Investigation into Flexural Bond Strength Test Method to Evaluate Influence of Surface Roughness on Bond Characteristics of UHPC with Precast Concrete

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Abstract:

The bond performance between UHPC and precast concrete was studied using three bond test methods – slant shear test, third-point flexural bond test and pull-off test methods. The influence of degree of surface roughness, prepared by sandblasting, on the bond between UHPC and precast was investigated. The surface roughness was quantified by two test methods – sand spread test and laser profiling. The test results showed that the third-point flexural bond test was a convenient and a realistic bond test to conduct. The increase in the duration of sand-blasting increased the roughness of the precast concrete surface which was quantified by both the sand spread test and the laser profiling. The laser profiling also reviewed that the mortar fraction was easier to be roughened than the coarse aggregate of the substrate precast concrete. Duration of sandblasting as short as 10 seconds was enough to achieve adequate bond between UHPC and precast concrete at the age of 7 days after casting UHPC, which was indicated by a failure in the precast concrete part and an ultimate load about same as the ultimate load of monolithic precast concrete specimen. Specimens without any surface roughened failed at the bond between UHPC and precast concrete, and the ultimate load was lower than that of monolithic precast concrete specimens. Moreover, the bond strength between UHPC and precast concrete cast on un-roughened sawn surface was higher than that cast on un-roughened molded surface.

Keywords:

UHPC, Precast Concrete, Bond, Roughness, sand spread test, laser profiling

1. Introduction

Ultra-high performance concrete (UHPC) refers to cementitious mixtures with superior workability, compressive strength (over 150 MPa or 21750 psi), pre-and post-cracking tensile strengths (above 5 MPa or 725 psi) and enhanced durability (Russell and Graybeal; Wille, Naaman and Parra-Montesinos; Graybeal). Because of its unique properties, UHPC has been increasingly adopted as a material for the construction of shear keys in Accelerated Bridge Construction (ABC) projects employing precast bridge elements. Of particular importance in the performance of shear key in precast concrete bridges is the bond between the UHPC and the precast concrete. The bond strength depends not only on the inherent characteristics of the two adjoining concrete mixtures, but also on the surface conditions of the substrate concrete such as its surface texture, cleanliness and its moisture content. While the importance of bond strength is well recognized, there is no broad agreement in the industry on the specific bond test method that is most reliable or representative for any given situation. Typical test methods used to determine the bond strength between UHPC and precast concrete include slant-shear test (ASTM C882) which evaluates the bond performance under shear, and pull-off test (ASTM C1583) which evaluates the bond performance under direct tension. Splitting tensile test has also been used to evaluate bond performance between two concrete mixtures under indirect tension (Munoz et al.; Tayeh et al.).

Several studies have been conducted in the past to evaluate the test methods and the surface roughness on the bond strength. In one study, the influence of surface roughness on the bond performance between UHPC and normal strength substrate concrete was evaluated with slant-shear test, splitting tensile test, and pull-off test (Munoz et al.). The substrate concrete surface conditions included sawn, brushed, chipped, sandblasted and grooved surface, and their degrees of roughness were evaluated by macro-texture depth test according to ASTM E965 (Munoz et al.). The results of this study showed that the roughness of the substrate concrete surface was not a critical factor to obtain a good bond when the substrate surface was in saturated surface dry condition (Munoz et al.). This was attributed to the saturated substrate concrete surface which helped to generate hydration products and create enough cohesion between UHPC and substrate concrete, considering the un-hydrated cement presented in UHPC (Munoz et al.). However, de-bonding failure mode likely occurred when the ambient dry substrate surface was not roughened sufficiently (Munoz et al.).

In another study, the bond performance between UHPC and substrate concrete was studied using slant-shear test and splitting tensile test (Tayeh et al.). The conditions of the substrate surface (saturated surface dry) included as-cast without roughening, sandblasted, wire brushed, drilled holes and grooved surface (Tayeh et al.). The results showed that the highest bond strength was achieved by sandblasting the substrate surface, and the failure always occurred at the substrate concrete in both the bond test methods (Tayeh et al.). The other four surface conditions did not provide adequate bond as de-bonding failure occurred in either of the two bond test methods (Tayeh et al.). One of the shortcomings of this study was that it did not provide quantitative surface roughness measurement on the different roughening methods (Tayeh et al.). Another shortcoming of the past studies was that test methods such as slant-shear test and pull-off test did not reflect flexural tensile stress conditions that were expected in shear key connections or in any other flexural elements of bridge decks.

The present study investigates the bond performance between UHPC and precast concrete under the influence of different degrees of surface roughness of the substrate concrete surface prepared by sandblasting. The experimental study was carried out in two phases. In the first phase, the bond performance between UHPC and precast concrete was studied using three different test methods: pull-off test, slant-shear test and third-point flexural bond test. Third-point flexural bond test had not been extensively used in previous literature. In the second phase, third-point flexural bond test was used to study the effect of surface roughness on the bond performance between UHPC and precast concrete. Sandblasting of different durations was used to achieve different roughness of precast concrete surfaces which were originally sawn faces or as cast/molded faces. In this study, the degree of surface roughness was quantified using sand-spread test and laser profiling. The UHPC formulation was developed using local materials in the authors' previous research (Li et al.; Rangaraju et al.; Li and Rangaraju). The precast concrete used in this study had 28-day compressive strength of 49 MPa (7105 psi) which was similar to the substrate concrete used in local precast bridge structures, and was similar to substrate precast concretes employed in other studies discussed above (Tayeh et al.; Munoz et al.).

2. Experimental Program

2.1. Materials for Preparing UHPC

A Type III portland cement conforming to ASTM C150 specification was used. The principal oxide composition of cement was as follows: CaO - 64.4%, SiO_2 - 20.4%, Al_2O_3 - 6%, Fe_2O_3 - 3.5%, SO_3 - 3.5% and Na_2O_{eq} - 0.49%. The specific surface area of cement was 540 m^2/kg (293 yd^2/lb). A low loss-on-ignition (LOI) silica fume (SF) was used as a supplementary cementitious material. Its LOI value and the SiO_2 content were 0.22% and 96%, respectively. Its specific surface area was 20000 m^2/kg (10850 yd^2/lb) determined by Brunauer–Emmett–Teller method (nitrogen adsorption).

The steel micro fibers (SMF) were 13 mm (0.5 in.) in length and 0.2 mm (0.008 in.) in diameter. The specific gravity and ultimate tensile strength of SMF were 7.8 and 2000 MPa (290 ksi), respectively. Fine aggregate was a sub-rounded natural siliceous sand meeting ASTM C33 gradation specification. The percent passing values through each of the standard sieves are as follows (1 inch =25.4 mm): 9.5-mm sieve – 100%, 4.75-mm sieve – 99.8%, 2.36-mm sieve – 97.1%, 1.18-mm sieve – 82%, 600-μm sieve – 41.9%, 300-μm sieve – 14.0%, 150-μm sieve – 0.5% and 75-μm sieve – 0.1%. The specific gravity, water absorption, and fineness modulus of the fine aggregate were 2.62, 0.30%, and 2.65 respectively. A polycarboxylic ester based high-range water-reducing admixture (HRWRA) in a powder form was used to improve the workability.

2.2. Mixture Proportions

2.2.1. Ultra-high Performance Concrete (UHPC)

Two UHPC mixtures, a non-fiber reinforced mortar and a fiber reinforced mortar, were prepared for study. The relative mass proportions of each component of the non-fiber reinforced mortar are as follows: w/cm = 0.20, SF/c = 0.20, sand-to-cementitious materials (s/cm) ratio = 1.25 and HRWRA/cm = 0.010. The fiber reinforced mortar was prepared by adding SMF to the former mortar at a dosage of 2% by volume of the total mixture. The quantities of materials used for 1 m^3 (1.3 yd^3) of UHPC mixtures are presented in Table 1.

Table 1. Quantities of Materials Used for 1 m^3 of UHPC Mixture (kg/m^3)

Mixture ID	Cement	SF	Water	Sand	SMF	HRWRA
UHPC 1	819	164	197	1229	0	9.8
UHPC 2	803	160	193	1204	156	9.6

2.2.2. Precast Concrete

The mixture proportions of the precast concrete was typically employed by a local precaster. The mixture proportions for 1 m^3 (1.3 yd^3) of precast concrete are given as follows (1 kg = 2.2 lb): Type I cement - 392 kg, fly ash – 60 kg, coarse aggregate – 973 kg, fine aggregate – 731 kg, water – 147 kg and HRWRA – 2.8 kg. The fly ash used in the precast concrete is a Class F fly ash with the sum of silica, alumina and iron oxide (S+A+F) contents of 90% and lime content of 1.34%.

2.3. Specimens Preparation

2.3.1. Preparation of Fresh UHPC Mixture

In the first phase of the study, UHPC mixture was prepared in a 0.25 m^3 (0.325 yd^3) Whiteman mortar mixer. A sequential mixing procedure was followed to avoid overloading the mixer when the UHPC mixture was very viscous. As a first step, half of the dry material including cement, SF, sand and HRWRA were mixed for 1 to 2 minutes. Then half of the mixing water was added. When the mixtures became flowable, the rest of the dry materials and water were gradually introduced into the mixer. SMF was added as the last step after ensuring that the non-fiber mortar was visually flowable in the mixer. The entire mixing process lasted for 15 to 20 min.

In the second phase of the study, UHPC mixture was prepared in a 0.019 m^3 (0.025 yd^3) UNIVEX M20 planetary mixer. At first, all the dry materials were mixed for 1 to 2 min at low speed (100 RPM). Then the mixing water was added to the dry mixture, and the mixing continued at low speed for 3 to 4 min before the mixture became flowable. After that the mixing continued for another 1 to 2 min at medium speed (300 RPM). SMF were added as the final step, and the mixing continued for another 3 min. The entire mixing process lasted for 8 to 11 min.

2.3.2. Preparation of Specimens for Mechanical Properties of UHPC and Precast Concrete

Specimens for evaluating the mechanical properties of UHPCs and precast concrete were cast in the lab. Specimens were cast on a vibrating table to remove any unintended entrapped air. Then the specimens were kept in a moist room conforming to ASTM C511 specification. After demolding at the age of 24 hours, specimens were stored in the moist room until testing.

2.3.3. Specimens for the Study of Bond between UHPC and Precast Concrete

For the first phase of the study, the specimens for the pull-off test, slant shear test and third-point flexural bond test were prepared. The specimen for the pull-off test was prepared by placing a 25 mm (1 in.) thick layer of fresh UHPC mixture on top of a precast concrete slab. The slant shear specimen was a cylindrical specimen with a diameter of 75 mm (3 in.) and length of 150 mm (6 in.). Plastic inserts were placed in the molds during casting precast concrete to create an inclined surface that was 30° measured from the longitudinal axis of the specimen. The specimen for the third-point flexural bond test was a composite prismatic specimen with dimensions of 75 mm × 75 mm × 285 mm (3 in. × 3 in. × 11.25 in.). Half of the specimen comprised of precast concrete and another half consisted of the UHPC. For this purpose, precast concrete prisms of the same dimensions as the composite prisms were sawn in the middle perpendicularly to the longitudinal axis into two half-prisms. For all the specimens, the substrate surface was sandblasted for 1 min.

For the second phase of the study, six different surface conditions of the substrate concrete surface of the flexure beams were used. Four out of the six surface conditions were prepared by sandblasting the sawn surface for periods of 0 s, 10 s, 30 s and 60 s. The other two surface conditions were prepared by sandblasting the molded surface for periods of 0 s and 10 s.

For all the specimens, the precast concrete was cast 28 days earlier. The substrate surface was moistened to a saturated surface-dry state before applying UHPC. A gentle external vibration was applied to remove any trapped air-voids during casting. The specimens were de-molded at the age of 24 hours. The slant shear specimen and flexural bond specimens were stored in the moisture room. The pull-off specimens were stored in the lab under ambient temperature (23 ^{o}C/73 ^{o}F). Tap water was sprayed on the UHPC layer of the slab periodically to keep the surface wet and cured.

2.4. Test Methods

2.4.1. Material Properties of UHPC and Precast Concrete

Immediately after mixing, the workability of UHPC was measured as described in ASTM C1437. The compressive strength, third-point flexural strength and modulus of elasticity (MOE) of UHPC were measured following methods described in ASTM C109, ASTM C78 and ASTM C469, respectively. The compressive strength, third-point flexural strength and MOE of precast concrete were measured following methods described in ASTM C39, ASTM C78 and ASTM C469, respectively. Three specimens were tested for each of the mechanical properties.

2.4.2. Roughness of the Sandblasted Precast Concrete Surface

Sand-spread test and laser profiling were used to quantify the degree of roughness of the substrate surface. For sand-spread test (see Figures 1a and 1b), a sample of fine sand weighing 1 gram with a particle size distribution of 100 percent passing 150-micron sieve and 100 percent retained on 75-micron sieve was used. The sample of sand was first filled into a plastic tube with a diameter of 10 mm (0.4 in.) resting on the substrate surface. After gently lifting the plastic tube, the sand was spread evenly under a circular motion of a flat-tipped steel rod until no noticeable rim of excess sand remained on the outer edges of the patch was observed. The steel rod used to spread the sand had a diameter of 10 mm (0.4 in.). The surface roughness was quantified as sand-spread value (percent ratio between the final diameter of the sand spread and the inside diameter of the plastic tube).

Laser profiler (LEXT OLS4000) gave visual and numerical information of the surface roughness of the substrate surface (see Figures 1c and 1d). It provided the profiling image and the value of surface roughness index Sa of a square area with a width of 640 μm (0.025 in.) on the substrate surface. Sa was the arithmetic average of the roughness profile (ISO25178). Considering the difference in the strength of mortar fraction and coarse aggregate fraction in precast concrete, the roughness index Sa was distinguished between these two fractions.

(a) Initial diameter | (b) Final diameter | (c) Laser profiler | (d) Laser profiling image

Figure 1. Sand-Spread Test and Laser Profiling

2.4.3. Bond Strength between UHPC and Precast Concrete

The slant shear specimens and third-point flexural specimens were loaded following the procedures described in ASTM C39 and ASTM C78, respectively. The pull-off specimens were loaded following ASTM C1583. Shallow cores with a depth of 50 mm (2 in.) and a diameter of 57 mm (2.25 in.) were drilled into the slab. Thus, the core specimens consisted of 25 mm (1 in.) thick UHPC on the top and 25 mm (1 in.) thick precast concrete at the bottom. A high strength epoxy was used to glue the aluminum disc on the top of core specimen to apply the tensile load. For all the test, three specimens of the same combination of precast concrete and UHPC were used.

3. Results

3.1. Bond Performance under Different Test Methods

The mechanical properties of precast concrete and UHPCs at selected ages are shown in Table 2.

Table 2. Mechanical Properties of the Precast Concrete and UHPC at Selected Ages

	Precast				UHPC 1				UHPC 2			
Age (day)	28		56		7		28		7		28	
	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV
Compressive strength (MPa)	49.1	2.0	49.2	9.1	87.5	4.9	123.5	5.8	127.7	8.6	158.2	5.5
Flexural strength (MPa)	6.4	7.4	6.6	7.2	-	-	13.9	4.3	-	-	32.1	5.3
MOE (MPa)	28961	2.5	-	-	-	-	53468	7.5	-	-	52455	2.1

Both the two UHPC mixtures exhibited a flow value of 150%. The test results of the three bond test methods are shown in Table 3.

Table 3. Ultimate Load and Failure Mode of Bond Tests at Selected Ages after Casting UHPC

Test method	Mixture ID	7-day				28-day			
		Average load (kN)	COV (%)	Max. interface stress (MPa) [a]	Failure mode [b]	Average load (kN)	COV (%)	Max. interface stress (MPa) [a]	Failure mode [b]
Slant shear	UHPC 1	148.0	8.4	16.2	Precast	254.8	5.2	28.0	Precast +UHPC
	UHPC 2	292.8	6.6	32.1	Debonding or precast	264.8	9.6	29.0	Precast
Flexural bond	UHPC 1	-	-	-	-	12.6	11.5	6.7	Precast
	UHPC 2	-	-	-	-	12.2	3.7	6.5	Precast
Pull-off	UHPC 1	3.9	5.1	1.5	Precast	4.8	2.5	1.9	Precast
	UHPC 2	4.6	6.5	1.8	Precast	5.9	12.1	2.3	Precast

Note: [a] Max. interface stress indicates the calculated average maximum stress on the interface between UHPC and precast concrete when the ultimate load is achieved, and it does not necessarily mean the failure stress on the interface; [b] "Precast" failure in precast concrete, "De-bonding or precast" de-bonding failure or failure in precast concrete, "Precast+UHPC" failure in precast or both precast concrete and UHPC

As shown in Table 3, the basic failure modes observed during the slant shear test were classified as (i) failure in precast concrete, (ii) failure at the bond and (iii) failure in both precast concrete and UHPC, based on the location of the main cracks. The failure modes are shown in Figure 2. The dashed line indicates the location of the interface between UHPC and precast concrete. The most frequent failure mode that occurred was the failure in precast concrete. In this failure mode, the main cracks occurred in the precast concrete portion, although some minor cracks at the bond between precast concrete and UHPC and propagating into UHPC portion were observed. However, the UHPC portion and precast concrete portion still had a strong bond after testing was completed. Another failure mode that occurred was de-bonding at the interface between precast concrete and UHPC. In this failure mode, minor cracks or no cracks occurred in either the precast or the UHPC portion of the specimen. The last failure mode was the failure in precast concrete or both precast concrete and UHPC. In this failure mode, the cracks initiated first in the precast concrete portion and then penetrated into the UHPC portion when the specimen failed. No cracks causing de-bonding of the UHPC and precast concrete were observed.

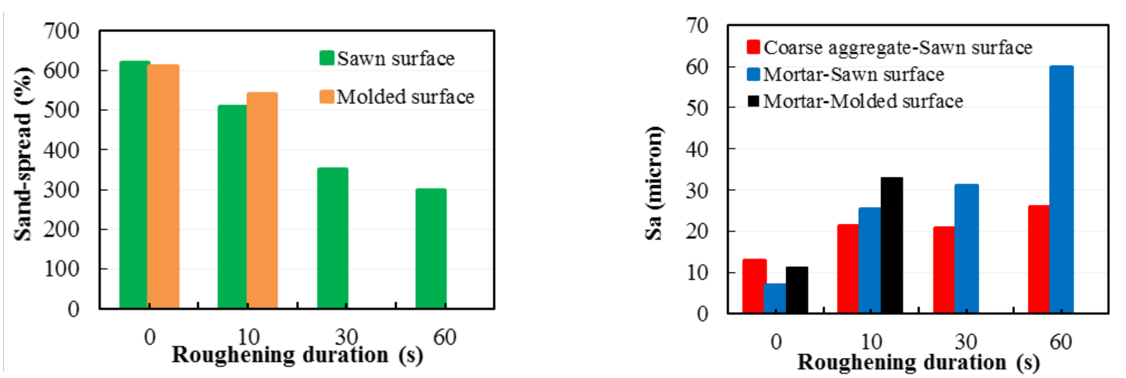
(a) Failure in precast (b) De-bonding (c) Failure in precast and UHPC

Figure 2. Failure Modes of Slant Shear Test

The only failure mode observed during the third-point flexural bond test and the pull-off test was the failure in precast concrete, which indicated that both UHPC 1 and UHPC 2 had an adequate bond with the precast concrete under flexure and direct tension.

3.2. Influence of Surface Roughness on the Bond Performance

The third-point flexural bond test was used to study the influence of surface roughness on the bond behavior between UHPC and precast concrete. Mixture UHPC 2 was used, as it exhibited 28-day compressive strength of 158.2 MPa (22939 psi) which fell into the range of compressive strength of UHPC. The test was conducted at the age of 7 days after casting UHPC, when the compressive strength and post-crack flexural strength of the UHPC were 128.5 MPa (18632 psi) and 32.0 MPa (4640 psi), respectively. The flexural strength of precast concrete was 6.7 MPa (972 psi). The influence of roughening duration on the degree of substrate surface roughness is shown in Figure 3.



(a) Sand-spread test (b) Laser profiling

Figure 3. Influence of Roughening Duration on the Substrate Surface Roughness

As shown in Figure 3, as the roughening duration increased, the sand-spread value decreased, and the roughness index Sa increased. This indicated an increase in the surface roughness due to the increase in the roughening duration. It was also noted that the mortar fraction was easier to be roughened than the coarse aggregate, as an increase in the roughening duration

from 0 s to 60 s resulted in more increase in Sa for mortar than that for the coarse aggregate (Figure 3b).
The test results of the flexural bond test are shown in Table 4.

Table 4. Influence of Surface Roughness on the Bond Performance between UHPC and Precast Concrete

Original surface	Roughening duration (s)	Failure load (kN)	Failure stress (MPa)	COV (%)	Failure mode
Sawn	0	12.2	6.2	10.4	Bond
	10	13.2	6.7	3.8	Precast
	30	13.4	6.8	7.4	Precast
	60	13.1	6.6	14.0	Precast
Molded	0	8.6	4.4	11.5	Bond
	10	13.3	6.7	6.9	Precast

As shown in Table 4, as the roughening duration increased, the sand-spread value decreased, and the roughness index Sa increased. This indicated an increase in the surface roughness due to the increase in the roughening duration. It was also noted that the mortar fraction was easier to be roughened than the coarse aggregate, as an increase in the roughening duration from 0 s to 60 s resulted in more increase in Sa for mortar than that for the coarse aggregate.

Two failure modes were observed during the test, failure in the precast concrete and failure at the bond between the precast and UHPC sections. Failure at bond only occurred when no sandblasting was applied, regardless of sawn surface or molded surface. The failure stress when de-bonding occurred was lower than the flexural strength of monolithic precast concrete. It was also noted that the bond strength obtained from using molded face of the precast concrete specimens was weaker than that obtained when sawn face precast specimens were used.

4. Discussions

In this study, slant-shear test, pull-off test and third-point flexural test were used to evaluate the bond performance between the two materials.

One of the problems with the slant-shear test is that the interface between UHPC and precast concrete is subjected to a combined influence of compressive stress and shear stress (Wall and Shrive; Momayez et al.). The complicated stress condition causes inconsistency in the test results. As observed in this study, even within the same group of specimens, different failure modes have been observed in the slant shear test. Specifically, two failure modes – de-bonding failure and failure in precast concrete - were observed between UHPC 2 and precast concrete at the age of 7 days, and two failure modes - failure in UHPC and failure in precast concrete - were observed between UHPC 1 and precast concrete at the age of 28 days. Such inconsistency in the test results gives confusing information.

The problem with the pull-off test is the difficulty of conducting the test including: the need for a large scale precast concrete slab to be cast; the effect of drilling on formation of any micro-cracking; strong bonding materials (usually ultra-strong epoxy) is needed to provide strong bond between the metal disc and the concrete specimen, and such bonding materials are costly; and all the preparation work needs to be done one day before the test as the bonding materials require certain curing time.

The third-point flexural test is new, as it has not been used for studying the bond performance between UHPC and precast concrete in previous literature. The test setup is easy. No special and costly device or materials are needed. The test results show that this method can give consistent results. As seen in Table 4, only one failure mode is observed within the same group of specimens. Also, the influence of surface roughness on the bond strength can be easily studied using the flexural bond test.

It was found in this study that 10 seconds of sandblasting (surface roughness: sand spread value at least of 510%, or Sa at least of 21.4 μm) was long enough to achieve adequate bond strength between UHPC and precast concrete, regardless of the original surface conditions (i.e. sawn or molded). It should also be noted that with increasing duration of roughening there was an increase in the COV of the ultimate stress at failure load. This trend suggested limiting the roughening to a minimal time possible, as extended duration of roughening might induce micro-cracking in the precast concrete due to the sandblasting operation.

5. Conclusions

In this study slant shear test, third-point flexural bond test and pull-off test were used in evaluating the bond behavior between UHPC and precast concrete. The influence of the roughness of the surface on the bond behavior between UHPC and precast concrete was also investigated using third-point flexural bond test. Based on the materials and test method used, the following conclusions are drawn:

- The third-point flexural bond test was an easy test to conduct and determine the bond behavior between UHPC and precast concrete. This test method yielded results that were in agreement with other test methods.
- The increase in the sandblasting duration resulted in an increase in the roughness of the surface of precast concrete, and the roughness was easily quantified by using the sand-spread test and laser profiling. The mortar fraction was easier to be roughened than the coarse aggregate fraction of the substrate precast concrete.
- All the flexural bond specimens with the surface roughened by sandblasting failed in the precast concrete part at the age of 7 days after casting UHPC. This indicated that sandblasting was effective to achieve adequate bond behavior between UHPC and precast concrete. In this study, it was observed that even with 10 s of roughening resulted in resulted in adequate roughness (i.e. sand spread value at least of 510%, or Sa at least of 21.4 μm). Flexural bond specimens with no surface roughening failed at the bond. The bond strength based on un-roughened molded face of precast concrete was weaker than that based on un-roughened sawn face of precast concrete.

6. References

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Graybeal, Benjamin A. *Material Property Characterization of Ultra-High Performance Concrete*: FHWA, U.S. Department of Transportation, 2006.

ISO25178, CD. "6. Geometrical Product Specification (Gps)-Surface Texture: Areal-Part 6: Classification of Methods for Measuring Surface Texture." *International Organization for Standardization,* 2007.

Li, Zhengqi, et al. *Development of Ultra-High Performance Concrete for Shear-Keys in Precast Bridges Using Locally Available Materials in South Carolina*. 2014 60th Anniversary Convention and National Bridge Conference. Precast/Prestressed Concrete Institute, 2014.

Li, Zhengqi, and Prasada Rao Rangaraju. "Effect of Sand Content on the Properties of Self-Consolidating High Performance Cementitious Mortar." *Transportation Research Record: Journal of the Transportation Research Board Vol.* 2508, 2015, pp.10.

Momayez, A., et al. "Comparison of Methods for Evaluating Bond Strength between Concrete Substrate and Repair Materials." *Cement and Concrete Research Vol.*35, No.4, 2005,pp. 748-57.

Munoz, M. A. C., et al. "Bond Performance between Ultrahigh-Performance Concrete and Normal-Strength Concrete." *Journal of Materials in Civil Engineering Vol.*26, No.8, 2014, pp.04014031.

Rangaraju, Prasad R., et al. *Development of High-Strength/High Performance Concrete/Grout Mixtures for Application in Shear Keys in Precast Bridges*: FHWA, U.S. Department of Transportation, 2013.

Russell, Henry G., and Benjamin A. Graybeal. *Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community*,2013.

Tayeh, B. A., et al. "Evaluation of Bond Strength between Normal Concrete Substrate and Ultra High Performance Fiber Concrete as a Repair Material." *2nd International Conference on Rehabilitation and Maintenance in Civil Engineering (Icrmce) Vol.*54, 2013, pp.554-63.

Wall, J. S., and N. G. Shrive. "Factors Affecting Bond between New and Old Concrete." *Aci Materials Journal Vol.*85, No.2, 1988, pp.117-25.

Wille, K., A. E. Naaman, and G. J. Parra-Montesinos. "Ultra-High Performance Concrete with Compressive Strength Exceeding 150 Mpa (22 Ksi): A Simpler Way." *Aci Materials Journal Vol.*108, No.1, 2011, pp.46-54.