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To cite this article: Ahmed J. Al-Basha *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 032007

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Ultra-High Performance Concrete Overlays for Concrete Bridge Decks

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Abstract. With much of the world's infrastructure needing rehabilitation, new and more effective methods of repair are required to ensure that concrete structures can continue to perform adequately. This work investigates the potential for using locally produced ultra-high performance concrete (UHPC) as an overlay material to rehabilitate existing normal strength concrete (NSC) bridge decks. Bond strength tests were conducted using NSC substrate with four different textures seven days after casting the UHPC overlay. Depths of the different textures determined in accordance with ASTM E965 were 0.05, 0.90, 1.6, and 2.8 mm. Results from slant shear, split cylinder, and split prism tests indicate good bond even when inadequate texturing was provided. Average shear strengths from slant shear (ASTM C882) specimens increased from 7.1 MPa for the 0.05 mm texture to 19.8 MPa for the 2.8 mm texture. Similarly, bond strengths from split cylinders (ASTM C496) increased from 1.8 MPa for the 0.05 mm texture to 2.4 MPa for the 2.8 mm texture. Bond strength testing of split prisms specimens was conducted using a modified version of ASTM C496 and produced results of 1.5 MPa for the 0.05 mm texture and 3.7 MPa for the rough texture. Direct tensile strength testing was performed in accordance with ASTM C1583 and produced a bond strength of 1.08 MPa for chipped texture with a depth of 1.00 mm. Testing of chloride permeability (ASTM C1202) of the UHPC indicated negligible charge passing through the specimens. Free shrinkage measurements initiated 90 minutes after placement resulted in a total shrinkage of 1800 micro-strain in the UHPC after seven days. Results from these tests indicate the potential of locally produced UHPC to serve as an alternative to traditional overlay materials.

1. Introduction

A major issue facing the world's infrastructure is rapidly degrading concrete bridge decks. Concrete bridge decks can be exposed to a wide range of environmental and mechanical distress and are critical elements since they not only provide a comfortable riding surface but also protect structural elements beneath them. According to 2016 United States National Bridge Inventory data, 23.9% of US bridges have concrete bridge decks in "Satisfactory" condition and only 10 out of 43 transportation agencies anticipate that their bridge deck overlays have service lives greater than 25 years [1].

Bridge deck maintenance is expensive because of harsh exposure that shortens anticipated service life. The high cost of maintenance has lead agencies to consider more durable materials for use as bridge deck overlays. This study focuses on assessing the possibility of using ultra-high performance concrete (UHPC) produced with local materials to overlay existing concrete bridge decks. UHPC's exceptional mechanical and durability properties [1-4] provide the potential to greatly improve the service life of existing bridge decks and their durability.

The work presented in this paper investigated the potential for using locally produced UHPC as an overlay material to rehabilitate concrete bridge decks in New Mexico, USA. Previous research at New



Mexico State University [5, 6] has shown that locally produced, non-proprietary UHPC has exceptional mechanical and durability properties. The use of locally available materials also makes it more economical and sustainable compared to proprietary UHPC products [7].

2. Background

2.1. Ultra-high performance concrete

UHPC is a modern type of concrete exhibiting exceptional mechanical and durability properties. These properties include compressive strength greater than 120 MPa [8], high ductility when fibre reinforced, and excellent resistance to frost damage, alkali-silica-reaction, and abrasion [2, 5, 9]. UHPC's properties are achieved through careful selection of its constituent materials to ensure optimized gradation and maximized packing density as well as detailed preparation methods to properly mix and cure UHPC elements [6].

2.2. Overlays

Concrete bridge decks play a crucial role in providing a comfortable riding surface and protecting structural elements beneath the deck from various environmental and physical attacks. However, exposure to environmental and mechanical distress can lead to rapid deterioration of bridge decks that requires frequent rehabilitation or, in extreme cases, replacement. Bridge deck overlays are commonly used to extend the life of concrete bridge decks. Common overlay materials include high-performance concrete (HPC), low slump concrete (LSC), latex-modified concrete (LMC), and polymer-based concrete (PBC). However, each of these alternatives has drawbacks such as cost, service life expectancy, or availability. Figure 1 shows a cost comparison in US dollars of the overlay alternatives mentioned, proprietary UHPC, and non-proprietary UHPC overlays assuming a 25 mm thickness. It should be noted that cost of local UHPC in figure 1 includes only materials cost (construction cost is not included) [1].

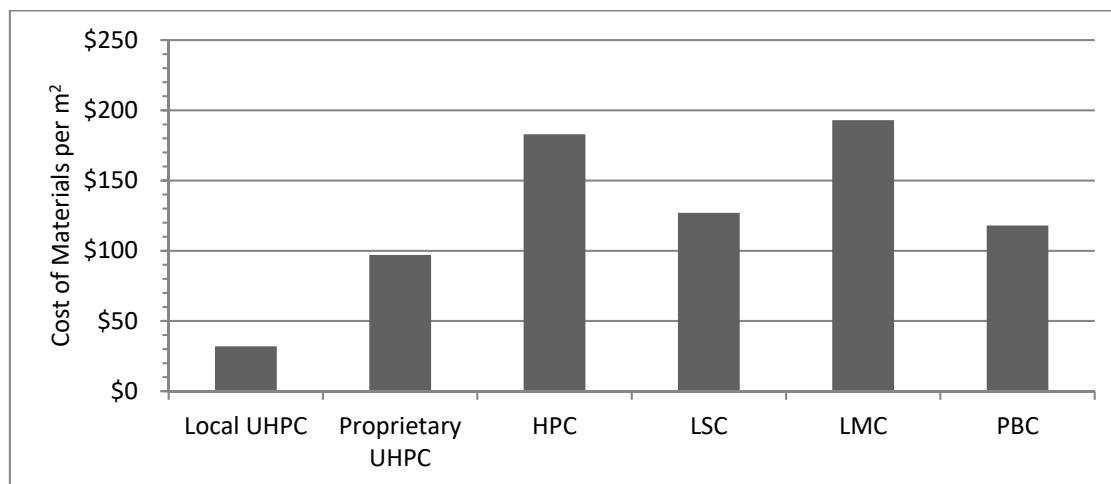


Figure 1. Material cost per m² of different overlaying material alternatives (values taken from [1])

3. Methodology

3.1. UHPC and NSC Mixture Designs

The UHPC mixture consisted of Type I/II portland cement, silica fume, fly ash, high-range water reducing admixture (HRWRA), water, and 1.5% by volume of 13 mm steel fibres. The sand, cement, and fly ash were obtained from local sources while the silica fume, steel fibres, and HRWRA were acquired from regional suppliers. 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. Tables 1 and 2 present the mixture proportions for concrete mixtures.

Table 1. Mixture proportions for UHPC

Material	Cement	Silica Fume	Fly Ash	Sand	HRWRA (L/m ³)	Water	Steel Fibres
kg/m ³	817	102	102	1010	45	153	119

Table 2. Mixture proportions for NSC

Material	Cement	Fine Aggregate	Coarse Aggregate	Water	Air-Entraining Admixture (mL)
kg/m ³	449	573	969	202	1120

3.2. Bond strength testing

Three different bond strength tests were used to characterize the bond between substrate and overlay material. These tests included slant shear, splitting tension, and direct tension tests. Each of these tests was conducted on NSC-UHPC composites with substrate textures that included a lightly ground texture with an average depth of 0.05 mm, two grooved textures with average depths of 0.9 mm and 1.6 mm, and a rough texture with an average depth of 2.8 mm. Average depth was determined in accordance with [10]. Figure 2 illustrates the different textures.

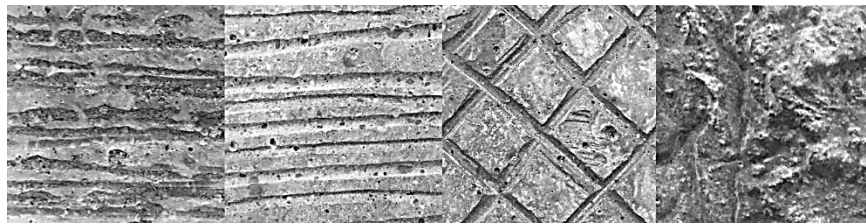


Figure 2. Lightly ground 0.05 mm (far left), grooved texture 0.90 mm (left), grooved-cross-hatch texture 1.60 mm (right), rough texture 2.80 mm (far right)

3.2.1. Slant-Shear Testing. The slant-shear strength of composite NSC-UHPC specimens was determined in accordance with [11]. An oblique NSC cylindrical substrate was cast at a 60° incline and allowed to cure in a wet-room (22°C) for seven days prior to texturing and application of UHPC overlay material. After demoulding, specimens were cured at ambient lab temperatures (20°C, 30% relative humidity) for seven days prior to testing. Specimens were then tested in compression to determine the bond strength. Figure 3 shows an illustration of the test setup.

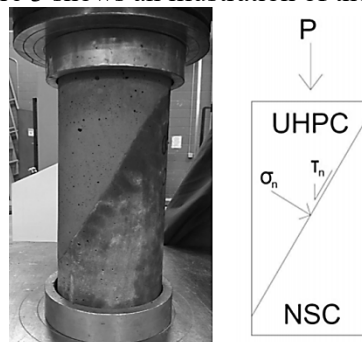


Figure 3. Slant-shear strength testing setup

3.2.2. Splitting Tension Testing (cylinders and prisms). Splitting tensile strength was determined in accordance with [12]. A modified version of the test was adopted from [13] to test prismatic specimens. Substrates were cured and textured similarly to the slant-shear specimens. Figure 4 shows the setup for splitting tension testing.

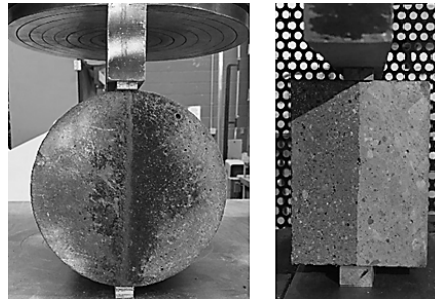


Figure 4. Splitting tensile cylinder (left) and prism (right) test setup

3.2.3. Direct Tension Testing. The tensile strength of the composite specimens' bond was determined using a modified version of [14]. The standard specifies using a pull-off device to determine the tensile strength from cored slabs. However, this study tested 51 mm cylindrical cores taken from prismatic specimens. Figure 5 illustrates the specimens and test setup which includes pivot points at both ends of the specimen to ensure that the axial force was applied concentrically to the specimen.

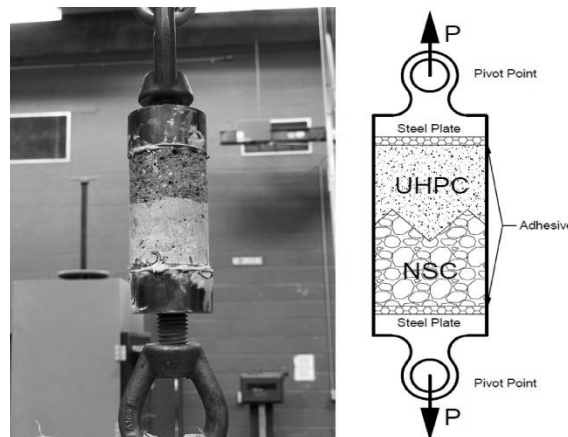


Figure 5. Direct tension test setup

3.3. Early-age and longer term shrinkage

Early-age and longer term shrinkage of the UHPC overlay material was studied since shrinkage can induce shear stresses on the bonded interface between an overlay and the substrate. Figure 6 illustrates the test setups for short and long term shrinkage testing.

Early-age shrinkage of UHPC was monitored for seven days. A 152x152x610 mm beam was cast into a mould lined with two layers of plastic separated by talc powder to allow shrinkage to occur without restraint. Within 90 minutes of casting, two hangers were embedded into the UHPC as shown in figure 6 and Linear Variable Displacement Transducers (LVDTs) were used to measure the displacement due to shrinkage at 15 second intervals. Longer term shrinkage testing was performed on 76x102x406 mm prisms with gauge studs embedded at the ends. Length measurements were recorded 24 hours after casting using a length comparator as shown in figure 6. Specimens were wet-cured for seven days prior to ambient curing in the laboratory until 28 days of age. Measurements were recorded daily.

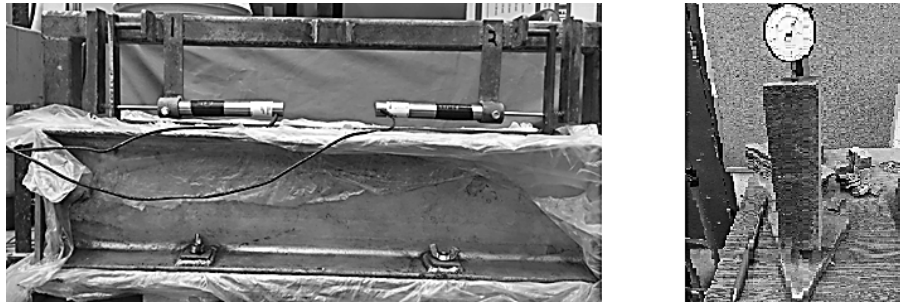


Figure 6. Short term (left) and long term (right) shrinkage testing setup

3.4. Chloride permeability testing

The chloride permeability of UHPC was determined in accordance with [15]. 51 mm slices were cut from 102x203 mm cylinders then vacuumed for three hours in a desiccator before being submerged in deionized water for 18 hours. UHPC slices were then placed in the testing cell shown in figure 7. A power supply unit maintained a 60V DC voltage across the cell with the negative lead attached to the NaCl reservoir and the positive lead attached to the NaOH reservoir. A multi-meter was used to measure the current passing through the specimen at 30 minute intervals over a six-hour period.

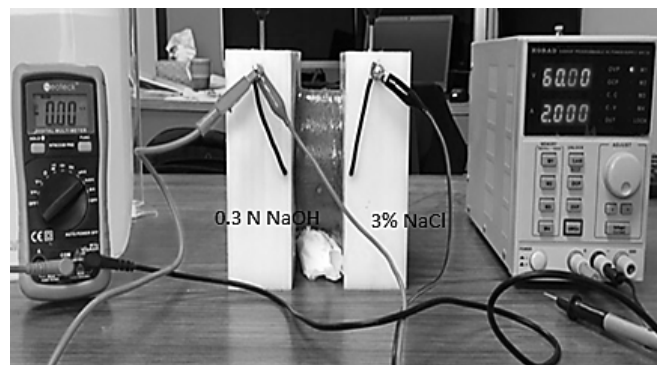


Figure 7. Rapid chloride permeability testing setup

3.5. Coefficient of thermal expansion testing

The coefficient of thermal expansion of UHPC was determined using the process described in [16].

4. Results and Discussion

4.1. Slant-shear strength

Table 3 presents the average bond strengths for the different slant-shear specimens. The data show that regardless of the texture depth, shear strengths of the bonded interface were greater than the required strength of 7 MPa [17].

Table 3. Average shear stresses, normal stresses, and standard deviations from slant-shear tests

Texture (average texture depth)	Shear Stress (MPa)	Normal Stress (MPa)	Stdv. of Shear Stress (MPa)
Lightly Ground (0.05 mm)	7.1	8.2	1.8
Horizontal Grooves (0.9 mm)	12.0	13.9	1.7
Cross-Hatch Grooves (1.6 mm)	12.0	13.8	1.0
Diagonal Grooves @ 45° incline (1.6 mm)	11.4	13.2	0.7
Vertical Grooves (1.6 mm)	9.8	11.3	0.9
Rough (2.8 mm)	19.8	22.9	2.8

However, greater bond strengths were achieved from textures that provided greater interlocking such as the rough texture, horizontal grooves, and diagonal/cross-hatch grooves. Figure 8 shows the shear strength results with error bars.

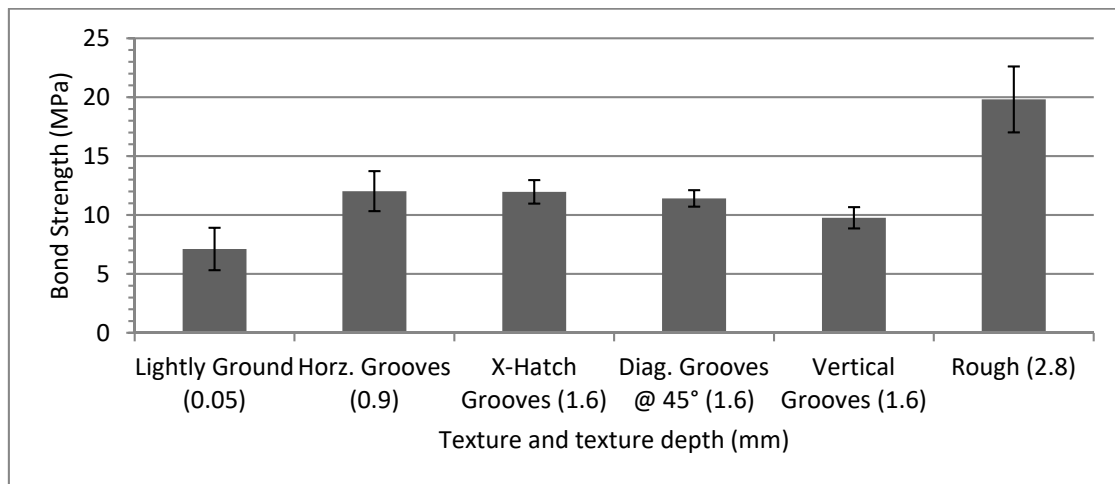


Figure 8. Shear strengths from slant-shear specimens with different textures

4.2. Splitting tensile strength (cylinders and prisms)

Splitting tension testing was used to determine the bond strength of composite NSC-UHPC cylindrical and prismatic specimens under indirect tensile loading. The prismatic specimens were 76x102x102 mm. These dimensions were selected so that the results could be compared to results from similar testing by [13].

Figure 9 and table 4 show that the bond strength of composite, cylindrical specimens did not correlate well with texture depth. However, the bond strength of prismatic specimens appeared to be strongly influenced by texture. The data show that there was a wide disparity between splitting tensile strengths from 1.5 MPa to 3.7 MPa. This can be attributed to the greater surface area available for bonding provided by the more textured surfaces. It is also important to note that all of the bond strengths from cylindrical and prismatic specimens were greater than the required minimum strength for direct tension testing (1 MPa) [17] regardless of texture depth.

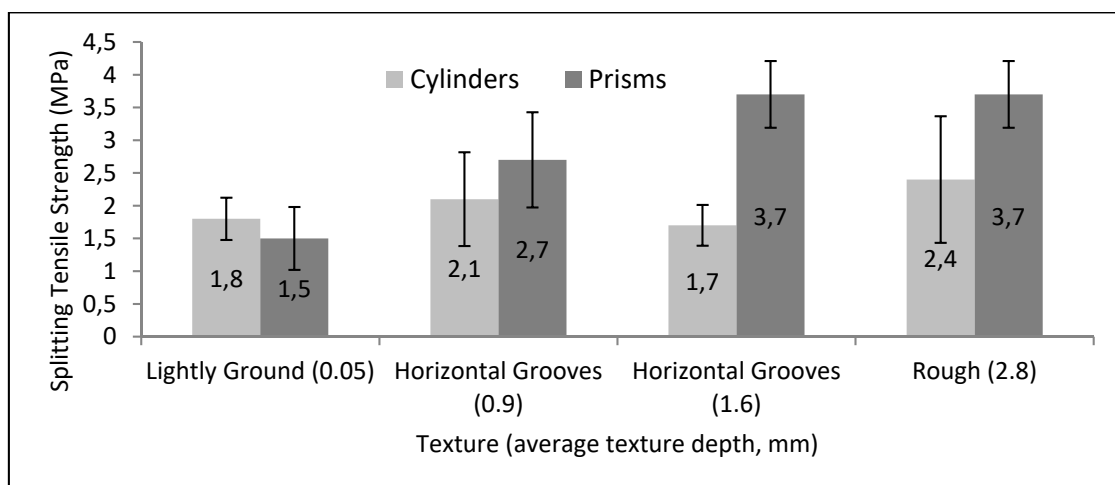


Figure 9. Average splitting tensile strength of cylindrical and prismatic specimens

Table 4. Splitting tensile strength for direct textures of cylinder and prism specimens

Specimens	Lightly Ground (0.05) [STDV]	Horizontal Grooves (0.9) [STDV]	Horizontal Grooves (1.6) [STDV]	Rough (2.8) [STDV]
Cylinders	1.8 [0.32]	2.1 [0.72]	1.7 [0.31]	2.4 [0.97]
Prisms	1.5 [0.48]	2.7 [0.73]	3.7 [0.51]	3.7 [0.51]

4.3. Direct tensile strength

Direct tensions tests were performed on specimens with three different textures, rough (2.8 mm), horizontal grooves (0.9 mm), and chipped. The chipped specimens were made using an air-hammer tool and had an average texture depth of 1 mm. Table 5 presents the results for direct tensile strength testing.

Table 5. Average direct tensile strengths for different textures

Texture (average texture depth)	Rough (2.8 mm)	Horizontal Grooves (0.9 mm)	Chipped (1 mm)
Average Tensile Strength (MPa)	0.96	0.44	1.06

The data show that type of texture greatly affected the tensile strength developed. All of the horizontal grooves specimens had strengths less than 1 MPa, which is considered unacceptable by [17]. However, one of the specimens displayed a substrate failure (figure 10) indicating that the observed strengths may have been limited by the tensile strength of the immature substrate (14 days old at testing). Rough and chipped textures had greater strengths than the grooved texture achieved by grinding that can be attributed to greater surface area and exposure of aggregate and pores that allowed UHPC to bond more easily. However, the rough texture still did not provide adequate strength (less than 1 MPa). It is worth noting that most failure modes were bond failures, especially for the grooved texture.

To investigate the cause of the low strengths, chipping was used to produce a substrate with a minimally acceptable texture of 1 mm that was selected based on observations by [13]. The acceptable bond strength of the chipped specimens seems to indicate that grinding plugs pores that are essential for bond of the overlay. It is also important to note that results of from the rough and chipped textures are considered “fair” according to similar work performed by [18].

**Figure 10.** Fractured substrate in grooved direct tension specimen

4.4. Shrinkage testing

Early-age shrinkage results were compared to those observed by [19]. About 1500 $\mu\epsilon$ of shrinkage was observed in both this work and Allena and Newton's [19] after 24 hours. Figure 11 presents the data

from early-age shrinkage testing over a period of seven days. Additionally, longer term shrinkage testing results are presented in figure 12 and show a total shrinkage of about 475 $\mu\epsilon$ at 28 days.

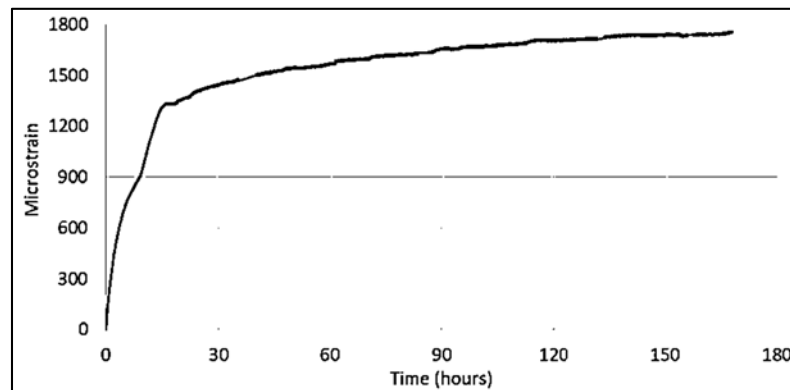


Figure 11. Early-age shrinkage of UHPC

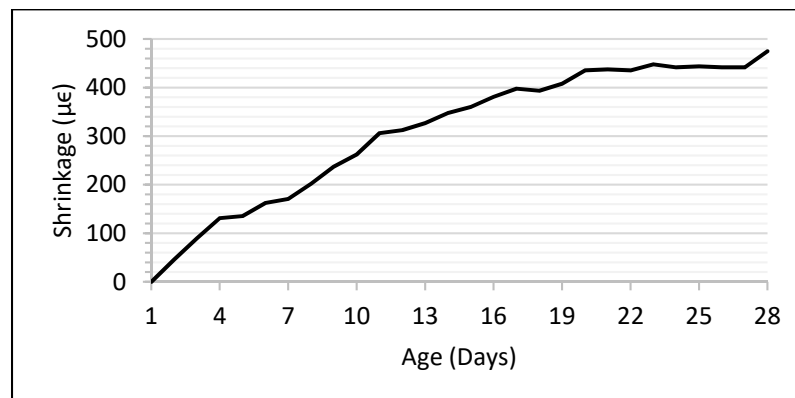


Figure 12. Longer term shrinkage of UHPC

4.5. Chloride permeability

Chloride permeability was determined for both fibre reinforced and non-fibre reinforced specimens. Results from these tests showed that in both cases a negligible charge passed through specimens over the period that voltage was applied. A total charge of 0.96 Coulombs and 1.08 Coulombs were observed for fibre reinforced and non-fibre reinforced specimens, respectively. The negligible charge can be attributed to the high density of UHPC that may have limited saturation when specimens were submerged in deionized water and discontinuity in the UHPC capillary pores. Additionally, fibre reinforcement tends to be discontinuous which can prevent significant charge from passing through specimens. The results of chloride permeability testing are important to some transportation agencies as an indication of UHPC's ability to improve durability against deicing salts that can cause corrosion of steel fibres or reinforcement.

4.6. Coefficient of thermal expansion

Coefficient of thermal expansion was determined to be 19.5 $\mu\epsilon/^\circ\text{C}$. This value will be used in continuing work to assess bond stresses caused by combined shrinkage and thermal effects.

4.7. Ongoing work

Currently, NSC slabs with UHPC overlays are being monitored to study combined shrinkage and thermal effects.

5. Conclusions

The following conclusions were drawn from this work:

- Development of a proper bond between UHPC and NSC can be achieved without the use of bonding agents. However, bond strength is highly dependent on the texture of the substrate material.
- Acceptable bond strengths were achieved for all texture depths (0.05 mm to 2.8 mm) with the exception of direct tension bond strengths.
- Desirable bond strength from slant-shear and splitting tension specimens was achieved even in the case of inadequate texturing (lightly ground texture).
- Acceptable direct tensile strengths were achieved by rough and chipped textures. Although, grooved textures failed to provide adequate tensile strength, one substrate failure was observed that indicates that the strengths may have been limited by the immature substrate.
- The results of this study indicate that locally produced UHPC seems to have the potential to serve as an overlaying material as long as proper measures are used in texturing the substrate to ensure that proper bond is achieved.

Acknowledgements

The authors would like to thank the following organizations for their contributions to this project:

- TranSET for funding the project.
- New Mexico Department of Transportation for their continued support of UHPC research and collaboration.
- BASF Chemical Company for their donations of silica fume and admixtures.

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