Effects of Substrate Texture and Moisture Conditions on Ultra-High Performance Concrete and Silica Fume Concrete Overlay Bond Strengths

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Abstract. Direct tension tests were conducted to investigate the effects of substrate moisture conditions and texture on ultra-high performance concrete (UHPC) overlay bond strengths. Improper substrate surface preparation can result in inadequate bond strengths and, in severe cases, lack of bond. To demonstrate the importance of surface preparation, pull-off tests were performed on overlaid slabs that had two extreme substrate surface moisture conditions (saturated and dried) prior to overlay application. Saturated slabs had a tined, tined-light sand blasted, or tined-medium sand blasted substrate surface texture. Dried slabs had either a tined or an exposed aggregate surface texture. Saturated specimens with tined, tined-light sand blasted, and tined-medium sand blasted surface textures achieved average bond strengths of 0.924, 1.45, and 1.95 MPa, respectively. Dried substrate surfaced specimens had zero bond strength. Surface moisture conditions that ranged from saturated to dry were also investigated by allowing the substrate surfaces to dry for 15, 30, 45, and 60 minutes prior to application of an UHPC overlay. Tined-light sand blasted specimens with surfaces that dried for 15, 30, 45, and 60 minutes achieved average bond strengths of 2.86, 2.01, 1.59, and 0.165 MPa, respectively. Results showed tined-light sand blasted specimens with proper saturating achieved adequate bond strengths, and properly saturated, tined-medium sand blasted specimens produced excellent bond strengths. Results also exposed the drastic consequences of not maintaining a saturated substrate surface prior to overlay application and delaying overlay application up to 60 minutes can drastically reduce bond strength.

1. Introduction
Overlaying existing concrete bridge decks is a common rehabilitation technique to repair deteriorating concrete bridge decks. Concrete overlays can extend the service life of the bridge and be a cost-effective alternative to full deck reconstruction. Concrete bridge decks are critical bridge components because they protect underlying structural elements from environmental and mechanical factors that can cause distress, such as curling, delamination, cracking, and spalling [1].

The effectiveness of an overlay depends greatly on the bond between the overlay and substrate material. Improper substrate surface preparation can contribute to lack of bond between the substrate concrete and the repair concrete. Therefore, effort should be made to provide sufficient surface preparation of the substrate concrete to ensure bond between the overlay and substrate material is achieved. Proper surface preparation includes adequate surface texturing to facilitate bond by removing
surface paste and exposing aggregates. Providing proper surface preparation also includes saturation of the substrate surface for portland cement-based overlay materials.

To investigate the importance of surface texture and moisture condition of the substrate on overlay bond strength, pull-off tests were performed on overlaid laboratory slabs. Surface texture was assessed using three surface textures: tined, tined-light sand blasted, and tined-medium sand blasted. Saturated and dried substrate surface conditions prior to application of an UHPC overlay were used to investigate the effects of the extreme substrate moisture conditions on bond strength. This research also investigated substrate surface moisture conditions that ranged between saturated to dry by allowing the substrate surfaces to dry for a predetermined amount of time (15, 30, 45, and 60 minutes) prior to application of an ultra-high performance concrete (UHPC) overlay. Results from this study can be used to provide specific guidance for contractors for best practices.

2. Background

2.1. UHPC research at NMSU
Recent research has demonstrated that UHPC may have the ability to increase service lives of bridge decks and reduce maintenance costs when used as an overlay [2-6]. A 2017-2018 research project at New Mexico State University (NMSU), funded by the Transportation Consortium of South-Central States (Tran-SET), demonstrated that UHPC produced with local materials was able to achieve adequate bond strength when proper surface preparation of the substrate was provided [2]. Consequently, the New Mexico Department of Transportation implemented the UHPC overlay technology by specifying UHPC as the overlay material for a bridge in Socorro, NM, USA.

2.2. Mock placement experiences
This research is associated with the field implementation of a silica fume concrete (SFC) overlay to a concrete bridge deck in Socorro, NM, USA. The SFC had a 28-day compressive strength of 63.9 MPa and had the mixture proportions presented in Table 1. To prepare contractors for construction of the overlay, a mock placement was conducted. During the mock placement a SFC overlay was applied. After the overlay cured for 56 days, direct tension pull-off tests were conducted to assess the integrity of the bond. Figure 1 is an illustration that shows the general locations of the direct tension pull-off tests.

### Table 1. Overlay mixture proportions.

| Material | Cement | Silica Fume | Fly Ash | Sand | HRWRA (L/m³) | Water | Steel Fibers |
|----------|--------|-------------|---------|------|---------------|-------|--------------|
| kg/m³    | 740    | 116         | 69.4    | 950  | 42            | 145   | 136          |

The SFC was mixed in batches and was placed on the slab in sections beginning at the west end of the slab which is the top of the slab illustration in Figure 1. Subsequent batches were placed where the previous overlaid section stopped and the placement continued eastward (downward in Figure 1). The lower portion of the figure identifies where the overlaid section stopped by labelling the location that was not overlaid as “No Overlay”. Locations of the direct tension pull-off tests are identified by the circles shown in Figure 1. Pull-off tests in the areas depicted as “Zero Strength Locations” were identified as unbonded because the overlay broke from the substrate during core drilling and pull-off tests could not be conducted. However, locations 1 through 6, which were located in the portion of the overlay that was placed first while the substrate surface was still wet. These core locations were successfully cored and pull-off tests were conducted that produced the bond strengths presented in Table 2. Although a majority of the strengths were zero, six spots located along the edge of the slab that was...
overlaid first produced cores that appeared to be reasonably well bonded. However, on average the bond strengths are not acceptable (less than 1.7 MPa) according to ACI 546 [7].

![Figure 1. Direct tension pull-off locations on the mock placement slab.](image)

| Location | Strength, MPa |
|----------|--------------|
| 1        | 0.7          |
| 2        | 3.2          |
| 3        | 1.4          |
| 4        | 1.8          |
| 5        | 1.8          |
| 6        | 0.7          |

The mock placement slab was saturated overnight and saturation was maintained until application of the SFC overlay. However, the substrate surface was allowed to dry after the first batch of overlay material was applied. This resulted in the marginal bond strengths for locations 1-6 (Table 2) and the zero strengths for the remainder of the overlaid slab. The lack of bond was attributed to improper surface preparation of the substrate concrete. The inadequate surface preparation in this region included drying of the substrate surface prior to overlay application and a surface texture that did not remove surface paste to expose the aggregate, which is considered essential for bonding the overlay to the substrate concrete. To address the poor pull-off test results for the mock placement overlay, a series of laboratory tests were conducted to demonstrate the importance of surface preparation, including substrate surface texture and the moisture condition of the substrate surface prior to application of the overlay.

3. Methodology
To investigate the effects of surface preparation, two extreme substrate surface moisture conditions were investigated in combination with four substrate surface textures produced on slab specimens. The extreme moisture conditions were saturated or dried prior to application of an UHPC overlay. The textures used for the saturated specimens included a tined texture, a tined-light sand blasted texture, and
a tined-medium sand blasted texture. The textures used for the dried specimens included a tined texture and an exposed aggregate texture. This study also investigated the effects of varying the substrate moisture condition by allowing the substrate surface to dry for a specified amount of time before application of the overlay material. The following subsections cover the production of the slab specimens, characteristics of the overlay material, characteristics of the substrate material, substrate surface preparation, overlay application, preparation for direct tension testing, and direct tension testing.

3.1. Production of slab specimens
The substrate concrete had a depth of 114 mm and was cast in 152x152x610 mm steel moulds. After casting, the substrate specimens were moist cured (23°C and 98% relative humidity) for six days and then sand blasted to a light or medium sand blasted substrate surface texture. Following the texturing process, the specimens were returned to the moist room before applying the overlay at a substrate age of seven days. Figure 2 illustrates the geometry of the specimens after application of the 38-mm thick overlay. After the overlays were applied, the composite specimens were cured at ambient conditions (20°C and 30% relative humidity) for 24 hours and then moist cured (23°C and 98% relative humidity) to an overlay age of seven days.

3.2. UHPC overlay material.
Two UHPC mixtures were used in this research. The UHPC used as the overlay material for the extreme surface moisture conditions was developed to accommodate the use of a high strength steel fibre produced by Concrete Fiber Solutions (CFS) that were 13 mm long with a length/diameter aspect ratio of 22. This mixture used 62.5% silica fume and 37.5% class F fly ash as the supplementary cementitious materials to replace 20% of the portland cement.

The UHPC used for the varied surface moisture condition was developed using high strength fibres produced outside of the U.S. and that were 13 mm long. This mixture used 50% silica fume and 50% fly ash as the supplementary cementitious materials replacing 20% of the cement.

3.2.1. Mixture proportions. Both UHPC overlay materials consisted of Type I/II portland cement, silica fume, fly ash, high-range water reducing admixture (HRWRA), and water. The UHPC used for the extreme moisture conditions had 1.75% by volume of 13 mm long, high strength steel fibres and the UHPC used for the varied moisture conditions had 1.5% by volume of high strength steel fibres. The sand, cement, and fly ash were obtained from local sources while the silica fume and HRWRA were acquired from regional suppliers. The proportions for the UHPC mixtures used in this research are presented in Table 3.
Table 3. UHPC mixture proportions.

|                      | Cement, kg/m³ | Silica Fume, kg/m³ | Fly Ash, kg/m³ | Sand, kg/m³ | HRWRA, L/m³ | Water, kg/m³ | Steel Fibers, kg/m³ |
|----------------------|---------------|--------------------|----------------|-------------|-------------|--------------|--------------------|
| UHPC (Extreme moisture condition) | 740           | 116                | 69             | 950         | 42          | 145          | 136                |
| UHPC (Varied moisture condition)   | 817           | 102                | 102            | 1010        | 45          | 153          | 119                |

3.2.2. Compressive strength. Table 4 presents the average compressive strengths obtained from 100 mm cube specimens cured at ambient conditions (20°C and 30% relative humidity) for both UHPC mixtures. ASTM C1856 requires that UHPC attain a 28-day strength of at least 117 MPa [8]. Both of the UHPC mixtures used in this research met that requirement.

Table 4. Average 1, 3, 7 and 28-day compressive strengths for non-proprietary UHPC.

|                      | 1-day Strength, MPa | 3-day Strength, MPa | 7-day Strength, MPa | 28-day Strength, MPa |
|----------------------|---------------------|---------------------|---------------------|----------------------|
| UHPC (Extreme moisture condition) | 68.7                | 87.8                | 102.8               | 119.1               |
| UHPC (Varied moisture condition)   | 24.7                | 76.3                | 101.1               | 118.8               |

3.3. NSC substrate material.
The NSC mixture used as the substrate material in the laboratory investigation consisted of Type I/II portland cement, fine and coarse aggregates, water, and air-entraining admixture as shown in Table 5. The NSC mixture had a 0.4 w/c ratio and an average 28-day compressive strength of 45.5 MPa.

Table 5. NSC substrate mixture proportions.

|                      | Coarse Aggregate, kg/m³ | Fine Aggregate, kg/m³ | Cement, kg/m³ | Water, kg/m³ | Air Entraining Admixture, L/m³ |
|----------------------|--------------------------|-----------------------|---------------|--------------|-------------------------------|
| NSC                  | 915                      | 660                   | 446           | 322          | 1.47                          |

3.4. Surface preparation
Maintaining saturated conditions for 24 hours prior to overlay application, is considered to be a “best practice” when using a highly cementitious material such as UHPC as the overlay material. Saturating the substrate surface prevents the substrate concrete from taking the water from the repair concrete. The following subsections provide details regarding the surface textures and moisture conditions of the substrate material.

3.4.1. Surface texture. Photographs showing the saturated surface textures are presented in Figure 3. The tined texture (Figure 3a) was produced in the fresh state thirty minutes after placing the substrate concrete to mimic the texture observed on the mock placement slab. Sand blasting was performed when the substrate concrete was at an age of six days. The tine-light sand blasted texture (Figure 3b) removed the surface paste material and exposed fine aggregate. The tined-medium sand blasted texture, defined by ACI 303 [9], was achieved by sand blasting until the coarse aggregate was slightly exposed as shown in Figure 3c. For the textures presented in Figure 3, the saturated surface condition was produced by
removing the slab specimens from the moist room at a substrate age of seven days, removing debris from the surfaces using a wire brush, rinsing away any fines left from wire brushing, and keeping the substrate surfaces saturated until application of the UHPC overlay.

![Figure 3](image)

**Figure 3.** Slab specimen textures: a) tined, b) tined-light sand blasted, and c) tined-medium sand blasted.

The dried surface condition was produced by removing the slab specimens from the moist room at an age of seven days, removing any debris from the surfaces using a wire brush, rinsing away any fines left from wire brushing, and then allowing the specimens to dry in ambient lab conditions (20°C and 30% relative humidity) for two hours. **Figure 4** presents photographs of the dried surfaces with tined and exposed aggregate textures.

![Figure 4](image)

**Figure 4.** a) Dried tined and b) dried exposed aggregate texture.

### 3.4.2. Moisture condition

Two extreme moisture conditions (dried and saturated) were evaluated for bond strength of a UHPC overlay. The saturated condition was achieved by maintaining a saturated surface condition until application of the UHPC overlay. The dried surface condition was achieved by allowing the substrate to dry for two hours prior to overlay application. This study also investigated a range of surface moisture conditions of the substrate prior to UHPC overlay application. The range of moisture conditions was achieved by saturating the substrate surface then allowing the surface to dry for 15, 30, 45, or 60 minutes before application of the UHPC overlay. The texture used for the varied
surface moisture condition specimens was the tined-light sand blasted texture. Figure 5 presents photographs of the various substrate surface moisture conditions.

![Figure 5](image_url)

**Figure 5.** Varied degrees of saturation based on surface drying time: a) 15 minutes, b) 30 minutes, c) 45 minutes, and d) 60 minutes.

3.5. Direct tension test (pull-off test) procedure

The overlaid slab specimens were cured for six days in a moist room (23°C and 98% relative humidity). Then, the specimens were removed from the curing chamber, core drilled, and returned to the curing chamber. The following day, the specimens were removed from the curing chamber, dried, and steel platen load heads were epoxied to the tops of the cores as shown in Figure 6a. The epoxy (ChemCo Systems Bonder Paste LWL) was allowed to cure for 24 hours prior to pull-off testing. A photograph of the pull-off tester (HYDRAJAWS M2050 Tester) and pull-off test setup is presented in Figure 6b. The direct tension (pull-off) tests were conducted in accordance with ASTM C1583 [10]. During pull-off testing, two failure types were observed (failure of the bond and failure in the substrate). Failures that occurred in the substrate were most likely caused by lack of maturity in the substrate. Results from tests with substrate failures provided conservative values for overlay bond strengths since the bonded interface remained intact.

![Figure 6](image_url)

**Figure 6.** Pull-off testing setup: a) epoxied steel platen load head and b) Direct tension tester.
4. Results and discussions

4.1. Dried and saturated substrate surface moisture conditions

Table 6 presents the results from the direct tension tests performed on the specimens with dried and saturated substrate moisture conditions prior to UHPC overlay placement. Each entry in Table 6 presents the average and standard deviation obtained from 12 tests. Although the overlay on the dry substrate specimen appeared bonded, the bond was not sustained through core sawing. Consequently, the slab specimens that had a dry substrate surface prior to overlay application did not have any bond strength after core sawing. Saturated specimens with a tined texture did not achieve the recommended tensile bond strength of 1.0 MPa recommended by the American Concrete Institute (ACI 546 [7]) at seven days. However, specimens with a saturated and tined-light sand blasted surface texture produced adequate bond strengths (greater than 1.0 MPa) at seven days. Specimens with saturated and tined-medium sand blasted surface texture achieved excellent bond strengths (greater than 1.7 MPa at seven days) emphasizing the importance of surface preparation.

Table 6. Average direct tension pull-off strength and standard deviation for the dried and saturated substrate surface moisture conditions.

| Texture                             | Dried | Saturated, MPa |
|-------------------------------------|-------|----------------|
| Tined                               | 0 ± 0 | 0.924 ± 0.533  |
| Tined and light sand blasted        | -     | 1.45 ± 0.60    |
| Tined and medium sand blasted       | -     | 1.95 ± 0.68    |
| Exposed Aggregate                   | 0 ± 0 | -              |

4.2. Varied substrate surface moisture conditions

Table 7 presents the average 7-day direct tension (pull-off) strengths for tined-light sand blasted specimens with varied substrate surface moisture conditions produced by allowing the substrate surface to dry for various durations prior to application of an UHPC overlay. Each entry in Table 7 presents the average and standard deviation obtained from seven tests. Specimens that were allowed to dry up to 45 minutes before application of the overlay were able to achieve the recommended 1.0 MPa recommended by ACI [7] at seven days. However, specimens that were allowed to dry for one hour did not achieve the ACI [7] recommended tensile bond strength. The specimens that were allowed to dry 45 minutes or less had visibly moist surfaces (as shown in Figure 5a-5c) that facilitated the development of excellent bond strengths that exceeded the ACI [7] requirement of 1.0 MPa at seven days.

Table 7. Average direct tension pull-off strength and standard deviation for the range of surface moisture conditions.

| Dry Time, Minutes | Texture                        | Tensile Strength, MPa |
|-------------------|--------------------------------|-----------------------|
| 15                | Tined-light sand blasted       | 2.86 ± 0.63           |
| 30                | Tined-light sand blasted       | 2.01 ± 0.68           |
| 45                | Tined-light sand blasted       | 1.59 ± 0.56           |
| 60                | Tined-light sand blasted       | 0.165 ± 0.20          |

4.3. Summary of results and discussions

This study can be used to provide guidance to contractors and inspectors in regards to effective substrate surface preparation. The results of this study exposed the drastic consequences of not maintaining a saturated substrate surface prior to overlay application. Specifically, the lack of bond strength for specimens that were allowed to dry for 60 or more minutes is shown in Figure 7. The severity of the
loss of bond strength was exemplified by the inability of the dry exposed aggregate specimen (Figure 4b) to achieve bond. The results also revealed the importance of providing an exposed aggregate surface texture to achieve bond between the overlay and substrate. Although the tined-medium sand blasted specimens achieved excellent bond strengths, adequate bond strengths can be achieved by providing a light sand blasted texture that only exposes fine aggregate. Assessment of the range of surface moisture conditions further emphasized the importance of surface moisture prior to overlay application. Therefore, at a minimum, contractors must maintain a saturated substrate surface condition and provide an exposed fine aggregate texture to achieve adequate bond between the overlay and substrate concrete.

![Figure 7. Average direct tensile strength versus the substrate moisture condition.](image)

5. Conclusions
The conclusions drawn from this investigation are:

1. UHPC overlays applied to either tined or sand blasted textures did not develop bond when the substrate surface was allowed to dry prior to overlay placement.
2. Saturation of the substrate surface prior to overlay application is essential to achieve bond between the overlay and the substrate concrete.
3. Bond strengths that were slightly inadequate were observed when no effort was made to remove the surface paste of the tined texture.
4. Adequate bond strengths were achieved with light sand blasting of a tined texture when sufficient surface moisture was provided.
5. Excellent bond strengths were achieved with light and medium sand blasting of a tined texture when the substrate surface was properly saturated prior to overlay application.
6. Results from this study can be used to provide specific guidance for contractors and inspectors along with quantifiable repercussions that should be expected if best practices are not followed.

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References
[1] D.P. Bentz, I. De la Varga, J.F. Muñoz, R.P. Spragg, B.A. Graybeal, D.S. Hussey, D.L. Jacobson, S.Z: Jones, and J.M. LaManna, "Influence of Substrate Moisture State and Roughness on Interface Microstructure and Bond Strength: Slant Shear vs. Pull-off Testing," ELSEVIER,
Cement and Concrete Composites, 63-72, 2018.

[2] C.M. Newton, B.D. Weldon, A.J. Al-Basha, M.P. Manning, W.K. Toledo, and L.D. Davila, "Bridge Deck Overlays Using Ultra-High-Performance Concrete," Tran-SET final research report 17CNMS01. Transportation Consortium of South-Central States (Tran-SET), 2018.

[3] Z.B. Haber, B.A. Graybeal, and J.F. Munoz, "Field Testing of an Ultra-High Performance Concrete Overlay," FHWA-HRT-17-096, Federal Highway Administration, 2017.

[4] B.A. Graybeal, "Material Property Characterization of Ultra-High Performance Concrete," Federal Highway Administration, Report FHWA-HRT-06-103, McLean, VA, 2007.

[5] B.A. Graybeal, and M. Davis, "Cylinder or cube: strength testing of 80–200 MPa (11.6–29 ksi) ultra-high performance fiber-reinforced concrete," ACI Materials Journal, 105(6), 603–609, 2008.

[6] B.A. Graybeal, and J. Hartmann, "Strength and Durability Of Ultra-High Performance Concrete," Concrete Bridge Conference, 2003.

[7] ACI 546 (2004). "ACI Committee 546R-04: Guide to Materials Selection for Concrete Repair," American Concrete Institute ACI546R-04, 2004.

[8] ASTM C1856 (2017), "Fabricating and Testing of Ultra-High Performance Concrete," Annual Book of ASTM Standards, ASTM International, Conshohocken, PA, 2017.

[9] ACI 303 (2012). "ACI Committee 303R-12: Guide to Cast-In-Place Architectural Concrete," American Concrete Institute ACI303R-12, 2012.

[10] ASTM C1583 (2020). "ASTM C1583: Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-Off Method)," Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, 2020.