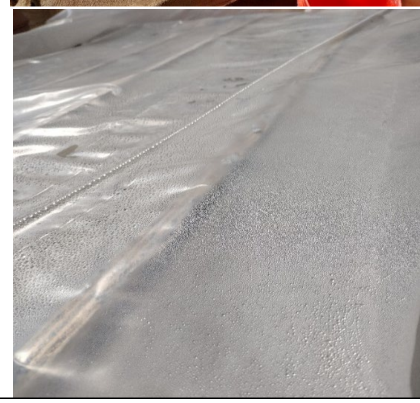
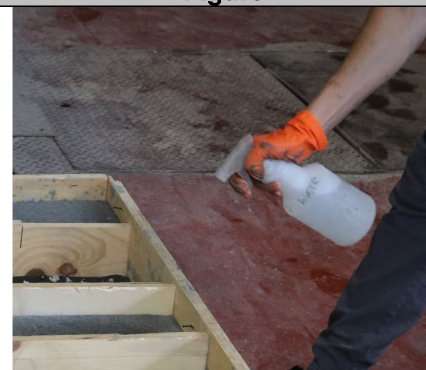
Step	Description	Figure
5	The overlay was covered with wet burlap and sealed with plastic sheeting. Burlap was kept wet for 14 days.	 

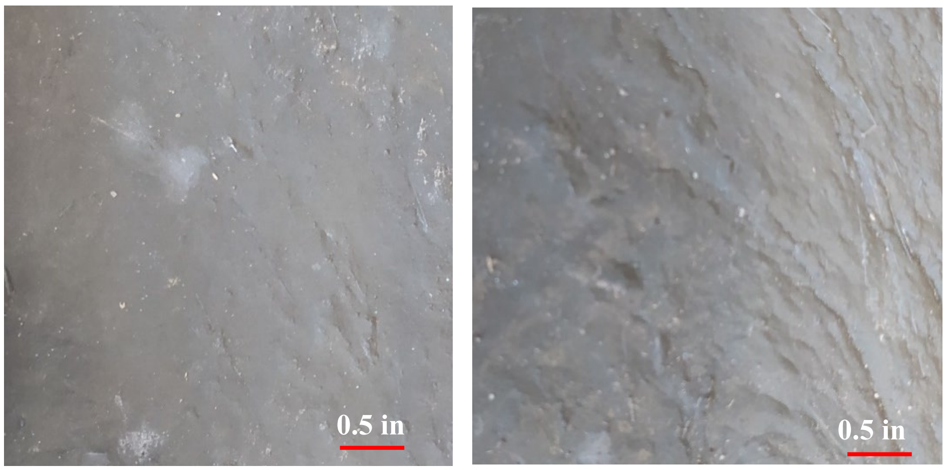
Table 8. LMC overlay mixing and placement.

Step	Description	Figure
1	UHPC surface was cleaned and dried as described in Table 6, step 1. An hour before applying the overlay, SSD was achieved on the substrate's surface by spraying tap water from a spray bottle.	
2	Tests on the fresh concrete were conducted. - Slump of 5.5 in. was measured which falls withing the acceptable range of 4 to 6 in. - Air content of 3.5% was recorded, which was below the maximum acceptable threshold of 6.5%.	 
3	LMC paste (without coarse aggregate) was brushed onto the UHPC surface for improved adhesion to the substrate, as recommended by the manufacturer.	

Step	Description	Figure
4	Freshly mixed LMC was placed immediately after applying the paste. The material was manually compacted and leveled along the strips.	 
5	Wet burlap was placed on the slabs while preventing water from pooling on top of the overlay surface. Plastic sheets were used to seal the slabs during curing. Moist-curing was performed for 48 hours.	 

5.1 Surface Preparation

The UHPC-overlay bond strength can be greatly influenced by the roughness of the UHPC substrate. This study considered NP, GSB, HD, and SR as surface preparation methods. Due to the properties of UHPC's w/cm ratio and limited bleeding, the exposed surface forms a texture reminiscent of elephant skin (Chen et al., 2019), which hinders outgassing of the fresh UHPC (Wetzel and Glotzbach, 2013), entrapping air bubbles beneath the UHPC surface. Unlike surface preparation techniques that result in relatively uniform texture across the entire surface, the texture of the NP UHPC is highly variable with "wrinkles" most typically located near the ends of UHPC strips (Figure 30). Despite the presence of "wrinkles" at the macro-scale, the surface is relatively smooth at the microscale level.



(a) (b)

Figure 30. Elephant skin on NP UHPC surface: (a) smooth surface, (b) wrinkles near the formwork edges/corners.

Grinding (Figure 31 a) was conducted using a hand-held concrete grinder with a diamond grinding wheel. The grinding process removed approximately 1/8 in. of material from the substrate surface exposing the air bubbles enclosed within the elephant skin. Grinding was followed by sandblasting using ALC Abrasive Blaster which shoots coal slag abrasive at a pressure of 80 to 110 psi. Sandblasting (Figure 31 b) was conducted until a uniform roughness was achieved across the entire UHPC strip, as determined by visual inspection. It was observed that air pockets located at the surface of the elephant skin disappeared following sandblasting.

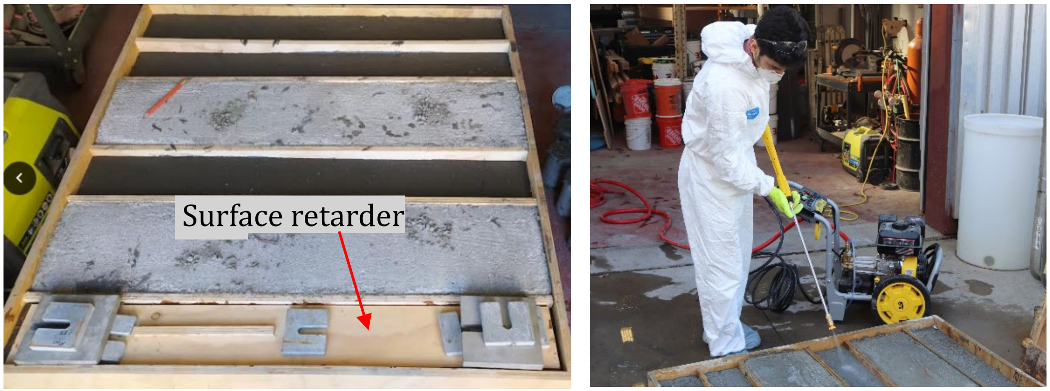
(a) (b)

Figure 31. (a) UHPC grinding; and (b) sandblasting.

HD (Figure 32) was conducted by Rampart® Hydro Services, a licensed contractor. This surface preparation method was done on day 3 after casting UHPC (enough to exceed a compressive strength of 10 ksi). The process of HD involved water jetting of high-pressure (34 ksi) to remove approximately 1/8 in. of material from the substrate surface (Figure 32). Unlike the GSB method, HD exposes the fibers.

Figure 32. HD process.

EUCLID Formula F surface retarder was used to slow down the hydration reaction at the UHPC surface. The SR was applied on a 4.5 x 40 in. plywood sheet and laid atop freshly placed UHPC (Figure 33). The UHPC surface was then pressure washed (at 3,200 psi) after 6 to 12 hours of retarder application, which was determined from a pilot study. The treatment time varied between 6 and 12 hours because the pilot study revealed that ambient conditions can have a significant effect on the setting time of UHPC.



(a) (b)

Figure 33. SR process: (a) surface retarder applied to plywood sheet and placed atop of UHPC; and (b) pressure-washing UHPC surface.

Chapter 6

EXPERIMENTAL PROCEDURES

6.1 Roughness Measurements

Roughness measurements were implemented to quantify the effectiveness of different surface preparation methods. The UHPC surface roughness was assessed via sand patching, surface profile gage, and ICRI CSP chips. The ICRI CSP chips method was developed for a rapid qualitative on-site assessment of concrete surface texture. It consists of a visual and tactile comparison between the concrete surface topography and ten reference CSP chips (Figure 34) to determine if adequate surface texture was achieved. The chips represent varying degrees of concrete surface roughness corresponding to different surface preparation methods. Five comparisons using ICRI CSP chips were performed (approximately 3 readings per square foot) to account for the varying roughness along each UHPC strip.

Sand patching generally used to determine the average macrotexture depth of pavement surfaces. This method is conducted by spreading a specific volume of sand (glass beads) using a rubber spreading tool to form a circle of filled voids, following ASTM E965 (Figure 34). Sand patching is region-specific and, therefore, at least five tests were done for each strip (or 3 measurements per square foot). With a known volume of sand and the measured diameter of the circle, the mean texture depth is calculated as the ratio of the sand volume over the circle area, which provides the average depth of the voids:

$$MTD = \frac{4V}{\pi D^2} \tag{3}$$

where:

MTD: mean texture depth, in. (mm),

V : sample volume, in^3 (mm^3), and

D : average diameter of the area covered by the material, in. (mm).

Note: The mean texture depth (MTD) is not the equivalent of the mean profile depth (MPD) of the same surface.

Finally, a fine-pointed probe was used to measure the depth of the profile at multiple consecutive points. the device used is Positector surface profile gauge (SPG 1) which has a digital depth micrometer allowing to record the peak-to-valley profile heights conforming with ASTM D8271. The device can record 1000 readings with and accuracy of ± 5 µm. The gage's tip has a radius of 50 µm and 60° angle, it is designed to rest on the highest peaks of a surface, and each measurement is taken by measuring the distance between the highest local peaks and the specific valley into which the tip is placed. This type of instrument is ideal for measuring up to 6 mm of profile height The gage is particularly useful for measuring the roughness of concrete surfaces that have been prepared through methods such as blasting, scarifying, grinding, or acid etching as mentioned by the device's manufacturer. For each strip of UHPC, at least 500 readings were taken (approximately 370 per square foot).

Figure 34. Roughness measurement methods.

The data collected with the surface profile gauge can be represented as the Roughness Average (Ra) and the Root Mean Square (Rq) roughness of the measured depths. Ra and Rq are both measures of surface roughness, however they are computed differently. Ra is a common roughness parameter that describes the general height fluctuations of the surface and is less susceptible to major peaks and valleys, while the RMS calculates average height deviations of the mean line. RA and RMS were computed as follows:

$$RA = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (4)$$

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {x_i}^2} \qquad (5)$$

where:

x_i: individual profile guage readings.

N: total number of readings.

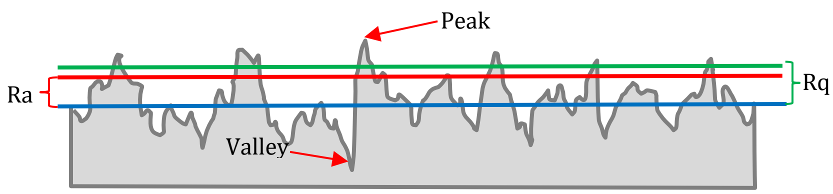
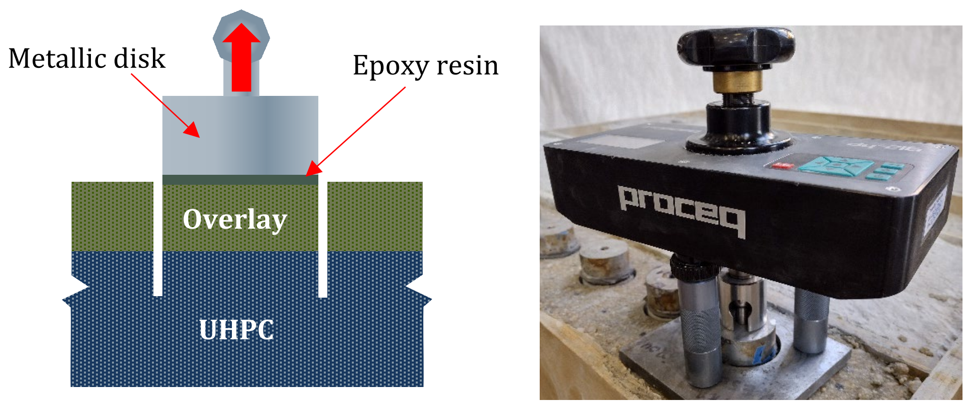


Figure 35. Illustration of Ra, Rq, Peaks, and valleys of a surface.

6.2 Bond Pull-off Test

Pull-off bond tests were performed according to ASTM C1583 (ASTM, 2020). In short, 2 in. cores were drilled to a designated depth using a Hilti DD120 rotary core drill with a diamond drill bit. The surface of the core was brushed with wire brush to remove lose material, then blown dry with high pressure air, finally, the core's surface was wiped with acetone. After cleaning the surface of the cored location, Sikadur-32 high-modulus epoxy (conforming with ASTM C881) was used to attach the 2 in. steel/aluminum pucks. The epoxy was allowed to cure for at least 24 hours prior to conducting the bond pull-off test. Bond pull-off tests were conducted using Proceq DY-216 bond pull-off tester at a constant rate of 5 psi/s.



(a) (b)

Figure 36. (a) Bond pull-off test schematic; and (b) Proceq DY-216 bond pull-off tester.

In addition to the pull-off strength, failure modes were assigned according to ASTM C881 (Figure 37), as follows:

- Mode A: Cohesive failure in the UHPC substrate indicating sound adhesion, i.e., the tensile strength of the overlay and bond (interface) strength is higher than strength of the UHPC substrate;
- Mode B: Adhesive failure at the UHPC-overlay interface, which indicates that the bond (interface) strength is lower than that of the substrate and overlay reflecting relatively poor adhesion;
- Mode C: Cohesive failure of the overlay material, indicating that both the tensile strength of the UHPC substrate and bond strength is higher than the tensile strength of the overlay; and
- Mode D: Adhesive failure at the puck-overlay interface; tests with this failure mode are discarded, and the test is repeated as directed by ASTM C1583 (ASTM, 2020).

Mixed failure mode was also observed in addition to the outlined failure modes. To address this issue in quantifying the failure modes, photographs of both fracture surfaces were taken. An image analysis procedure was implemented to calculate the contribution of each failure mode for specimens that failed by mixed mode (Figure 38). A Python code creates a mask to separate overlay from UHPC; in Figure 38, white color represents the overlay and black color reflects UHPC. The area corresponding to the Mode B (interfacial) is the summation of pixels where the two masks do not overlap. The overlapping UHPC areas represent the failure Mode A, and the rest of the area (overlapping white), is failure Mode C (overlay).

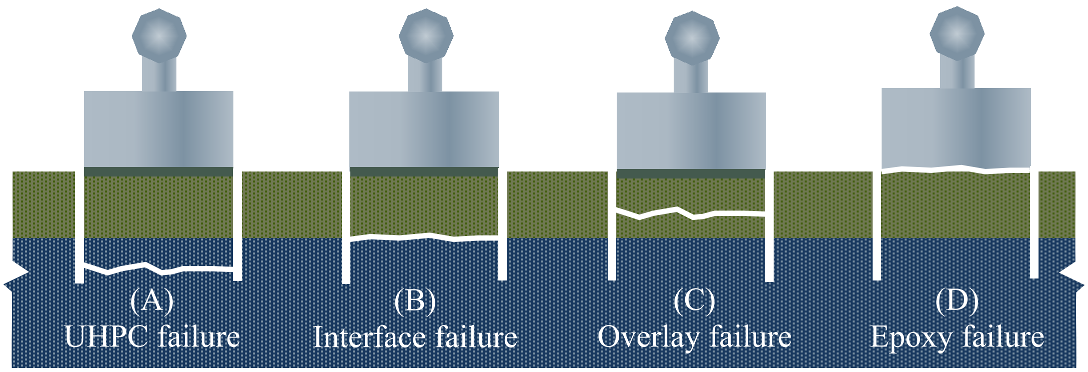


Figure 37. Schematic of possible failure modes.

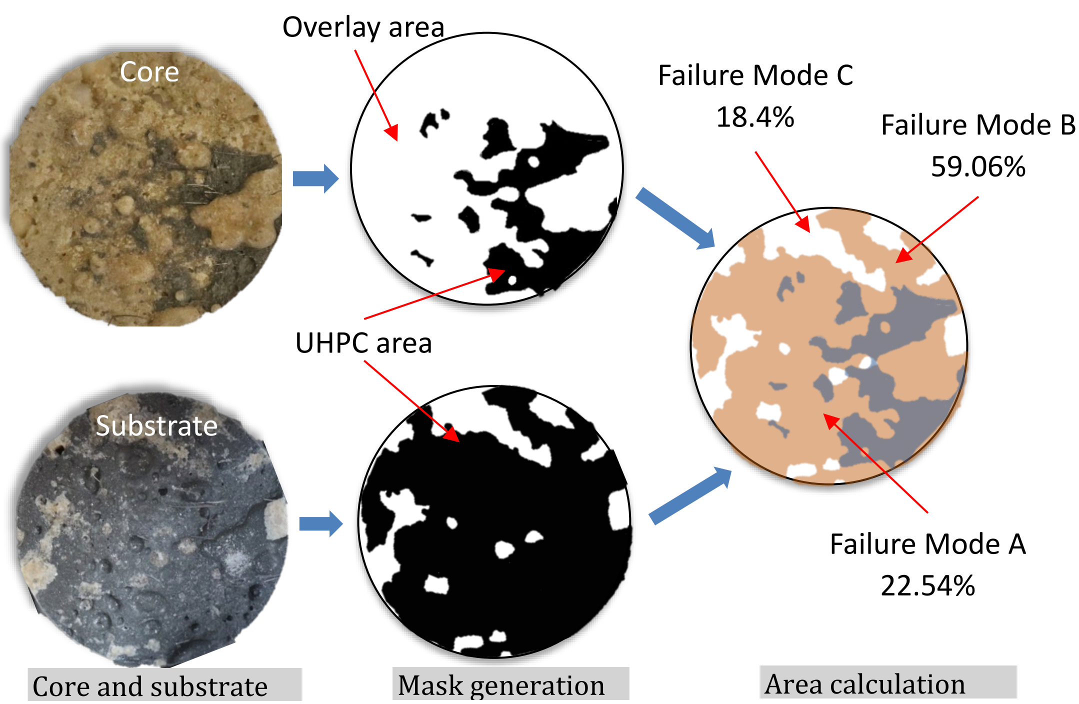


Figure 38. The process of calculating areas of each failure mode. This example is for a PPC overlay with a coring depth of 0.5 in.

Chapter 7

FIELD EVALUATION

A summary of the field work conducted to evaluate the bonding of PPC to UHPC on the bridge BR 1-251 is described in this chapter. The overlay was first visually inspected for evidence of PPC delamination. Next, visual inspection and ground penetrating radar (GRP) were used to locate the UHPC connection and select bond pull-off test ASTM C1583 (ASTM, 2020) locations. Finally—to determine appropriate coring depth for the bond pull-off test—clear cover over the internal steel reinforcement (within the UHPC connection region) was estimated using an electromagnetic covermeter and GPR. In total, six specimens were tested (three cores on each shoulder of the bridge).

7.1 Bridge Description

BR 1-251 on N355 Harmony Road over White Clay Creek in Ogletown, Delaware (Figure 39), constructed in 2018, was selected to assess the performance of PPC/UHPC bond in-service. BR 1-251 is a composite bridge with steel girders and concrete deck. UHPC was used in precast deck panel-to-panel connections and girder-to-panel connections, as shown in Figure 40 . Figure 41 shows plans of longitudinal and transversal UHPC connections in this bridge. Once UHPC reached 10 ksi, diamond grinding was conducted to ensure even UHPC surface across the connection, followed by sandblasting before placing a 1-in. PPC overlay. Visual inspection of the bridge revealed no evidence of overlay cracking. Some imperfections on the overlays surface were observed (Figure 42), which are likely related to placement, leveling, and curing PPC. In addition, visual inspection of the underside of the deck did not identify any defects or cracking within the UHPC joints (Figure 43).

Figure 39. Aerial view of BR 1-251.

Figure 40. UHPC connection between two deck panels. Blue lines indicate UHPC connection boundaries.

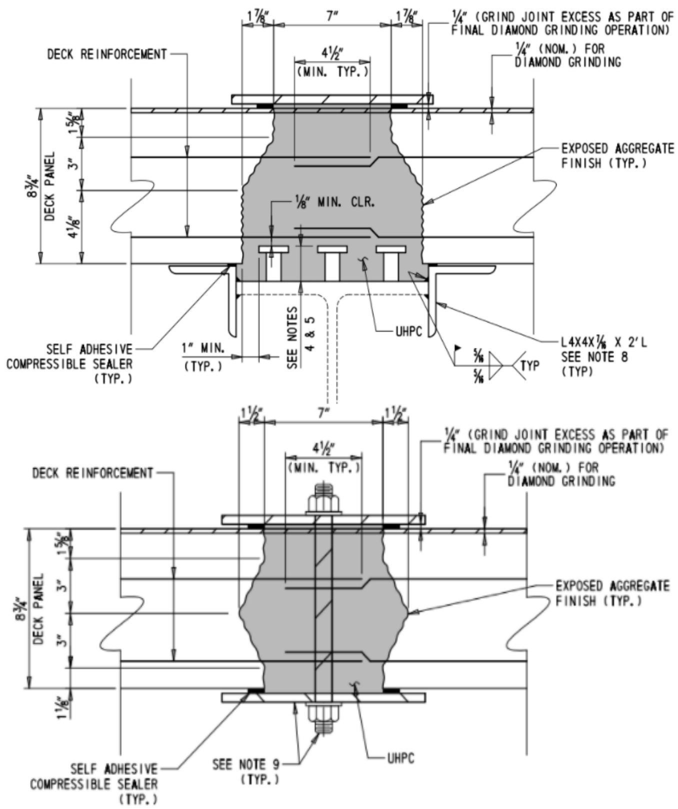


Figure 41. Longitudinal and transverse joint details as presented in BR 1-251 plans.

Figure 42. PPC on BR 1-251 shoulders.

Figure 43. UHPC connection close-up.

7.2 Locating UHPC connection

BR 1-251 has a shoulder width of approximately 11 ft 7 in. To locate the UHPC joint, the bridge bearing was used as a reference point (Figure 44). The distance was then measured from the bearing to the UHPC connection at the base of the deck where the UHPC joint is visible. This same distance was then projected at the top of the bridge using the same reference point. The connection considered is the one between the deck panels A1 and A3 on the East shoulder, and A2 and A3 on the West shoulder (Figure 44). As a secondary method to confirm the projected UHPC connection location, the edges of the UHPC strip were marked by two spray paint lines from underneath the bridge, then transferred to the top surface of the overlay across the barrier (Figure 45). The location was also confirmed using the GPR.

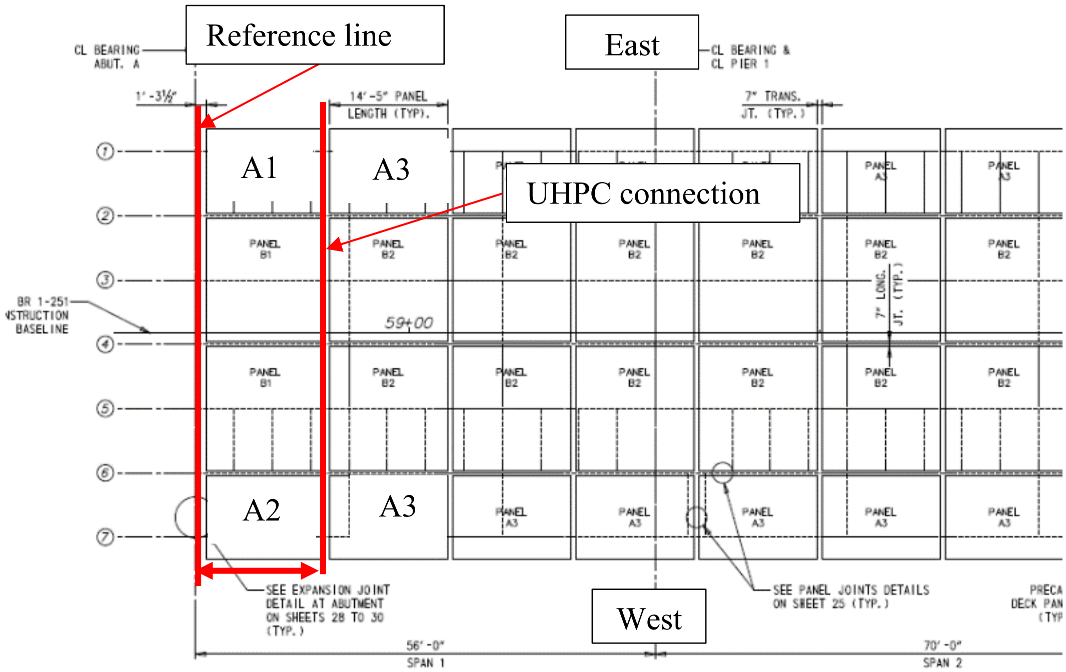
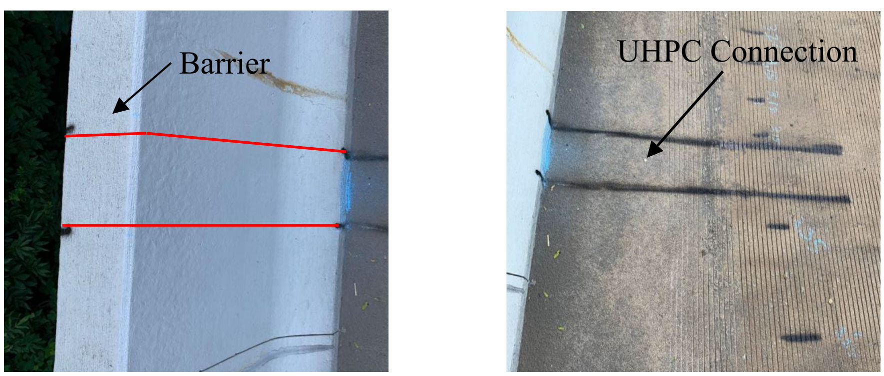


Figure 44. Plan view of the deck panel layout with the expansion joint as reference line.



(a) (b)

Figure 45. (a) Bridge barrier with the black spray paint lines indicating the location of the UHPC connection, transferred from underneath the deck where the UHPC is visible; and (b) marked UHPC connection region on the surface of the deck.

7.3 Locating Reinforcement and Clear Cover

A cover meter was used to map the location of the internal steel bars and clear cover at the location of the UHPC connection and 15 in. beyond joint boundaries. This was repeated on both shoulders of the bridge. No rebar was observed at UHPC joint due to the interference of steel fibers present in UHPC. However, the transversal reinforcement was successfully located using the cover meter within precast concrete adjacent to the joint. GPR was then adopted to verify the clear cover estimated via covermeter, and determine the actual location of the UHPC connection. Multiple scans were conducted in both longitudinal and transverse directions relative to the UHPC joint, as shown in Figure 46. Scan direction A1 – A5 is in the transverse direction to locate the longitudinal rebar and B1 – B5 is in the perpendicular direction.

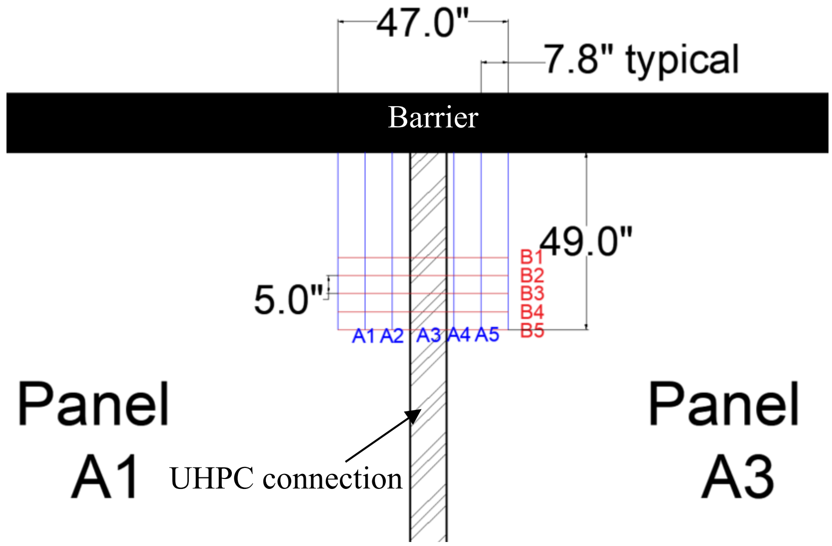


Figure 46. Plan view of the bridge showing GPR scanning location. Scan direction is from A1 to A5 and from B5 to B1.

A change in waveform palletes was observed from green color to blue color along the depth of the slab. According to Yelf (2007) it is important to analyze the GPR data in conjunction with site information in order to correctly interpret the survey results. By comparing the GPR data with known information about the area being analyzed, it is possible to identify multiple layers in the deck or repetitive targets such as steel reinforcing bars in concrete. Based on the interpretation of the provided drawing of the deck, the green layer appears to be the PPC layer at about 1.2 in. The longitudinal internal steel reinforcement appeared to be located at approximately 3.7-in. depth (Figure 47). However, upon moving into the UHPC connection region, the longitudinal reinforcement could not be distinguished in the signal likely due to the interference with steel fibers of the UHPC. By scanning in the longitudinal direction to locate the predetermined transverse reinforcement (using the cover meter), the transverse reinforcement wave can be seen more easily at a depth of about 2.9 in. In Figure 49 the wave pattern disappeared signifying the region of UHPC.

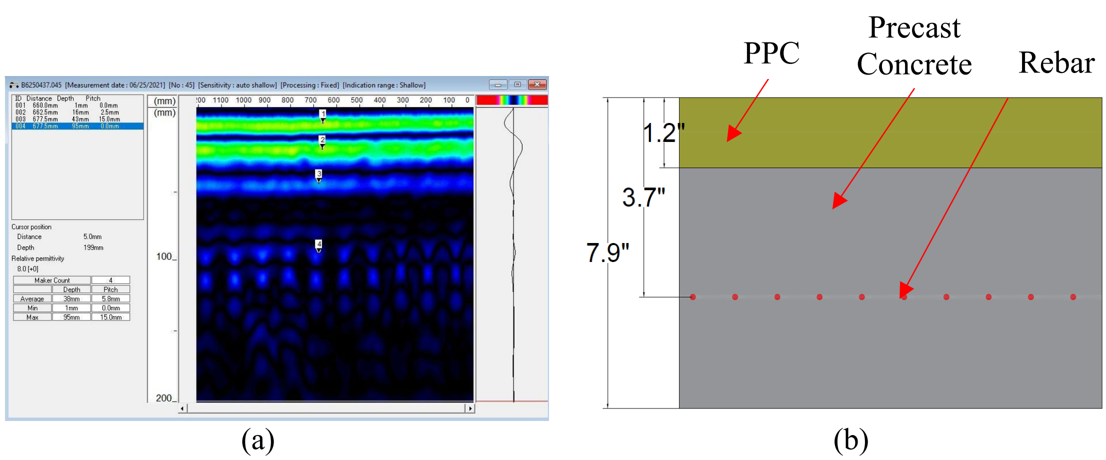


Figure 47. GPR scan in the transverse direction of the bridge deck: (a) GPR scan results; and (b) interpretation of GPR scan results.

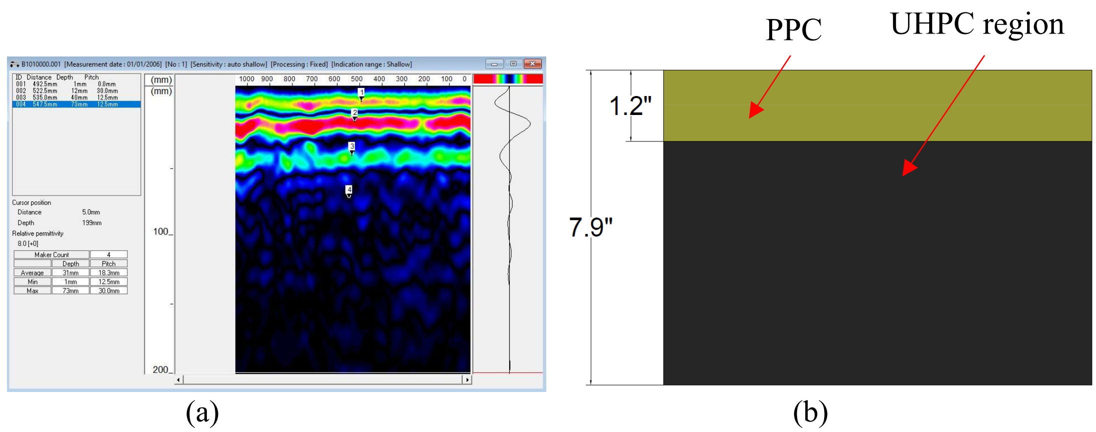


Figure 48. GPR Scan in the transverse direction of the UHPC joint (a) GPR scan results; and (b) interpretation of GPR scan results: no rebar was detected in the UHPC connection.

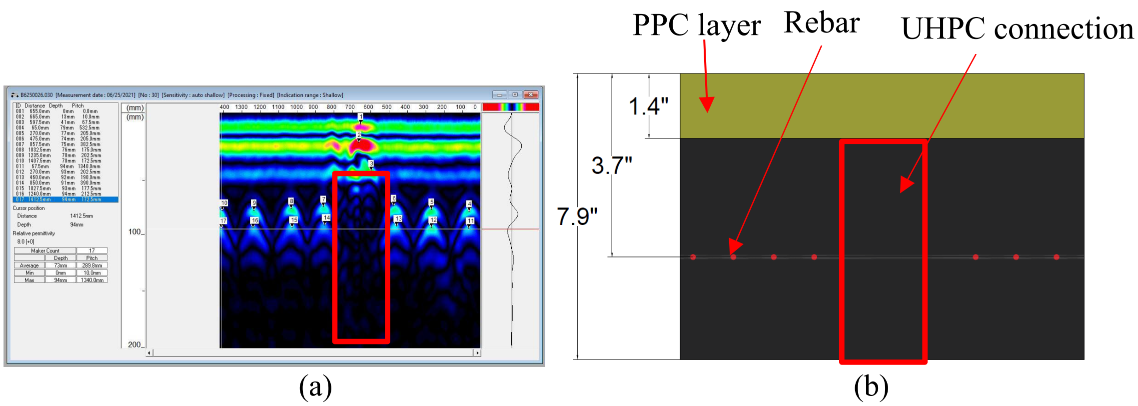


Figure 49. GPR scan in the longitudinal direction in UHPC joint: (a) GPR scan results; and (b) interpretation of GPR scan results: no rebar was detected within the UHPC joint.

The panel reinforcement details show the target reinforcement location for reference purposes. It should be noted that a clear distance of 2.75 inches before UHPC grinding and PPC application was specified (Figure 50). Also, the cover of 2.5 in. should not be exceeded after grinding. As shown in the figures, and confirmed by cover meter and GPR, the clear distance from the top of the deck to the rebar is approximately 2.99 in. Therefore, three 1.5-in. deep cores on the identified UHPC joint were drilled on both shoulders of the bridge.

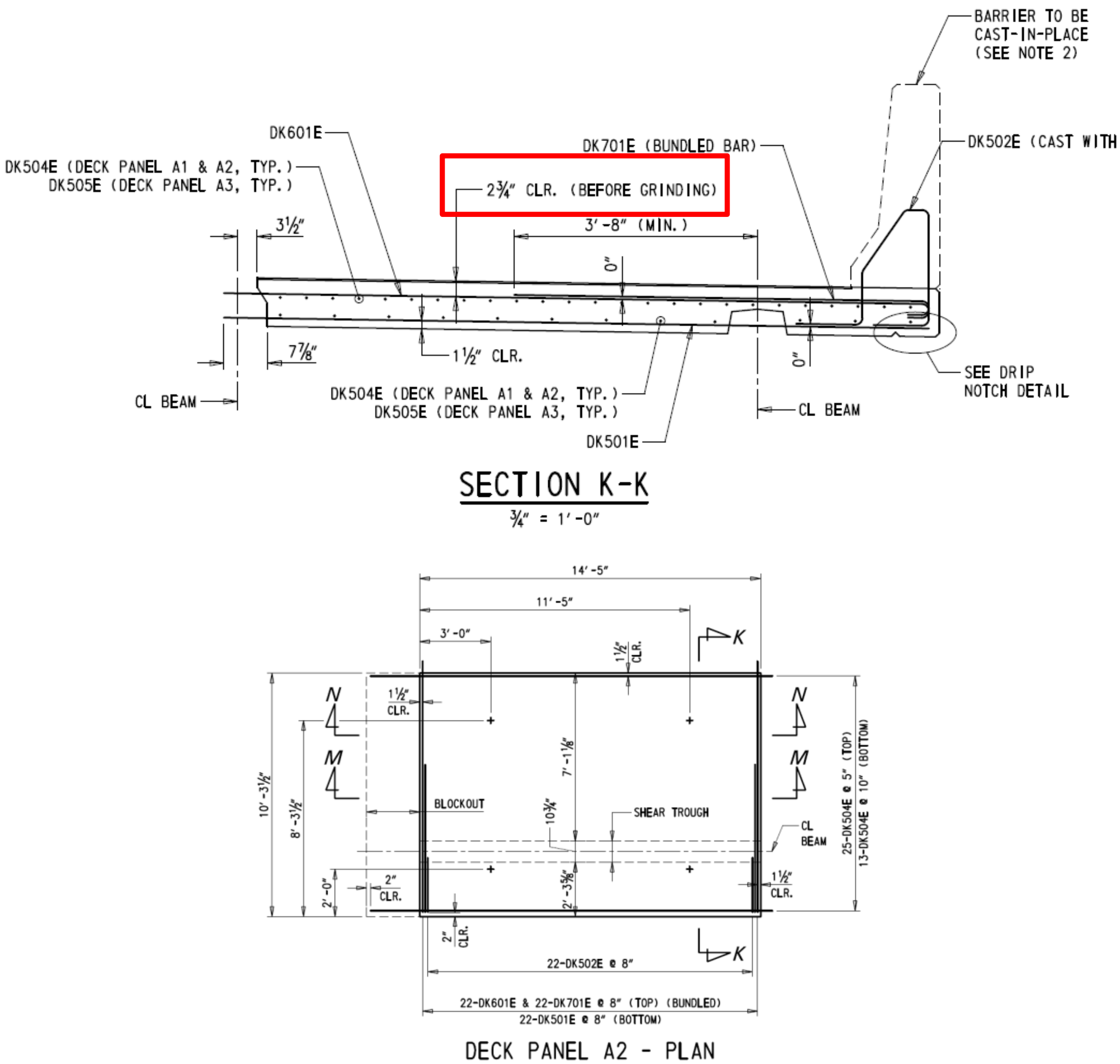


Figure 50. Joint details of deck panel.

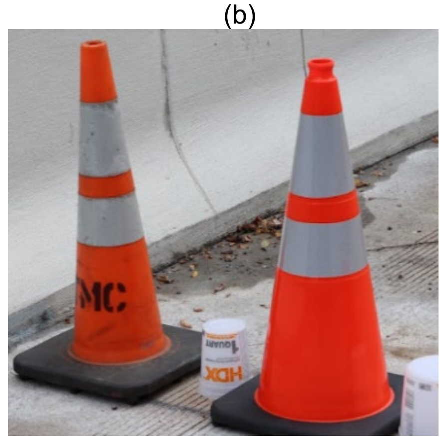
7.4 Specimen Preparation

After drilling 3 cores on each shoulder to a depth of 1.5 in. (Figure 51), the top surface of PPC was lightly grinded to remove loose particles that can potentially result in unacceptable failure Mode D. Before installing the steel pucks, the surface was thoroughly cleaned and whipped with isopropanol to remove surface contaminants. Then, 2-in. steel pucks were glued to the overlay using epoxy adhesive (Sikadur 30). Finally, to protect pucks from rain, each puck was covered with plastic cups and sealed with a silicone sealant. To deter vehicle traffic from the test locations, traffic cones were placed near the cores. The specimens were allowed to cure for at least 72 hours prior to testing. After conducting the tests, the holes were cleaned, repaired, and filled using Sakrete fast setting grout per DelDOT's recommendations (Figure 52).

(a)

(b)

(c)



(d)

Figure 51. (a) Cores at one of the bridge shoulders; (b) wet coring operation; (c) installed steel puck; (d) protected cores.

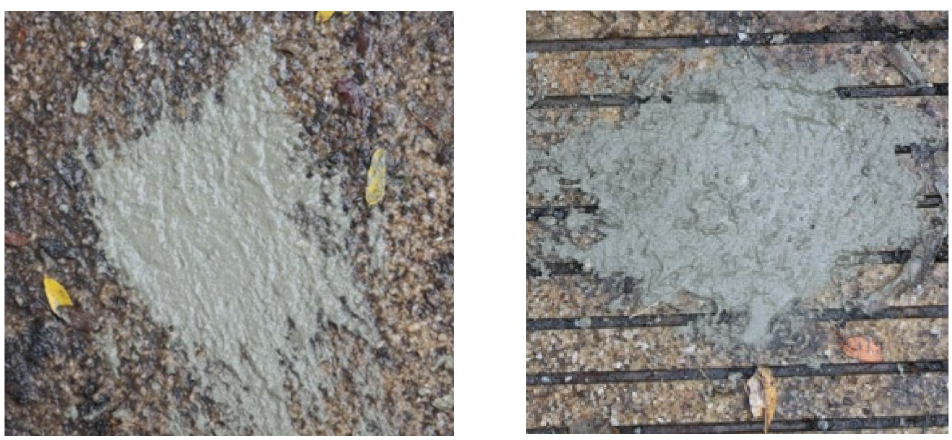


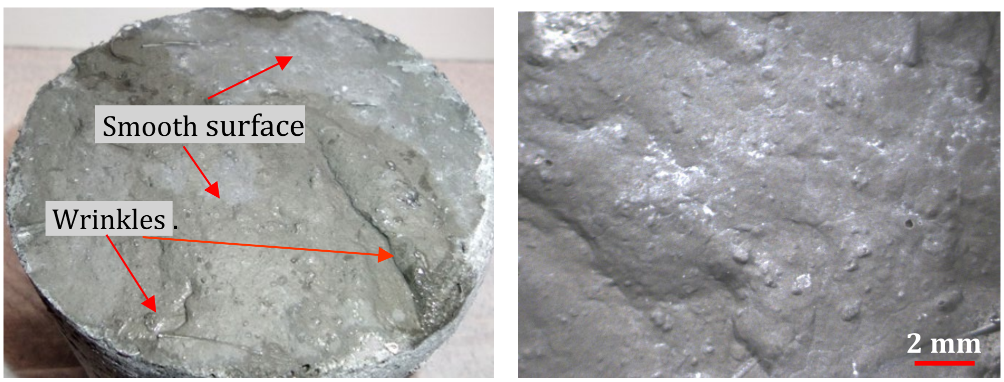
Figure 52. Examples of repaired cores.

Chapter 8

RESULTS AND DISCUSSION

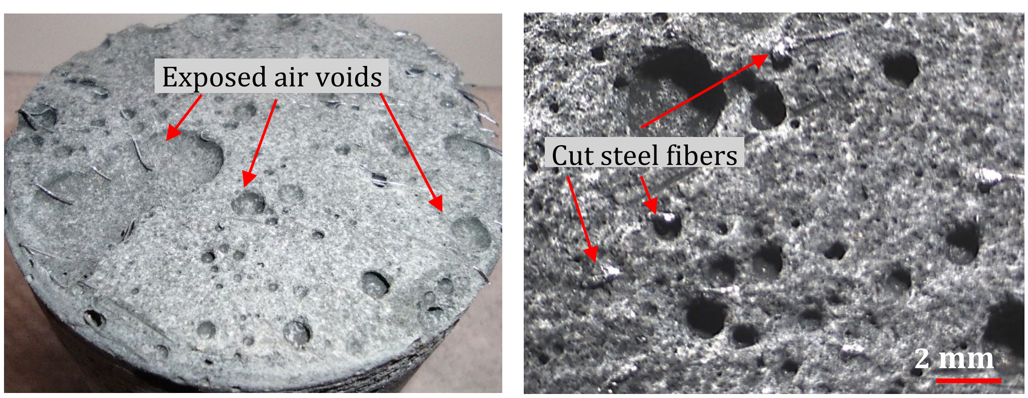
8.1 Surface Roughness

Visual inspection of NS surface revealed that the texture of the elephant skin was not uniform throughout the entirety of the strip. Although the wrinkles introduced the appearance of peaks and valleys, the surface of UHPC surrounding the wrinkles remained smooth. The NP surface texture (Figure 53) varied with the ambient conditions (i.e., temperature and humidity) at the time of UHPC placement. It was generally observed that relatively high ambient temperature leads to quicker setting of UHPC which exaggerated the appearance of elephant skin. The resulting surface from GSB shows an increased roughness compared to an NP surface (Figure 54). Air pockets (ranging in size from 1/8 to 3/4 in.) enclosed by the elephant skin were exposed and most of the steel fibers were cut during the grinding process.



(a) (b)

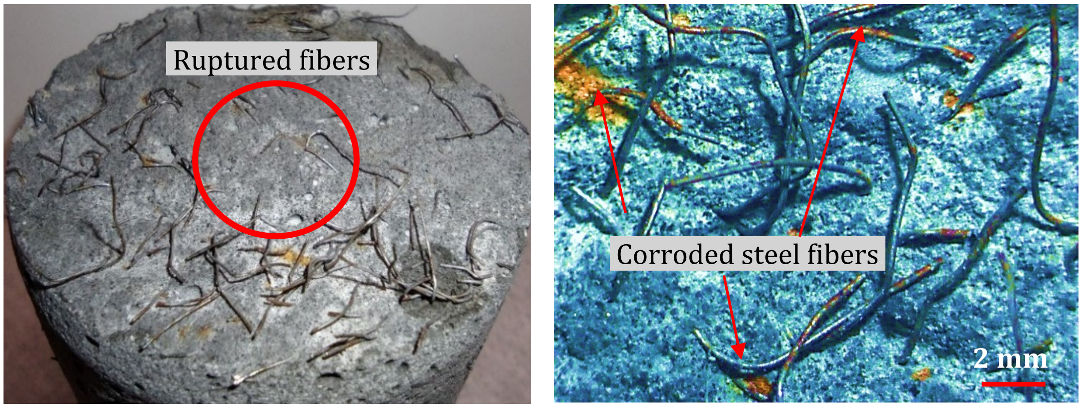
Figure 53. Typical NP surface: (a) core section photograph; and (b) stereo microscope photograph.



(a) (b)

Figure 54. Typical GSB surface: (a) core section photograph; and (b) stereo microscope photograph.

HD introduced increased roughness compared to GSB, and exposed steel fibers on the surface of the UHPC (Figure 55). However, it was observed that the fibers were damaged by the high-pressure water stream. The steel fibers appeared to be broken and curved in random directions. Attempts to clean the surface with a wire brush broke some of the weakened fibers. In addition, after 28 days (to allow UHPC to cure and limit the effect of the autogenous shrinkage), corrosion products formed on the steel fibers. The exposed fibers can potentially aid the mechanical interlocking of the overlay to UHPC, however, corrosion product on the surface of the fiber can reduce the adhesion strength and further weaken the fibers.



(a) (b)

Figure 55. UHPC surface texture following HD: (a) 2-in. core photograph; and (b) stereo microscope photograph. Colors and sharpness were manipulated to highlight corrosion in the microscopic image.

Pressure-washing the SR results in a comparable surface finish to that of the HD in terms of observed roughness and exposing the steel fibers (Figure 56). However, unlike in HD, the fibers were not disturbed by the application of SR and remained straight and intact. As expected, the fibers were oriented in the direction of UHPC flow during placement. Wire brushing the surface to clean it before applying the overlay did not affect fibers except changing their orientation.

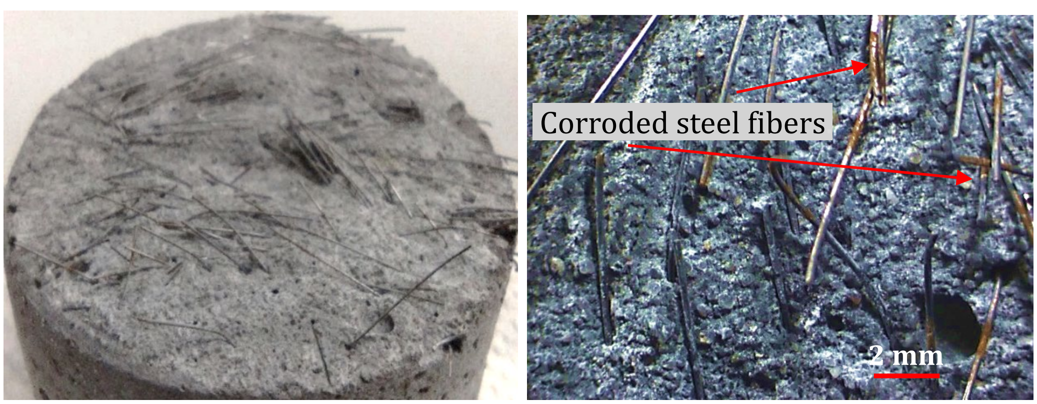
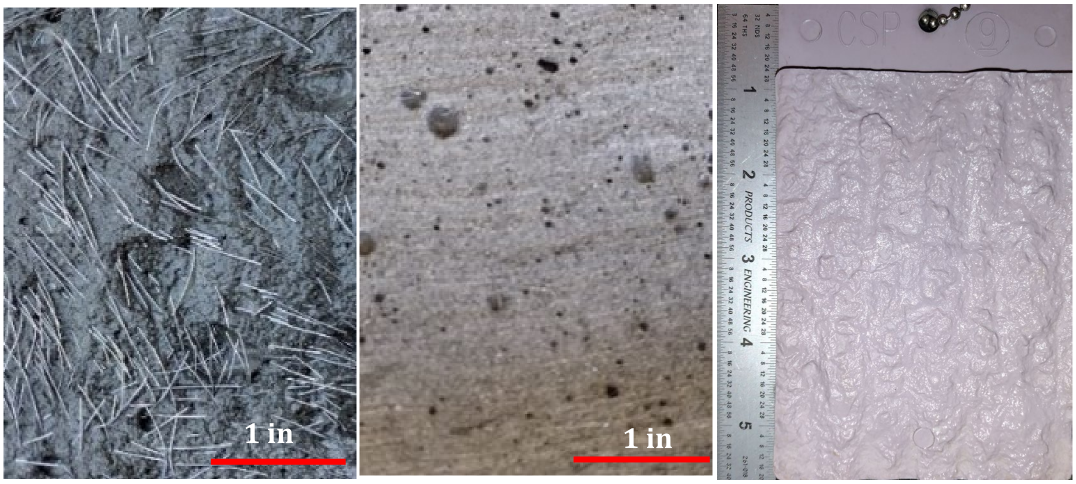


Figure 56. UHPC surface texture following SR: (a) 2-in. core photograph; and (b) stereo microscope photograph. Colors and sharpness were manipulated to highlight corrosion in the microscopic image.

The roughness measurement methods (ICRI CSP chips, sand patching, and surface profile gauge) were applied on the four surfaces to assess the practicality of each method in measuring the roughness of the UHPC surface. The ICRI CSP chips could not be used to assess the surface preparation of UHPC. The CSP chips were originally developed for normal concrete and, therefore, resemble texture of concretes with coarse aggregate and absence of fibers. In addition, since normal concrete is not characterized with elephant skin, the exposed bubbles and micropores from GSB were not resemblant of any CSP chips.



(a) (b) (c)

Figure 57. Comparison of UHPC (a) SR and (b) GSB surfaces to (c) an example ICRI CSP chip.

Sand patching could only be applied to NP and GSB surfaces. Spreading the sand using the rubber tool was not possible in the case of exposed fibers for the surfaces resulting from HD and SR. The mean texture depth (MTD) value measured with sand patching was equal to 0.7±0.12 mm for the NP surface. GSB had an MTD value equal to 1.2±0.16 mm, which indicated higher roughness compared to the NP surface. Finally, surface profile gage worked well on all surfaces. There was no statistically significant difference between SR and HD surface preparation methods based on the computed Rq and Ra (Figure 58). The average Rq for HD was 1.6 compared to 1.7 mm for SR, and the average Ra was 1.5 mm for HD and 1.4 for SR. HD and SR surface preparation methods had higher roughness compared to GSB which had a lower Rq of 1.19 mm and Ra of 0.95 mm. Finally, the NP surface exhibits the smoothest texture with an Rq of 0.98 mm and Ra of 0.78 mm.

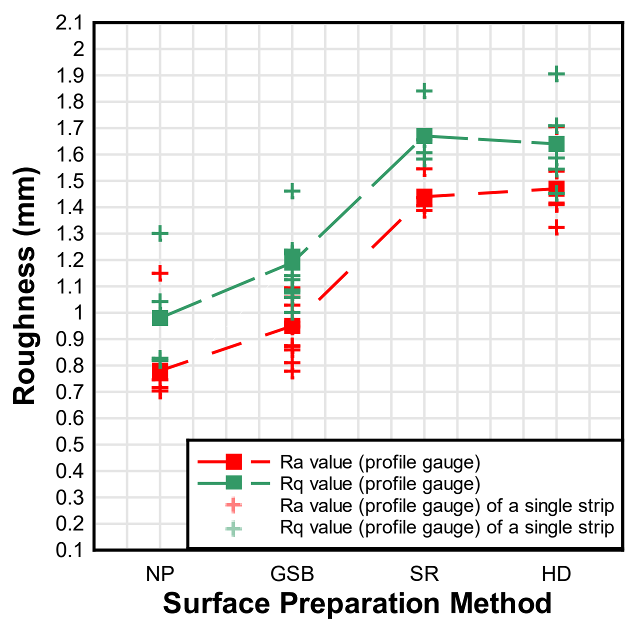


Figure 58. Surface profile gauge roughness measurement results for the different surface preparation methods.

Empirical cumulative distribution functions were used to visualize the surface profile gauge data as a means to compare the overall data distribution between different surface preparation methods (Figure 59). The graph demonstrates a clear order of roughness with the HD having the roughest surface. Following was the SR which exhibits a similar distribution of measured depths to HD. GSB had a smoother surface compared to the previous two methods. Finally, the NP surface data shows the lowest roughness as the curve is located first on the left.

For comparison purposes, 100 surface profile gauge measurements were performed on each CSP chip, some of which are presented in Figure 59. The corresponding Ra and Rq values for each CSP are given Table 9. Both the empirical cumulative distribution functions and measured Ra/Rq values reflected the increasing surface depth amplitude of CSP chips. The differences became especially apparent for CSP 5 and higher. Based on the Figure 59, CSP 2 through 4 were most representative of NP and GSB, while CSP 6 through 8 were comparable to SR and HD. Overall, it can be concluded that ICRI CSP chips can quantitatively be representative of UHPC surface texture; however, the chips have limited usefulness when used for qualitative comparison.

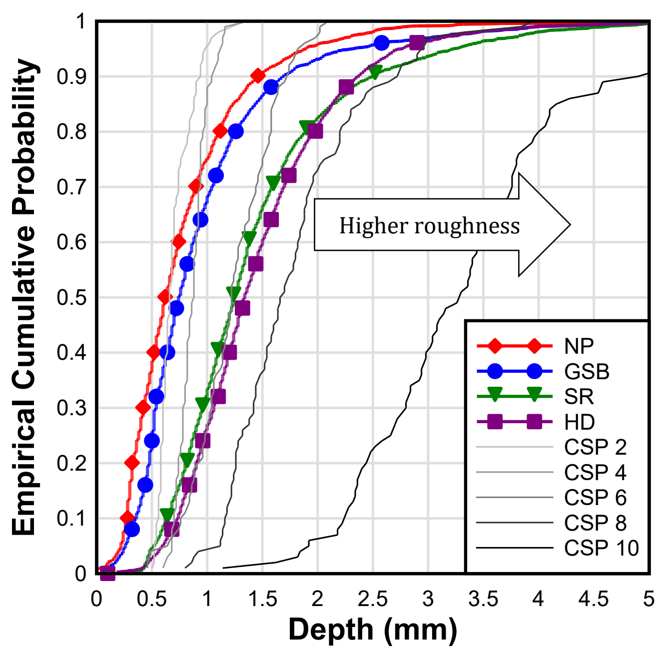


Figure 59. Surface profile gauge empirical cumulative probability functions for the different surface preparation methods.

Table 9. ICRI CSP chips and representative surface preparation methods.

Representative Surface Preparation Method*	ICRI CSP #	Surface Profile Gauge Average** (mm)	Rq** (mm)
Acid-etched	1	0.73 ± 0.03	0.75
Grinding	2	0.71 ± 0.03	0.72
Light Shotblasting	3	0.80 ± 0.03	0.82
Light Scarification	4	0.87 ± 0.03	0.88
Medium Shotblasting	5	0.95 ± 0.03	0.97
Medium Scarification	6	1.24 ± 0.07	1.29
Heavy Abrasive Blasting	7	1.55 ± 0.09	1.62
Scabbling	8	1.7 ± 0.1	1.78
Heavy Scarification	9	1.8 ± 0.1	1.90
Handheld Concrete Breaker or High-Pressure Hydrodemolition	10	3.37 ± 0.2	3.52

*on normal concrete

**100 readings

In summary, both the qualitative (visual inspection) and quantitative (surface profile gauge, sand patching) approaches indicated that HD and SR engender surfaces with higher roughness than GSB. In addition, it was observed that fibers can be successfully exposed via SR and HD to aid mechanical interlock with an overlay. GSB increased the roughness over NP; in addition, GSB exposed air pockets entrapped within the elephant skin.

When it comes roughness measurement methods, surface profile gauge proved to be the most versatile means of evaluating the roughness of UHPC surfaces via calculating the Ra and Rq, or by plotting the empirical cumulative distributions of the collected data. Sandpatch method was limited to the NP and GSB surfaces and could not be used on HD and SR substrates due to the presence of exposed fibers that hinder the spreading of the sand beads on the surface. ICRI CSP chips were developed for normal concrete, which significantly differs in microstructure from UHPC, so they could not be used to assess relative differences in surface texture of UHPC surfaces.

8.2 Bond pull-off test results

Evaluating the effect of the coring depth on the pull-off bond strength was needed before proceeding to test the influence of the overlay age, and the effect of the surface preparation method on the bond strength. Both the recorded failure strength and failure mode were taken into consideration to decide the coring depth. For each overlay, the influence of its age on the bond strength was investigated. The concluded appropriate age of each overlay was used for the last step of addressing the influence of the surface preparation method.

8.2.1 Coring Depth

ASTM C1583 (ASTM, 2020) test method was originally developed for overlays on conventional concrete substrates. Therefore, it is not clear whether the ASTM-specified test parameters, primarily coring depth, are applicable to a UHPC substrate. This work evaluated the sensitivity of pull-off bond strength to coring depth by varying the coring depth from 0 to 1.5 in. Since coring depth effects become more pronounced for overlays with strong adhesion to the substrate material, PPC overlay was selected for the sensitivity study because of its outstanding chemical bonding properties and high tensile strength (Robert J and W. Spencer, Guthrie, 2020) which were deemed to favor cohesive failure of UHPC over the other failure modes.

As shown in Figure 60, the recorded pull-off strength decreases with the increasing depth, from an average of 818 psi at 0 in. to approximately 614 psi at a depth of 1.5 in. No statistically significant difference in pull-off bond strength was observed between 0.5- and 1-in. coring depth. In general, testing a larger volume of material increases the probability of presence of critical flaws within the material; this phenomenon is commonly referred to as “size effect.” Multiple studies (Bažant et al., 1991; Kim et al., 2002) proved that size of the concrete specimen had a significant influence (decreased strength with increased size) on the compressive and tensile strength of concrete specimens. In addition, the coring process causes torsional friction which may have exacerbated microdamage in the UHPC substrate, overlay, and/or overlay/UHPC interface for higher drilling depths. Despite the negative correlation between the coring depth and pull-off bond strength, all average bond strength values exceeded the AASHTO T-34 recommended value and the manufacturer-specified bond strength to conventional concrete of 500 psi.

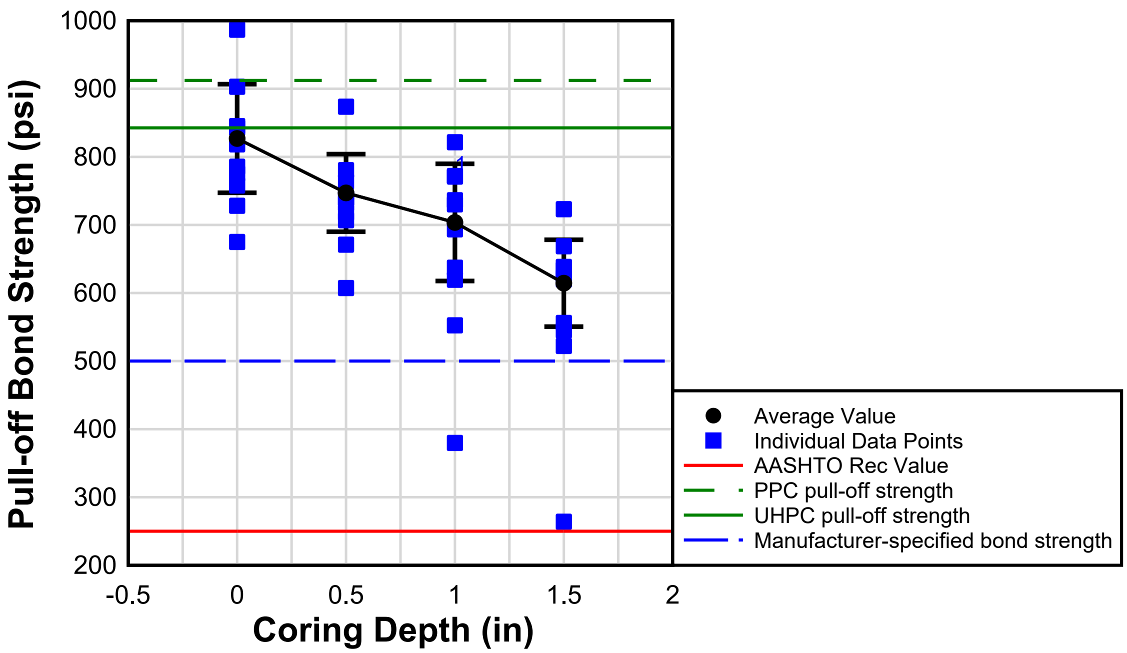
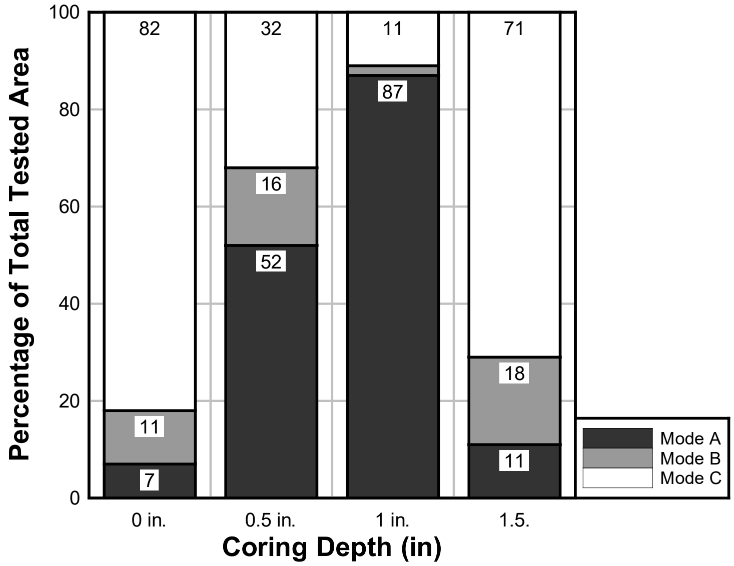
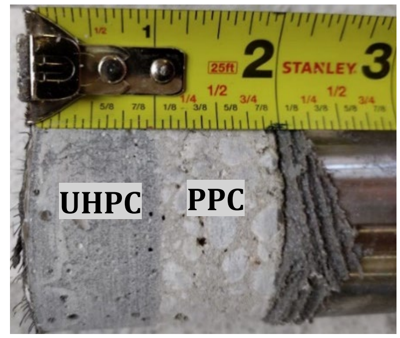


Figure 60. Bond pull-off strength data for PPC as a function of coring depth. Error bars indicate one standard deviation.

Figure 61 shows an increase of Mode A failure from 7% at 0-in. coring depth to 87% at 1-in. coring depth. On the other hand, Mode C decreased from 82% at 0 in. to 11% at 1-in. coring depth. However, at a coring depth of 1.5 in., the Mode C failure more abruptly increased to 71% while the measured bond pull-off strength decreased. The average strength of specimens that failed by Mode C at 1.5-in. coring depth was 611±54 psi which is significantly lower than the average strength of control and 0-in. groups. This indicates that the abrupt shift in failure mode of 1.5-in. group is likely due to relatively poor compaction of PPC. As expected, because of PPC's superior adhesive properties, the occurrence of failure Mode B was not significant. However, at the coring depth of 0.5 in., it was observed that several cores had a significant percentage (up to 59%) of area failed by Mode B. On the other hand, the highest percentage per core of Mode B in the 1.5-in. coring depth group did not exceed 26%.





(a) (b)

Figure 61. Failure mode of PPC overlay: (a) distribution of failure modes at different coring depths; and (b) example of Mode A failure from a 1-in. core depth sample.

The coring depth of 0.5 in. was selected for the remainder of the study because:

1. a depth of 0 in. implies coring through the entire depth of an overlay without proceeding into the UHPC substrate. This is not practical because the drilling process cannot be conducted with enough precision to ensure 0-in. coring depth;
2. there was no statistically significant difference in bond strength between 0.5 and 1 in. coring depth;
3. the depth of 1.5 in. resulted in the lowest strength and increased risk of damaging the core during the drilling process; and
4. the specified clear cover on the precast bridge decks is typically 1 to 1.5 in, so if the specified coring depth approaches the clear cover, one runs a risk of damaging the internal steel reinforcement;

8.2.2 Overlay Age

To evaluate the effect of overlay age on overlay/UHPC bond strength, PPC, MCD, and LMC overlays on the UHPC substrate were tested at 7, 14, 28, and 56 days. The considered surface preparation method for this study was GSB for consistency with the coring depth study.

Evolution of the pull-off bond strength of PPC is shown in Figure 62. In terms of the measured pull-off strength, all the data points were above the AASHTO T-34 recommendation of 250 psi and the manufacturer's specified value of 500 psi. For the ages of 14, 28, and 56 days, the results were comparable with no statistically significant difference. An exception was observed at 7 days with a relatively lower strength of 630 psi. The possible reasons for this lower pull-off bond strength are (1) a different batch of UHPC substrate and mixer were used for this test, (2) the different ambient conditions (mixed inside due to rain unlike the other batches), and (3) the observed increase in the viscosity of polyester primer compared to what was used for the other tests which might have affected its performance as an adhesive between the overlay and UHPC substrate.

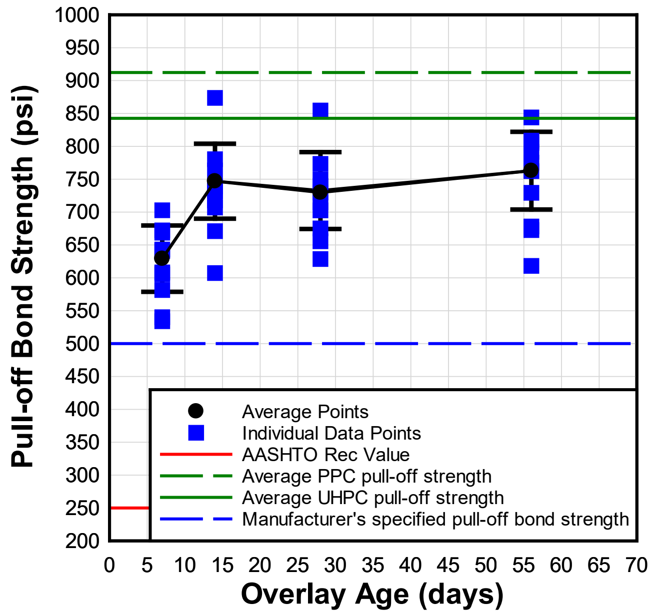


Figure 62. PPC bond pull-off strength as a function of overlay age. Error bars indicate one standard deviation.

A higher percentage of failure Mode B was observed at 7 days compared to other test times, which is ascribed to the abovementioned increased viscosity of the primer. Failure Mode B decreased to 16% at 14 days, with dominant failure Mode A of 52% The failure modes were dominated by Mode C at 28 and 56 days, with 78% and 77% respectively. Studies that evaluated PPC bonding to normal concrete reported primarily Mode A as the governing failure mode (Keith W. et al., 2019); this is not surprising considering the high fracture toughness and good adhesive properties of PPC. Consequently, the alternative acceptance criteria (to the 250 psi bond strength requirement) per ACI 548.5R recommend failure Mode A in over 50% of the tested area. While the pull-off strength requirement can be met on the UHPC substrate (Figure 62), the alternative acceptance criteria relative to Mode A failure is unlikely be met due to the high tensile strength of UHPC (Figure 63). Thus, a more appropriate alternative acceptance criteria for PPC bonded to UHPC substrate may be to specify both Mode A and Mode C as desired failure modes, in addition to the bond strength requirement.

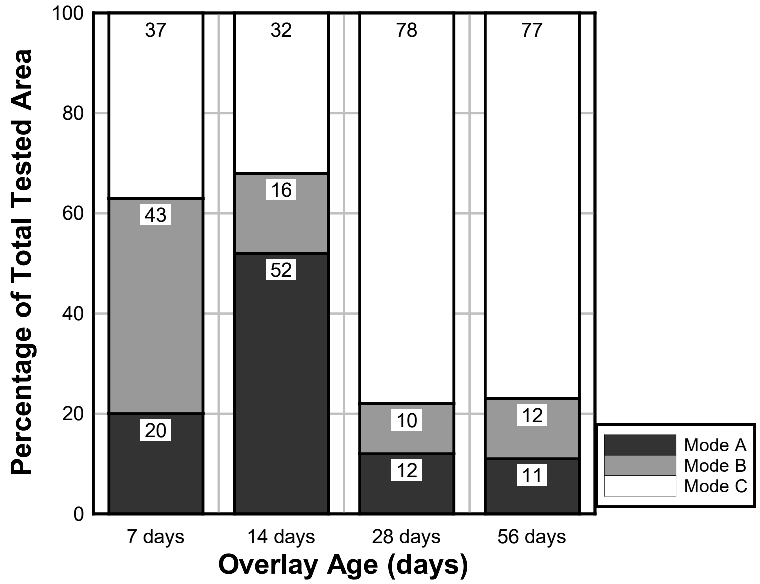


Figure 63. Distribution of PPC overlay failure modes as a function of overlay age.

During the curing period of MCD, the recorded pull-off bond strength increased from an average of 246 psi at 7 days to 338 psi at 16 days (two days after moist curing stopped) (Figure 64). The pull-off bond strength decreased to an average of 177 psi at 28 days and 273 at 56 days. All 14-day tests exhibited failure Mode D, indicating poor adhesion between the steel pucks and overlay. This likely occurred due to the implemented 14-day moist-curing protocol which introduced high moisture content at the MCD surface leading to poor adhesion of the epoxy adhesive used to bond the puck. Therefore, these tests were repeated at 16 days after allowing MCD surface one day to dry (Figure 64). This decline in strength is explained by the drying shrinkage of MCD following moist-curing. Other studies found that overlay shrinkage can have a significant effect on the bond strength (Keivan, 2010), while thin concrete overlays (below 2 in of thickness) have longer debonding lengths related to drying shrinkage and thermal gradient than thicker overlays (Shin et al., 2012).

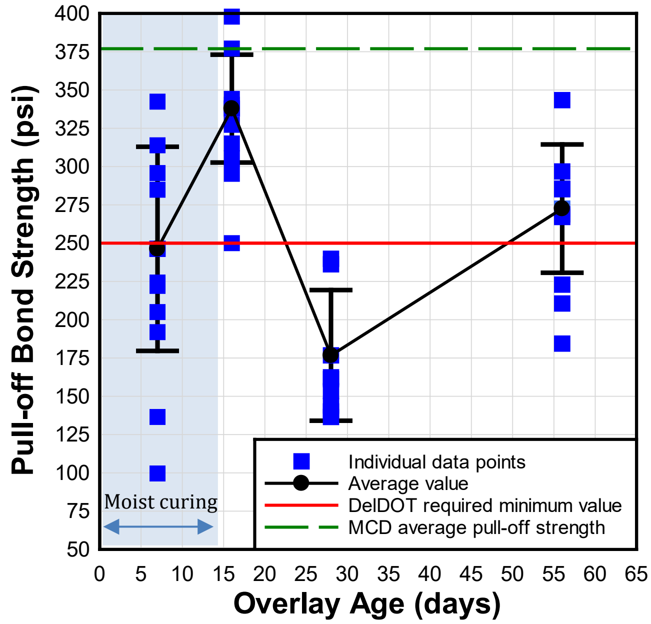
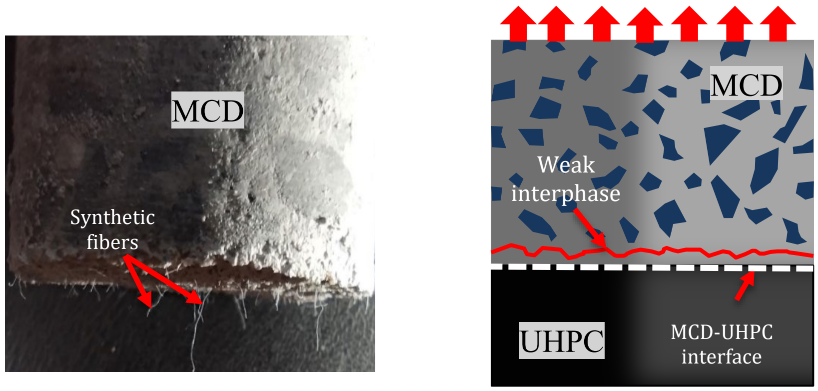


Figure 64. MCD overlay bond pull-off strength as a function of overlay age. Error bars indicate one standard deviation.

All tests on MCD overlay resulted in the same failure mode. Under the applied tensile stress, MCD cracked atop the MCD/UHPC interface, within the weak interphase likely caused by the wall effect. The wall effect (also known as boundary effect illustrated in Figure 65) is a phenomenon generally caused by a rigid barrier or formwork that perturbates the distribution of aggregates and mortar (Bazant, 2019), causing increased packing of smaller particles along the rigid boundary surface. This leads to a localized increase in cement content and acceleration of hydration reaction. According to Scrivener et al. (1996), the wall effect causes dehydrated cement depletion in the interface region, leading to a local increase in porosity. In the case of MCD bonded to UHPC, the UHPC substrate acts as a rigid boundary leading to wall effect. In addition, since UHPC is nearly impermeable, free water does not get absorbed by the substrate and accumulates at the bottom of the MCD layer leading to a local increase in water/cement ratio and, consequently, increased porosity along the UHPC-MCD interface. The absence of larger aggregate particles and increased porosity creates a weak interphase, thus localizing failure along that plane. These hypotheses are supported by the morphological differences between the cohesive failure in MCD and interphase failure mode shown in Figure 66. Further research is needed to develop methods to mitigate the effects of wall effect on the bond performance.



(a) (b)

Figure 65. (a) Failed MCD specimen, (b) illustration of the weak interphase at the MCD-UHPC interface.

(a) (b)

Figure 66. Typical MCD failure modes: (a) Mode C (core from cohesive tensile strength test, i.e., no UHPC substrate); and (b) Mode B observed for all tests on MCD-UHPC bonded specimens indicating lack of coarse aggregates within the weak interphase.

For LMC overlay, the average pull-off bond strength of the 7 days tests was comparable to the 14th-day average value, and there was no statistically significant difference between the two datasets (Figure 67). The pull-off bond strength increased to approximately 450 psi at 28 and 56 days. The difference between the 14- and 28-day tests was statistically significant, indicating an improvement in the bond strength of LMC with time. All the bond strengths exceeded the 200 psi minimum bond strength, recommended by AC I548.4M-11. The dominant failure mode was Mode B (Figure 68). Other studies (Konduru, 2009 and Russell et al,. 2013) reported more frequent Mode A with a conventional concrete substrate. In this study, failure Mode A was not observed likely because UHPC has a significantly higher tensile strength compared to conventional concrete (Russell, 2013).

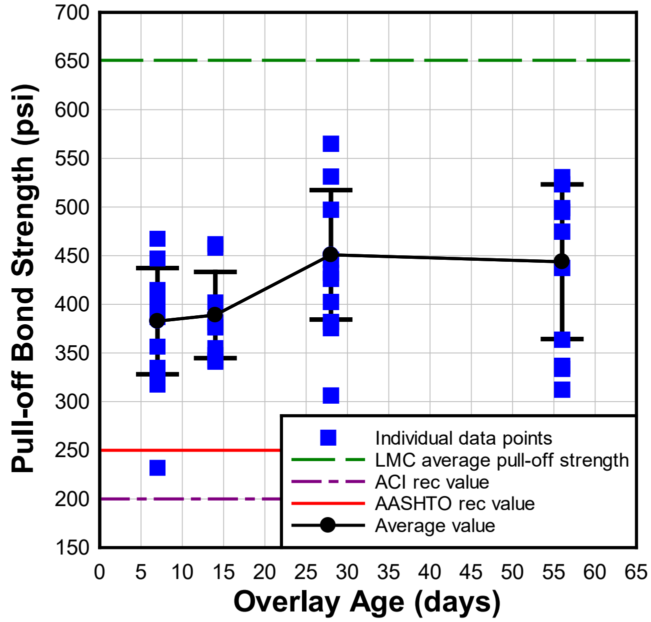
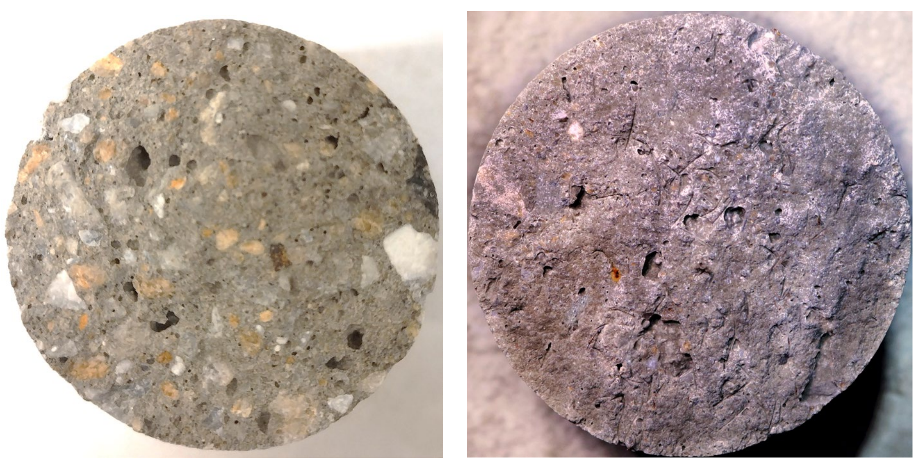


Figure 67. LMC bond pull-off strength as a function of overlay age. Error bars indicate one standard deviation.



(a) (b)

Figure 68. Typical LMC failure modes: (a) Mode C (core from cohesive tensile strength test, i.e., no UHPC substrate); and (b) Mode B observed for all tests on LMC-UHPC bonded specimens.

Based on the experimental results, the effect of the overlay age on the bond strength development of the three overlays to the UHPC substrate varied significantly. PPC had the highest average pull-off bond strength of up to 747 psi (at 28 days), considerably exceeding the recommended value of 250 psi at an early age (360 psi at 7 days) likely owing to its chemical bonding, high tensile strength, and high fracture toughness (Robert 2020). The percentage of failure Mode B of PPC decreased with time in favor of Mode C, indicating good adhesion between the overlay and UHPC. In contrast, MCD gained bond strength during its curing phase from under 250 psi at 7 days up to 338 psi at 16 days of age. However, the pull-off bond strength decreased to 177 psi at 28 days after moist curing stopped. The wall effect phenomenon is suspected to have a major influence on the strength and failure mode of the MCD overlay because all the recorded failures were within the interphase region between MCD and UHPC. Finally, the LMC overlay which combines a polymer (styrene-butadiene latex) and cement had results that reflect this combination.

LMC gained bond strength over time from 380 psi at 7 days to approximately 450 psi at 28 days which remained relatively constant until 56 days. The combination of a polymer (latex) and cement in LMC resulted in better bond than MCD; however, LMC did not match the PPC bond performance. This confirms findings from other studies on mortars with adhesive polymer admixtures (Atzeni et al., 1993). The dominant failure mode for the LMC overlay was Mode B.

8.2.3 Surface Preparation Method

To evaluate the performance of each overlay with respect to the surface preparation methods previously described, bond pull-off tests were conducted with a coring depth of 0.5 in. at an overlay age of 14 days for PPC and 28 days for MCD, and LMC. For MCD, the effect of the hygric state (dry versus SSD) of the substrate on the bond was also investigated.

The smooth NP texture led to poor bonding of PPC to UHPC (Figure 69), with most tests below the recommended value of 250 psi. A few data points exceeding 300 psi are likely due to the wrinkled texture of elephant skin at certain locations. For the other surface preparation methods, the measured pull-off strength proved to be acceptable. The relatively lower strengths associated with the HD and SR with an average of 616 psi and 675 psi respectively, are likely due to the different batches of materials used.

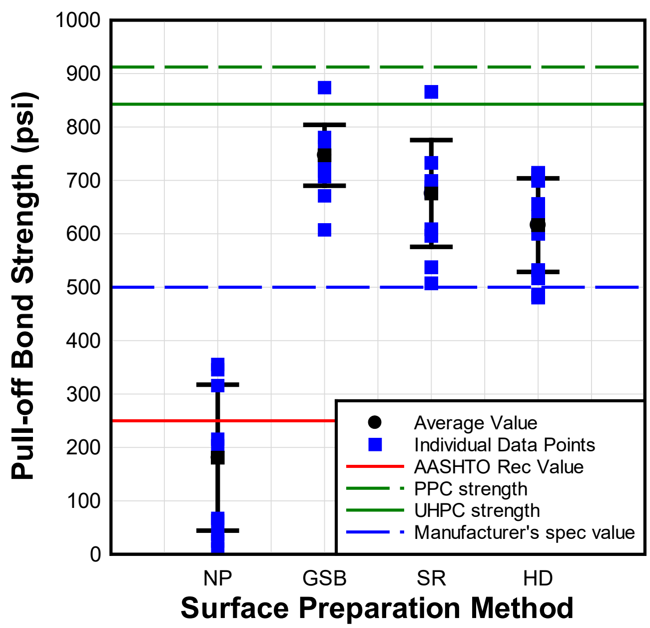
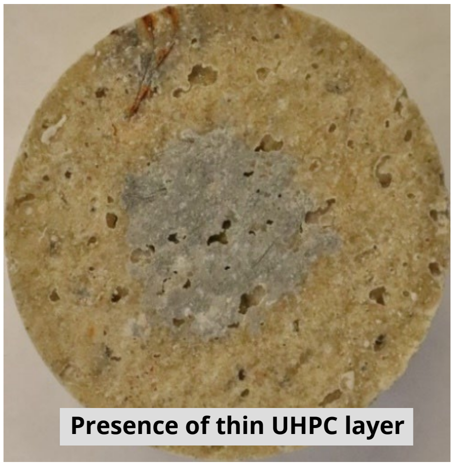
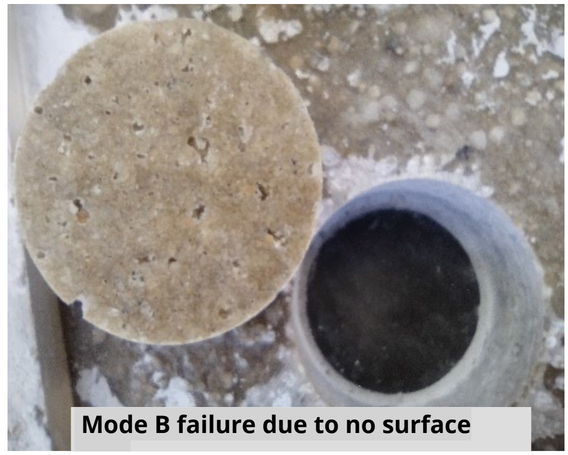


Figure 69. PPC bond pull-off strength as a function of surface preparation method. Error bars indicate one standard deviation.

The failure mode of PPC-UHPC bond for the NP surface was dominated by Mode B; the 20% corresponding to Mode C is due to the thin layer of UHPC that was present on some cores (Figure 70). GSB and SR resulted in an increase of the more desirable failure Modes A and C (Figure 71). The relatively higher percentage of failure mode B for the HD correlates with the relatively lower recorded pull-off bond strength values. Both the recorded bond strengths and failure modes for the NP surface show poor and unacceptable performance due to the low roughness of the surface. The other surface preparation methods improved the bond performance; therefore, to ensure sound bond between PPC and UHPC, it is required to prepare the surface with either GSB, SR, or HD. In addition, it must be emphasized that the exposed fibers on the UHPC surface following HD and SR proved to be advantageous. Due to the fiber-bridging effect (Figure 72), the specimens had to be reloaded after initial failure to completely separate PPC overlay from UHPC. The reapplication of load reached a stress of 250 psi in certain cases, indicating that the fiber-bridging effect is quite significant.



(a)



(b)

(c)

Figure 70. Typical failure modes observed for PPC overlay: (a) mixed failure Mode A and B (core side); (b) failure mode B (core and substrate side); and (c) failure Mode C (core side).

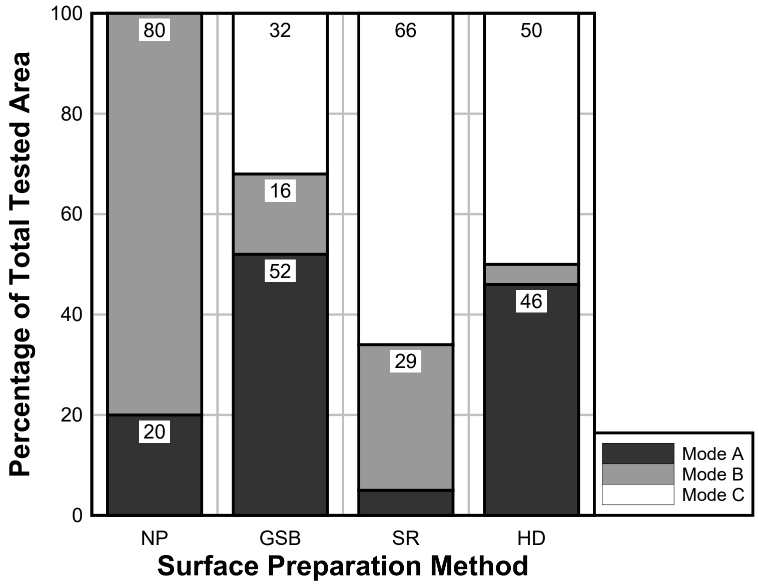


Figure 71. Distribution of PPC failure modes as a function of surface preparation method.

Figure 72. Example failure mode showing steel fibers from UHPC embedded in PPC.

Application of surface preparation methods did not improve MCD-UHPC bond pull-off strength. In addition, most of the recorded values were below DelDOT's minimum requirement of 250 psi. There was no statistically significant difference between the different surface preparation methods. Similarly, the hygric state of the substrate did not have a statistically significant effect the pull-off bond strength (Figure 73). Furthermore, the same failure mode—fracture along the weak interphase—was noted in specimens. Based on the presented results, it is likely that wall effect and MCD shrinkage govern the behavior of MCD-UHPC bond. As a result, varying the surface preparation method and hygric state does not have a pronounced effect on the bond strength and the interphase failure mode (Figure 74) was dominant in all tests.

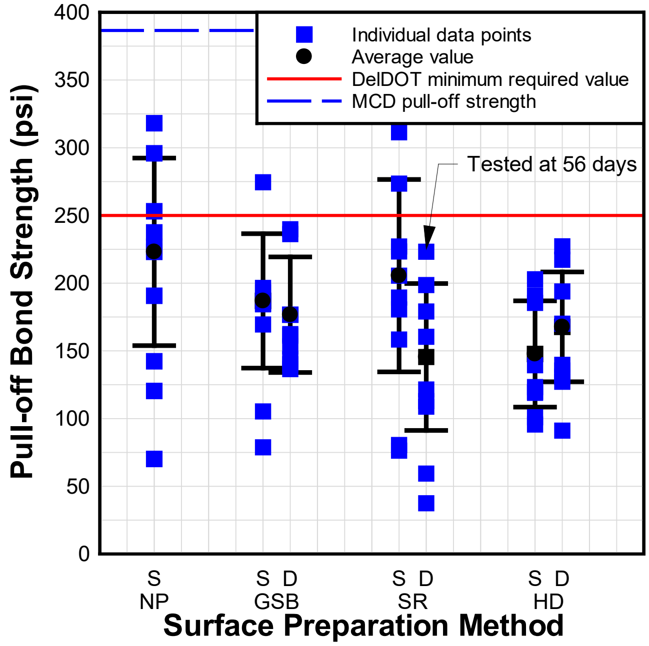
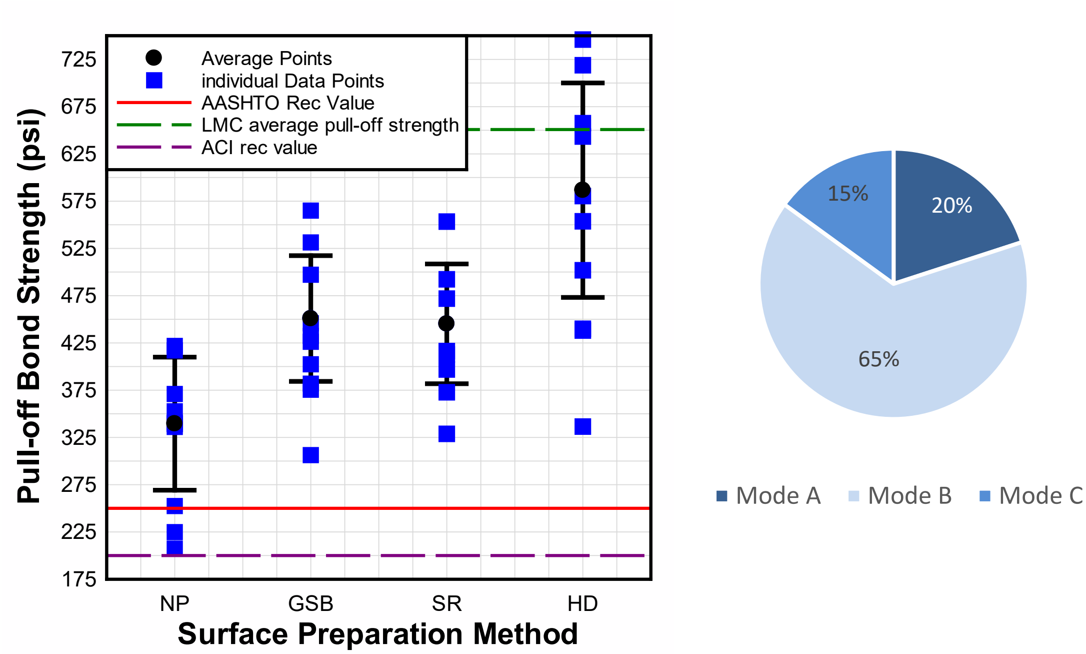


Figure 73. MCD bond pull-off strengths as a function of surface preparation method. 'S' and 'D' respectively indicate SSD and Dry substrates. Error bars indicate one standard deviation.

(a) (b)

Figure 74. Example of MCD failure Mode B (GSB): (a) core side; and (b) substrate side.

In contrast to MCD, the surface preparation method had a significant effected on the bond pull-off strength of LMC (Figure 75). The lowest average bond strength recorded (336.1 psi) was for the NP surface. Despite this measured strength being higher than the ones recorded for MCD and PPC for the same surface preparation method (NP), it was still lower than the bond strength recorded for LMC with GSB, SR, and HD. There was no statistically significant difference between the measured strength for GSB and SR. The highest recorded average bond pull-off strength of 586 psi was for the HD technique. The advantage of HD in offering the possibility of higher bond strength was also documented in other studies (Haber et al., 2017). However, it was also observed that the standard deviation for this method was larger than other methods. The bond strength associated with each one of the surface preparation methods was higher than the lower minimum recommended limit of 150 psi (for a conventional concrete substrate) in the literature (Sprinkel, 2005) and the ACI 548.4M-11 recommended minimum value of 200 psi. When it comes to the failure modes, all NP, GSB, and SR tested specimens exhibited failure Mode B, with post-failure fiber contribution in the case of SR. On the other hand, HD had 65% failure Mode B with post-failure fiber contribution, 20% failure Mode A, and 15% failure Mode C, an example of failure Mode B with HD surface preparation is shown in Figure 76. Studies on LMC that documented failure Mode A (Konduru, 2009) were done on conventional concrete substrates. Considering the pronounced desirable effect of HD on both the pull-off bond strength and failure mode, HD is recommended for LMC overlays.



(a) (b)

Figure 75. (a) LMC bond pull-off strengths as a function of surface preparation method; and (b) failure mode distribution of LMC for the HD method. Error bars indicate one standard deviation.

(a) (b)

Figure 76. Example of LMC failure Mode B (HD), (a) core side; and (b) substrate side.

The effect of the surface preparation method on the pull-off bond strength was evident for both PPC and LMC. For these two overlays, the NP surfaces resulted in lower bond strengths compared to GSB, SR, and

HD, which is likely due to the improved roughness provided by these surface preparation methods. In addition, the bond strengths of PPC and LMC to the UHPC substrate for all the surface preparation methods were higher than the AASHTO and ACI recommended values (250 psi for PPC and 200 psi for LMC) as well as the minimum recommendation of 150 psi mentioned in the literature (Sprinkel, 2005). Compared to GSB, HD and SR did not lead to the higher bond strength of the PPC overlay, but HD resulted in a notable improvement of bond pull-off strength over GSB and SR. Nonetheless, the SR and HD enabled fiber-bridging effect across the interface for both LMC and PPC overlays. Surface preparation method did not affect the MCD-UHPC bond strength, and all bond strength values remained low. MCD's poor performance compared to the other two overlays is accredited to the formation of weak interphase and its susceptibility to drying shrinkage.

8.3 Field Test Results

The summary of field test data are shown in Figure 77 and Table 10. The average of the measured pull-off bond strengths was 574 psi with a standard deviation of 83.6 psi. The lowest value recorded, 463.3 psi for E1 (Table 10) was higher than the AASHTO recommendation of 250 psi. The bond pull-off strengths are, therefore, similar to the laboratory test findings. Two failure modes were observed in field samples—Mode C and mixed Mode A/B. Interestingly, the samples with failure Mode B were both located near the outer edges of West and East shoulders; it is possible that the surface preparation was not as effective at these locations due to possible safety concerns. Nonetheless, despite the difference in the failure modes, the bond performance was satisfactory with all the specimens.

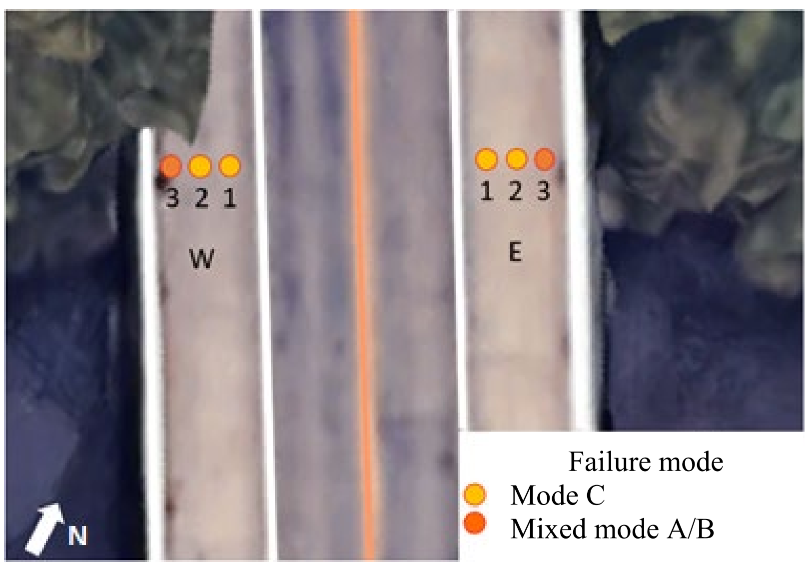


Figure 77. Specimen locations and failure modes. 'W' indicates west shoulder and 'E' indicates east shoulder.

Table 10. Recorded bond pull-off strengths with failure modes.

W1	W2	W3
 556.6 psi Mode C	 540.7 psi Mode C	 593.3 psi Mixed Mode A/B
E1	**E2**	**E3**
 468.3 psi Mode C	 722.3 psi Mode C	 567.0 psi Mixed Mode A/B

Chapter 9

SUMMARY AND CONCLUSIONS

Existing studies in the literature extensively evaluated the bond performance of overlays on conventional concrete substrates. UHPC is increasingly used in link slabs and bridge decks connections, but the literature addressing the bond performance of overlays with a UHPC substrate is limited to investigating LMC and UHPC as overlay materials. In addition, the studies that evaluated overlay-UHPC bonds considered only scarification and hydrodemolition as surface preparation methods. To address this knowledge gap, this project evaluated the bond performance of PPC, MCD, and LMC to UHPC by means of bond pull-off test method. The studied variables included coring depth, overlay age (varying from 7 to 56 days), and surface preparation method (GSB, SR, HD, and NP). Following each test, bond strength and failure mode were recorded. In addition, the research evaluated three methods—ICRI CSP chips, sand-patch method, and surface profile gauge—to assess surface roughness of UHPC substrate and contribute toward the development of surface roughness metrology for UHPC. The following conclusions were drawn from this experimental study:

1. ICRI CSP chips cannot be used to qualitatively assess the texture of the UHPC substrate. This is because ICRI CSP chips were created for normal concrete, which has significantly different microstructure compared to UHPC. These differences include the absence of coarse aggregates in UHPC, presence of air pockets within the elephant skin, and steel fibers. Sand patching could be applied only on NP and GSB surfaces due to the exposed fibers obstructing the spread of sand on the surfaces prepared by HD or SR.
2. The surface profile gauge was shown to be capable of effectively quantifying the roughness of prepared UHPC surfaces. High Rq roughness was associated with HD and SR (approximately 65% higher than NP and 38% higher than GSB). Despite the wrinkles that occur on the elephant skin of NP UHPC, the NP UHPC had a smoother surface than the other three methods. GSB increased the roughness and opened the air pockets enclosed by the "elephant skin" of UHPC, while SR and HR resulted in exposed fibers.
3. Pull-off bond strength decreased with coring depth (approximately 10% on average for each 0.5-in. depth increment). This is likely due to the size effects and torsional friction from the coring process. A coring depth of 0.5 in. was determined to be optimal for testing the bond of overlays to UHPC; this is because 0-inch depth is not practical and 1- and 1.5-in. depths would risk damaging internal steel reinforcement. In addition, shorter coring depths are thought to minimize the potential for erroneous test results due to the damage introduced by the drilling process.
4. PPC gained bond strength rapidly and the age sensitivity study showed a relatively high and constant bond strength (above 600 psi) during the testing period (7 to 56 days). LMC developed bond strength over time and plateaued at 28 days with a bond strength of approximately 450 psi. Bond strength of MCD decreased by approximately 48% (from 338 to 175 psi) following moist curing. This reduction in bond strength of MCD was accredited to the effects of restrained drying shrinkage.
5. Overall, overlays bonded to the NP surface had relatively lower bond strengths (with many values below the minimum requirement of 250 psi), likely because of the lack of substantial surface roughness. In PPC, the bond strength increased by up to 273% on average for GSB, SR, and HD methods when compared to NP, but there was no statistically significant difference in bond strength between the three methods. GSB, SR, and HD increased the bond strength of LMC by 34%, 33% and 74% on average over NP. Finally, the average bond strengths for MCD ranged from 150 to

225 psi; there was no statistically significant difference between different surface preparation methods, or SSD versus dry substrate.

6. For all the surface preparation methods, MCD had pull-off bond strength below DelDOT's minimum requirement of 250 psi. PPC and LMC exceeded the minimum pull-off bond strength requirements for all surface preparation methods. The NP surface had average bond strength below the minimum requirement for PPC. The average bond strength of LMC on NP UHPC substrate exceeded the minimum requirement, but several specimens failed below 250 psi. Field data on PPC overlay were consistent with the laboratory findings.

7. While PPC and LMC had mixed failure modes, MCD failed along the weak interphase. The presence of polymers with adhesive properties (i.e., latex and polyester) in LMC and PPC is a likely explanation for their improved bond performance compared to MCD.

Chapter 10

RECOMMENDATIONS FOR IMPLEMENTATION AND FUTURE RESEARCH

Based on the findings from this study, the following practical recommendations are made:

1. Using ICRI CSP chips is not recommended for assessing the surface texture of UHPC surfaces. Sand patch method can only be used for NP or GSB UHPC surfaces. The preferable method of measuring UHPC surface roughness is surface profile gauge. A good representation to classify surfaces based on roughness is the empirical cumulative probability, albeit not practical. Rq and Ra values are a simple representation of surface roughness and correlate well with observed textural differences between the surfaces.
2. The bond pull-off test is a reliable test method. To avoid high variability of test results, one must ensure consistent roughness over the tested are, good control over the drill to minimize/eliminate damage to the core prior to testing, and a uniform coring depth. A coring depth of 0.5 in. is recommended based on the coring depth sensitivity study.
3. PPC is recommended for the highest bond strength to prepared UHPC substrate, followed by LMC, and finally, MCD, which should be used with vigilance due to its inferior bond performance compared to PPC and LMC.
4. GSB was satisfactory to improve the mechanical interlocking of the overlays to UHPC and achieve adequate bond strength. HD and SR are recommended surface preparation methods to maximize mechanical interlock, which might provide benefits for the shear bond strength (which was not assessed in this study).

Further research can be conducted to further improve the measurement and testing methodologies. Based on the experience gained from this study, the recommendations for future work include:

- Although the surface profile gauge proved to be practical in the lab, this method is time consuming, especially when conducted on large areas. Developing an alternative approach for field assessment of UHPC texture—such as modified ICRI CSP chips—should be a priority.
- This study only investigated bond performance under direct tension. Shear stresses can be significant in overlays; thus, future research should investigate the effects of pure shear and mixed-mode loading conditions on bond performance.
- In this study, visual observations indicated that the wall effect was responsible for the low bond strength of MCD overlays. Further studies should investigate this phenomenon to determine how to minimize its effects on the MCD-UHPC bond performance.
- Surface preparation methods adopted in this study are GSB, SR, and HD. The effectiveness of other surface preparation methods, such as needle scaling, explosive blasting, scrabbling, shot blasting, should be explored.
- Investigating bond durability of overlays on UHPC under, for example, freeze-thaw cycles, moisture ingress, fatigue loading, would be another important contribution to the state-of-the-art.

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Appendix A

KwikBond PPC Product Data Sheet

KWIKBOND POLYMERS

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PRODUCT DATA SHEET: PPC 1121 Polyester Polymer Concrete

PPC 1121 Polyester Polymer Concrete is a pre-mixed polymer concrete made of polyester binder resin and graded aggregates with a High Molecular Weight Methacrylate (HMWM) primer system that develops true composite action at the bond line of the substrate. PPC 1121 is designed for bridge deck overlay, patching and joint header applications for the rehabilitation and preservation of existing and new bridge structures that require long term performance, impermeability to chlorides and moisture, abrasion resistance, ease of construction and rapid traffic return after placement.

SPECIAL FEATURES

- 2-hour traffic return at all placement temperatures
  - 40 to 100°F for overlays
  - -10 to 110°F for patches and headers
- Variable thickness placement ¾" to >12" in a single lift
- 0 coulombs permeability to moisture and chloride ions
- HMWM primer saturates and strengthens the substrate transition zone for true adhesive composite action at the bond line
- Over 35 years of proven performance

PPC 1121 Composite Properties		
Compressive Strength	ASTM C39	6,000 psi
Tensile Strength	ASTM C1583	800 psi
Flexural Strength	ASTM C78	2,000 psi
Modulus of Elasticity	ASTM C469	1,500 ksi
Coefficient of Thermal Expansion	ASTM T336	<10 x 10^{-6} in/in/°F
Abrasion Resistance	CT 550	< 2g weight loss
Bond Strength	CT 551, SSD w/ HMWM	>700 psi
	CT 551, SSD w/o HMWM	>500 psi
Permeability	ASTM C1202	0 coulombs
Linear Shrinkage	ASTM C157 (4-hr initial)	< 500 με

APPLICATION

SURFACE PREPARATION:

PPC 1121 is applied to concrete or steel substrates that are sound, strong, clean, visibly dry, and abrasively blasted.

Identify unsound concrete by chain-drag or hammer sounding. Remove unsound areas to sound concrete. Rebar exposure is not required for composite action between PPC 1121 and substrate material.

Complete removal of existing overlay materials below the existing bond line is recommended. Existing concrete overlays that are both structurally sound and also placed below the top mat of rebar may remain in place.

Abrasive blasting is required for all substrate surfaces, including new CIP concrete, new precast concrete, existing concrete, milled concrete, diamond ground concrete and all steel. Abrasively clean concrete substrate surfaces by shot blasting to remove all visible contaminants and excess cement paste, yield an open pore structure and expose some aggregate within the concrete. Sand blasting is acceptable for patches and headers as well as vertical surfaces and boundaries of overlay areas inaccessible to the shot blasting machine. Abrasively clean steel surfaces by shot or sand blasting to remove all visible contaminants and flash rust leaving a clean steel finish.

PATCHING:

Complete patches with PPC 1121 or HCSC for optimal thermal compatibility. PPC 1121 and HCSC patches may be overlaid with

PPC 1121 after 2 hours and 4,000 psi manual rebound hammer reading per ASTM C805.

Patches made with most cementitious materials must reach both 80% expected ultimate strength AND a minimum of 3-days open air cure after wet-curing prior to overlay.

UHPC closure pours must reach 14 ksi compressive strength prior to PPC 1121 overlay. It is recommended that UHPC surface is ground to remove air pockets, laitance, and weak cement paste prior to surface preparation for overlay by abrasive blasting.

Avoid placing PPC 1121 on patches with high expected shrinkage. Do not use patching materials with CTE >15x10^{-6} in/in/°F.

FORMING:

Suggested materials to form expansion joint gaps include rigid foam board wrapped in polyethene sheeting or closed cell backer rod. Closed cell spray foam used for small gaps and holes must form a hard shell prior to PPC 1121 installation. Do not use open cell spray foam.

Overlays placed with a vibratory screed can be formed with wood strips or steel set to finished grade.

Line bottom formwork for full depth PPC 1121 elements such as patches, joints and closure pours with polyethylene sheeting.

TOOLS & EQUIPMENT:

KBP ProPrime is mixed in buckets and placed with rollers, brooms and brushes.

PPC 1121 is mixed in batches using ≥ 9 CF paddle or drum mixers, or continuously using volumetric mixing trucks specifically designed for production of PPC 1121 material. Mix in single, double or partial batches as needed. A single batch is 2.5 CF.

PPC 1121 is placed to grade using a vibratory screed or automated slip form paver specifically designed for PPC 1121. Do not use a roller screed. Finish with standard concrete finishing tools such as hand floats, bull floats and fresno trowels.

HMWM PRIMER INSTALLATION:

KBP ProPrime is a pre-promoted version of KBP 204 with the cobalt promotor pre-mixed into the HMWM resin prior to shipment. For applications that require delivery of un-promoted KBP 204 primer instead of KBP ProPrime, follow KBP 204 mixing directions.

KBP ProPrime Components:

- ProPrime HMWM Resin
- Cumene Hydro Peroxide (CHP) Initiator (3 oz per gal of ProPrime)
- ZCure Accelerator (varies based on temperature 0 to 3oz/gal)

Ensure substrate temperature is within the specified range using an infrared temperature gun. Premix the entire container of KBP 204 ProPrime to ensure that contents are well mixed before portioning out material to be used. Combine up to 4 gal KBP ProPrime HMWM resin, CHP and ZCure in a clean, dry bucket and mix for 30 seconds with a drill mixer. Follow mix ratios given by KBP technical service representative for exact mix proportions.

Within 5 minutes of mixing, empty contents onto the substrate surface. Evenly spread primer to refusal using brooms or rollers and brushes. Reapply to dry areas and redistribute excess puddling as necessary leaving a deeply saturated substrate. Application rates range from 70-120 sf/gal depending on porosity and surface texture of the deck. Place PPC 1121 within 15-120 minutes after priming.

PPC 1121 MIXING:

PPC 1121 Components:

- Polyester Binder Resin
- Graded silica-quartz aggregates
- Methyl Ethyl Ketone Peroxide (MEKP) Initiator
- ZCure Accelerator

To mix a single 2.5 CF batch of PPC 1121, combine 4 gallons of Polyester Binder Resin, (7 to 15 oz) MEKP and (0 to 4 oz) ZCure in a clean, dry bucket and mix for 30 seconds with a drill mixer. Exact levels to be used are dependent on placement conditions, temperature, application, and dimensions. Follow KBP technical support guidance for specific mix design.

While clean mortar mixer is turning, add catalyzed Polyester Binder Resin, 2 each 50 lb bags of KBP number 39 Stone (B39, S39, KBEC39) and 4 each 50 lb bags of KBP Blended PPC Sand (B11, S11, KBEC11). Alternately, 6 each 50 lb bags of KBP blended single bag aggregates (Blend 84, KBEC 84) may be used. These are the premixed equivalent of sand and stone at the 2:1 ratio.

Mix for 1-2 minutes and until all aggregate appears wetted.

Dump catalyzed material into a wheelbarrow, buggy, or other transfer device. Immediately recharge mixer with proper volume of catalyzed Polyester Binder Resin and continue mixing ONLY if crew is ready for another mix. If mixing operation is expected to stop for ~10+ minutes, clean mixer with acetone and allow to evaporate prior to resuming.

Adjust catalyst levels as needed to account for changes in temperature, application type, environmental conditions, and proper strength gain requirements. Temperature and application timing impact working time and strength development of PPC 1121. Mix to achieve a 30 minute initial set time and rapid strength gain thereafter.

Continuous volumetric mixers specifically designed for mixing PPC 1121 may also be used for high output applications. Volumetric mixers must be properly calibrated and equipped with appropriate resin/catalyst/accelerator pumping systems as well as computer tracking system capable of meeting specifications for output tracking and calibration.

KBP PPC Easy Patch kits include the same component materials as PPC 1121, pre-proportioned in a 0.43 cubic foot kit, packaged in a 5-gallon bucket.

FINISHING

Place PPC 1121 mixture to grade using a vibratory screed, a slip form paving machine, or standard hand finishing tools for smaller areas. Strike off and fill to finished grade using concrete finishing tools as needed. Properly finished PPC 1121 should yield a well-compacted material with a slight glossy sheen without excessive bleed resin. Immediately hand broadcast top sand leaving an evenly covered finished surface free of mirroring or glossing. Texture with tine rake as required by the specification (or 1/8" teeth @ ≥3/4" spacing) after sanding and prior to initial set, or mechanical saw-cut grooving (minimum 48 hours after installation). Broadcast top sand may be cast after tining ONLY when tines are mounted directly to the slip-form paver.

PPC 1121 can be placed for overlay application at temperatures between 40-100°F. Patching, joint headers, and other work with minimal surface area may be performed at temperatures between -10-110°F. Trial batches can be used to determine working time and set time based on anticipated application temperatures, conditions, and strength gain requirements.

CLEANUP

Clean tools, screed and mixer with acetone, or other suitable solvent prior to initial set. Cured material may have to be chipped off. Mixers in continuous operation do not need to be cleaned between batches.

STANDARD PACKAGING

- Polyester Binder Resin: 4 gal pail, 55 gal drum, 40,000 lb tankers
- Mix Aggregates: 50 lb bags, 2 ton super sacks
- Top Sand: 50 lb bags
- KBP 204 ProPrime: 4 gal pails, 50 gal drums, 250 gal totes
- MEKP & CHP: 12 oz and 1 gal bottles
- Z Cure: 12 oz and 1 gal bottles & 5 gal pails

SAFETY & STORAGE

Follow all OSHA, and other guidelines as well as all applicable fire codes. Refer to SDS for storage, handling, and use. Gloves, eye protection, and other protective clothing should be worn while working with PPC 1121 and KBP ProPrime. Respirator with Organic Vapor cartridges may be desired while working with PPC1121 Binder Resin. Dust protection must be worn while working with neat aggregates. If liquid components come in direct contact with skin, wash off with soap and water. If any component gets in eyes, flush immediately with eye wash. If customer requests to have Cobalt promoter supplied separately from HMWM resin, extra care must be taken to avoid contact between Cobalt promoter and peroxide catalysts as a violent exothermic reaction will occur.

Store all components in a cool, dry location out of direct sunlight and in their original containers. Always protect components from moisture. Minimum shelf life is 12 months when properly stored.

Appendix B

L&M™ EVERBOND™ Data Sheet

L&M™ EVERBOND™

DS-176.2-0620

Globally Proven Construction Solutions

1. PRODUCT NAME
L&M™ EVERBOND™

2. MANUFACTURER
LATICRETE International, Inc.
1 LATICRETE Park North
Bethany, CT 06524-3423 USA
Telephone: +1.203.393.0010, ext. 1235
Toll Free: 1.800.243.4788, ext. 1235
Fax: +1.203.393.1684
Website: laticrete.com

3. PRODUCT DESCRIPTION
EVERBOND is a versatile acrylic polymer emulsion that can be used either as a bonding adhesive or as an admixture that enhances portland cement-based mixes, giving these mixes improved flexural, tensile and bond strength. EVERBOND is a milky white, high solids emulsion that will not re-emulsify upon exposure to water, and is non-oxidizing and ultraviolet light stable. EVERBOND, when used as a bonding agent, becomes an integral part of the interface between the cementitious material and the surface to be bonded. EVERBOND creates a strong bond between materials to be bonded.

Uses
- EVERBOND improves the adhesion of cementitious materials such as concrete toppings, stucco and terrazzo to structurally sound concrete, plaster or masonry.
- EVERBOND may be used as an admix by adding to portland cement-based repair mortars to increases their adhesion, freeze-thaw resistance, flexural strength, and durability.
- EVERBOND may be used as a bonding agent when applied at full strength to aid in bonding concrete repairs made in sidewalks, driveways, steps, floors, brick pointing and stucco. It will help bond portland cement mortars to brick, concrete block, clay tile, marble and even glass block.
- EVERBOND may be used as a bonding slurry/bonding grout when added to portland cement to create a very strong and effective bonding slurry for concrete toppings and repair materials.

Advantages
- Improved adhesion between cementitious materials
- Use as bonding adhesive or admixture
- High abrasion resistance
- Rapid drying time

Suitable Substrates
- Concrete

Packaging
5 Gal (18.9 L)
55 Gal (208 L)

Approximate Coverage

Finish	Approximate Coverage
Roughened Concrete	200-300 ft^2/gal (4.9-7.4 m^2/L)
Plaster or Smooth Concrete	300-400 ft^2/gal (7.4-9.8 m^2/L)
Bonding Slurry over CSP 8-10 Concrete	80-100 ft^2/gal (2.0 - 2.5 m^2/L)

Shelf Life
Containers are to be kept tightly sealed and stored in a clean, dry area between 45-100°F (7-38°C). Shelf life is a minimum of one year when stored properly. Do not allow to freeze.

Limitations
- Surfaces to which EVERBOND is applied must be clean and structurally sound
- Do not apply over frozen surfaces, water soluble paints, rust, laitance or peeling paint
- Apply at temperatures of 40(F (4(C) and rising

- Do not use as an admixture with concrete or mortar mixes containing air entraining admixtures
- Do not expose newly placed EVERBOND-modified cement mixes to water immersion for at least 24 hours
- Protect EVERBOND™ film from dirt or other contaminants until topping is placed
- Do not allow film or slurry to dry before placing repair mortar or topping
- Cover with wet burlap in hot weather to protect from rapid drying. Do not cure EVERBOND modified mortars on toppings with solvent based curing compounds

Cautions

- Consult SDS for safety information
- Protect finished work from traffic until fully cured
- Keep out of reach of children
- Mock-ups and field test areas are required in order to validate performance and appearance related characteristics (including but not limited to color, inherent surface variations, wear, anti-dusting, abrasion resistance, chemical resistance, stain resistance, coefficient of friction, etc.) to ensure system performance as specified for the intended use, and to determine approval of the decorative flooring system.

4. TECHNICAL DATA

VOC/LEED Product Information

25 g/L

Physical Properties

Property	Standard	Results
Tensile Strength	ASTM C190	600 psi (4.1 MPa)
Shear Strength	ASTM C1042	>1250 psi (8.6 MPa)
Shear Strength (Slurry Coat)	ASTM C1042	2100 psi (14.5 MPa)
Flexural Strength	ASTM C78	725 psi (5 MPa)
Freeze Thaw Scaling	ASTM C672	No scaling
Abrasion resistance	---	Good resistance

Working Properties

Property	Results
Dry time (2 mil film) at 70F (21C)	**1 hour**

Specifications subject to change without notification. Results shown are typical but reflect test procedures used. Actual field performance will depend on installation methods and site conditions.

5. INSTALLATION

Surface Preparation:

All surfaces must be clean, sound and free of all dust, curing compounds, oil, dirt, efflorescence, mildew or loose material. Dull all shiny surfaces mechanically. Thoroughly pre-dampen all concrete surfaces with clean potable water to a saturated, surface dry (SSD) condition to reduce absorption.

Application:

Apply EVERBOND by brush, spray or roller in a thin continuous film. Broom out puddles before installing any topping. Do not allow to dry.

Bonding Slurry/Bonding Grout:

Place bonding slurry first. Prepare the bonding slurry by adding equal amounts by volume, L&M EVERBOND and dry portland cement (example: 1 gallon of EVERBOND to 1 gallon of dry portland cement) into a bucket then drill mix to a creamy, thick paint like consistency. The bonding slurry should be applied to the floor in segments keeping only a short distance ahead of the placing of concrete topping. Pour and scrub or broom the bonding slurry thoroughly into the prepared concrete base slab. Do not leave puddles of bonding slurry mix on the surface. The bonding slurry must remain wet and tacky. Re-apply bonding slurry to areas that are dry and not tacky to the touch before installation of concrete topping. Do not overmix. Allow topping to cure a minimum of four days before exposing it to heavy wheeled traffic.

Flatwork Repairs:

Concrete toppings should be a minimum of 3/4" (19 mm) and are to be butted to a temporary vertical edge. Place EVERBOND and cement bonding slurry first, followed by repair mortar. Place within 20 minutes. Avoid overworking.

EVERBOND™ Reinforced Floor Toppings:

A reinforced floor topping is suitable for feather-edge work in light traffic areas. Place bonding slurry first. Do not overmix. Allow topping to cure a minimum of four days before exposing it to heavy wheeled traffic.

6. AVAILABILITY AND COST

Availability

LATICRETE materials are available worldwide.

For Distributor Information, Call:

Toll Free: 1.800.243.4788
Telephone: +1.203.393.0010

For on-line distributor information, visit LATICRETE at laticrete.com

Cost

Contact a LATICRETE Distributor in your area.

Appendix C

MCD Mix Design

Plant…	Bear Concrete			Date…	12/29/22
Class…	D-BM&MT			W / C Ratio…	0.370
Design Form ID…	D-50-50- #8 2" LINE PUMP MIX			Air %…	5.0
Air Entrainment…	4.0-7.0%			Yield in CY…	1.000
WRA…	Sika Viscocrete 2100 HRWR			Sacks / CY…	7.50
Designed by…	Bear Materials				
Remarks…L1	Batch Weights based on Air Entrainment of 5 %				
Remarks…L2	Srinkage reducing admixture Control 75 and Control SC				
	%	S.G.	Source of Materials	Type / class	
Sand…	48.0	2.60	Pennsy Sand		
Stone…1	52.0	2.85	Martin Marietta #8		100%
Cement…	50.0	3.15	Lafarge Holcim	I/II	
Slag / Flyash…	50.0	2.92	Walan	120	100%
Silicafume…	0.0	2.20	Silica fume		
Admix1 oz / C.Y.	3.0	1.10	Sika 2100	0.0	% Solids
Admix2 oz / C.Y.	3.0	1.06	Plastocrete 2020	0.0	% Solids

Mix Calculations by Volumetric Method

Cement	3.750	x	94.0	=	353	lbs	/	62.40	x	3.15	=	1.796	ft^3
Walan	3.750	x	94.0	=	353	lbs	/	62.40	x	2.92	=	1.937	ft^3
Silica fume	0.000	x	94.0	=	0	lbs	/	62.40	x	2.20	=	0.000	ft^3
Water	0.369	x	705	=	260.1	lbs	/	62.40			=	4.168	ft^3
Air	5.0	x	27.00	/	100						=	1.350	ft^3
Admix 1	3.0	/	128.00	=	0.02	gal	/	7.48			=	0.003	ft^3
Admix 2	3.0	/	128.00	=	0.02	gal	/	7.48			=	0.003	ft^3
Total Volume less Aggregates											=	9.255	ft^3
Aggregate Calculation													
Total	27.000	-	9.255	=	17.745	=	**Volume of Aggregates Needed**						
FA	17.745	x	0.480	=								8.518	ft^3
CA	17.745	x	0.520	=								9.228	ft^3
Aggregate Weight Calculation													
FA	8.518	x	62.40	x	2.60	=	1382	lbs					
CA	9.228	x	62.40	x	2.85	=	1641	lbs					

Summary:

Cement	1.796	ft^3	=	353.0	lbs	Gal Water / Sack	4.16
Slag	1.937	ft^3	=	353.0	lbs	Sacks Cement / cy	7.50
Silica Fume	0.000	ft^3	=	0.0	lbs	Unit Wt: lbs / cf	147.76
Water	4.168	ft^3	=	31.2	gal		
Air	1.350	ft^3	=	5.0	% AE	Water Cement	
FA	8.518	ft^3	=	1382.0	lbs	Ratio by Weight	0.370
CA	9.228	ft^3	=	1641.0	lbs		
Admix 1	0.003	ft^3	=	0.2	lbs	Sand Stone	
Admix 2	0.003	ft^3	=	0.2	lbs	Ratio	1:1.08 (48% - 52%)
Batch Size	27.003	ft^3					

Appendix D

LMC Data Sheet

What is Latex?

- Styrene-butadiene Latex
- Styrene-butadiene latex is a suspension of tiny polymer particles in water, typically made up of about 48% polymer solids
- Styrene-butadiene polymers are known for their hydrophobicity or excellent water resistance
- The polymer particles coalesce or fuse together when in contact to form a highly waterproof polymer film

WAGMAN

Surface preparation equipment

- Scarifying machine
- Hydro demolition equipment
- Abrasive blast equipment
  - Shot blast
  - Sand blast
  - Water blast
- Power driven hand tools

WAGMAN

What is Latex Modified Concrete?

- Concrete consisting of cement, aggregates, water, and styrene-butadiene latex
- Concrete that is designed for thin bonded overlays
  - Excellent bond strength
  - Low permeability
  - Low modulus of elasticity
  - Increased tensile and flexural strength
  - Improved freeze thaw and abrasion resistance

WAGMAN

Mixing equipment

- Mobile mixing unit

WAGMAN

Typical LMC Mix Design (per cubic yard)

Cement (7 Bags)	=	658 lbs
Sand*	=	1644 lbs
Stone*	=	1105 lbs
Latex (24.5 gals)	=	207.5 lbs
Water (17.5 gals)	=	144 lbs
Water Cement Ratio	=	0.38

* Adjusted for local specific gravity and moisture

WAGMAN

Placement limitations

- Place when ambient temperature is 45 degrees and rising
- Place when mix temperature is between 50 and 80 degrees
- Install bulkhead in case of major delays, and for delays of short duration place wet burlap over end of pour
- Do not place during rain
- Take precautions when evaporation rate is .10 lbs/sf/hr or greater

WAGMAN

What is Latex Modified Concrete?

- Concrete consisting of cement, aggregates, water, and styrene-butadiene latex
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WAGMAN

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* Adjusted for local specific gravity and moisture

WAGMAN

Pouring LMC

- Wet deck at least 1 hr. prior to placement and cover with plastic (Surface should be damp)
- Have necessary equipment to remove excess water from deck
- Broom lmc onto all horizontal and vertical surfaces and remove excess aggregates
- Place lmc to approx. ¼" above final grade
- Use spud vibrator along joints, gutters, deep pockets, and where finish machine cannot reach

WAGMAN

Complete final finish

- Allow finishing machine to do most of the work
- Hand finish gutters and joints (Hand finish as little area as possible)
- Texture overlay with tine rake or mechanical grover
- Place wet burlap as close behind finishing operation as possible

WAGMAN

"The Do Not's" of placing LMC

- Do not allow standing water on prepared surface
- Do not apply bond coat too far in front of operation
- Do not over finish
- Do not throw water on finished surface (No "Hail Mary's")
- Do not wait to cover surface with wet burlap
- Do not leave bridge unattended in areas where pedestrian traffic may be expected

WAGMAN

Curing LMC

- Soak burlap in water long enough to fully saturate (particularly important if burlap is new)
- Place wet burlap on finished surface close behind finish operation (Do not allow surface to dry-out)
- Cover with layer of white polyethylene film 4 mil min. thickness
- Secure edges of poly. film to prevent wind from getting underneath
- Wet cure for a minimum 48 hrs.
- After wet curing, remove burlap and allow to air cure as required

For questions or technical information

- Please contact Brandon Zerilla

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