frontiers | Frontiers in Built Environment

TYPE Hypothesis and Theory
PUBLISHED 09 May 2024
DOI 10.3389/fbuil.2024.1354657

OPEN ACCESS

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RECEIVED 12 December 2023
ACCEPTED 23 April 2024
PUBLISHED 09 May 2024

CITATION
Shokrgozar A, Aryal B, Ebrahimpour A and Mashal M (2024), Bond-slip behavior of steel reinforcing bars in ultra-high performance concrete for field-cast connection of precast bridge decks.
Front. Built Environ. 10:1354657.
doi: 10.3389/fbuil.2024.1354657

Bond-slip behavior of steel reinforcing bars in ultra-high performance concrete for field-cast connection of precast bridge decks

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In Accelerated Bridge Construction (ABC), Ultra-High Performance Concrete (UHPC) is often used for connecting precast concrete bridge components, including deck portions of the Deck Bulb-T girders. An alternative low-cost non-proprietary UHPC has been proposed for use in place of the proprietary UHPC for connecting the precast components. The pullout behavior of steel reinforcing bars in closure pour with typical range for embedment lengths is studied for both proprietary and non-proprietary UHPC materials.

KEYWORDS

accelerated bridge construction (ABC), ultra high-performance concrete (UHPC), pullout test, closure pour, experimental tests

1 Introduction

Accelerated Bridge Construction (ABC) technologies are being adopted by many Departments of Transportation (DOTs) in the United States. ABC increases safety by lowering exposure to construction activities and increases mobility and economic opportunities by reducing traffic interruptions and delays. ABC requires that bridge precast concrete components to be effectively connected to one another in the field. In ABC, most of the bridge components are prefabricated off-site. The prefabricated components are transported to the construction site and are assembled. While assembling the components, gaps are provided between the bridge segments for connecting the components in the field; these gaps are referred to as closure pours. There are various materials available for use in the closure pour. Normal weight concrete, high early strength concrete with fibers, high strength grout, and Ultra-High Performance Concrete (UHPC) are some of the materials that are used.

UHPC is an advanced material that is commonly used for the casting of closure pour in highway bridges because of its excellent material properties. The compressive strength of UHPC reaches up to 140 MPa (20 ksi) or more. Despite having various advantages, UHPC also comes with some downsides. UHPC is typically a proprietary material that has high installation cost requires rigorous quality control requirements (Ebrahimpour et al., 2018). Wille and Boisvert-Cotulio (2013) were among the first researchers in the United States (U.S.) who spearheaded the development of the first set of non-proprietary UHPC materials. The research was supported by the U.S. Federal Hughway Administration

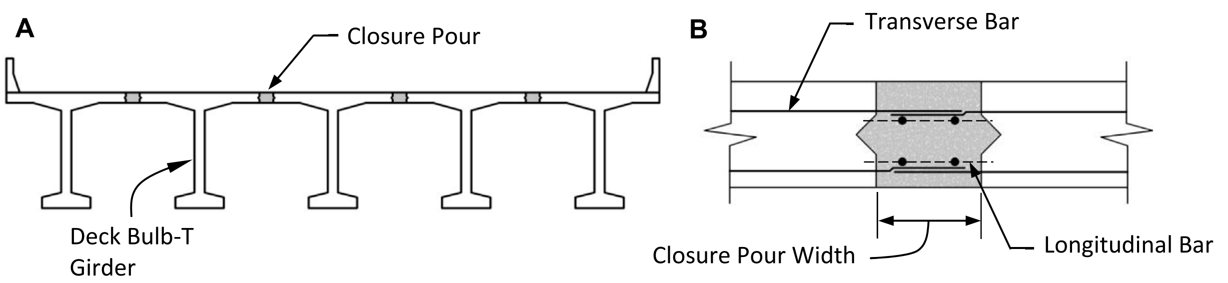

FIGURE 1
(A) Cross-section view of the bridge, and **(B)** closure pour detail.

with the long-term goals to facilitate the use of UHPC among U.S. suppliers and contractors, accelerate its application in construction, and promote a more resilient and sustainable future infrastructure. Among other researchers developing non-properiatray UPHC are Qiao, et al. (2016), Berry, et al. (2017), El-Tawil, et al. (2018), and Morcous, et al. (2020).

Recently, at Idaho State University (ISU) a non-proprietary UHPC was developed for bridge applications (Shokrgozar, 2023). At 28 days, the non-proprietary mix has a compressive strength of 124 MPa (18 ksi) with a cost of approximately $390 per cubic meter ($300 per cubic yard). Since very often UHPC is a proprietary product and because of its cost, bridge engineers are searching for alternative mixes. The cost of proprietary UHPC exceeds $1,600 per cubic meters (Berry et al., 2017). An on-site engineer who is responsible for inspecting and guiding the process is also needed while using the proprietary UHPC which increases the overall costs. The purpose of this research project was to understand the pullout behavior between steel bar and UHPC, both for proprietary and non-proprietary UHPC.

2 Background

Figure 1A shows a bridge cross-section composed of five Deck Bulb-T girders and four closure pours between the deck portions. Figure 1B shows the detail drawing of a closure pour with both transverse and longitudinal reinforcing bars. The typical width of the closure connections ranges from 152 mm (6 in.) to 254 mm (10 in.), with embedment length of the transverse bar having a range of 127 (5 in.) to 229 mm (9 in.).

Two types of bonds should be considered for field-cast connections. First, the bond between the steel bar and the concrete and second, the bond between the field-cast concrete and the precast bridge elements (Xing et al., 2015). This research focuses on the bond between the steel bar and the field-cast concrete. Early work on the study of pullout bond strength and bond-slip behavior of reinforcing bars in conventional reinforced concrete is abounding (Mathey and Watstein, 1961; Lutz and peter 1967; Goto, 1971). These studies investigated bond response mechanism of deformed bars in normal concrete and the effect of lateral reinforcement on bond-slip and bond strength. Rao et al. (2007) studied the reinforcing bar bond strength in high-strength concrete (HSC). Various parameters such as bar diameter, strength of concrete, lateral confinement, and embedment length were studied. Two concrete mixes with compressive strength of 30 MPa (4,350 psi) and 60 MPa (8,700 psi) were used. Cubes of size 150 mm × 150 mm × 150 mm (5.9 in × 5.9 in × 5.9 in) were used for compressive strength of concrete as well as for pullout specimen. The bars were placed in the middle of the specimen and the embedment length was achieved by using PVC tubes. Three types of specimens were used: unconfined, confined with spirals, and confined with ties (Rao et al., 2007). Monotonic load was applied by means of the actuator and the rate of the stroke control was maintained at 0.025 mm/s. Bond stress was expressed as:

$$\tau = \frac{P}{\pi d_b l_b} \tag{1}$$

Where, τ = bond stress, P = pullout force, d_b = diameter of the bar, and l_b = bar embedment length. For unconfined specimens, longitudinal splitting failure occurred. In confined specimens, splitting cracks developed initially, but due to the confinement the cracks could not get larger. It was found that the lateral confinement increased the bond strength significantly, and the bond strength decreased with increasing bar embedment length (Rao et al., 2007). More recently, Rashique et al. (2022) used the existing bond-slip relations in computer modeling of a closure pour connection between laboratory beams and compared results with experimental work. The connection in that study was made with high early strength concrete with polypropylene fibers. Also, recently, Shao and Billington (2021) investigated the bond between steel reinforcement and UHPC with two fiber volumes in flexure using beam-end specimens. They showed that the bond strength of UHPC is much higher than that of conventional concrete making it prone to cone-type failures. The work presented in this paper focuses on the pullout strength and bond-slip behavior of transverse bars in UHPC materials that are used in the longitudinal joints connecting deck portions of Deck Bulb-T bridge girders.

2.1 Non-proprietary UHPC

For the research project presented herein, based on prior experimental work on developing UHPC, the material constituents necessary for UHPC were defined, and locally available materials in the northwestern United States were identified (Shokrgozar, 2023). This included different types of cement, silica fumes, supplemental materials, high-range water reducers (HRWRs), aggregates and fibers. Next, these materials

TABLE 1 Mix proportions for non-proprietary UHPC for one cubic meter. (1 mm = 0.0394 in.).

Materials	Amount kg (lb)
Water	136 (300)
High-Range Water Reducer (HRWR)	30 (65)
Portland Cement Type I/II	590 (1,300)
Silica Fume	113 (250)
Type F Fly Ash	168 (370)
Fine Aggregate (volcanic rock)	706 (1,557)
Steel Fiber (0.5 mm diameter by 13 mm in length)	120 (263)

were preselected based on availability, cost, region, particle size distribution, and chemical and physical composition.

The mix design of the non-proprietary UHPC used in this paper is shown in Table 1. More information about the materials is provided in the dissertation by Shokrgozar (2023). The cost of the non-proprietary UHPC is less than $390 per cubic meter ($300 per cubic yard). The cost of shipping and placement is not included. The fine aggregate used for this mix is volcanic rock (Shokrgozar, 2023).

The gradation specifications of upper and lower limits of ASTM C144, *Standard Specification for Aggregate for Masonry Mortar* (ASTM, 2020), and the gradation of the modified Andreasen & Andersen (A&A) used for UHPC used in this research are shown below in Table 2. In preliminary trial mixes, different aggregate gradations were used. This gradation proved to provide the best workability and compression strength.

The mixing process of the non-proprietary UHPC was similar to typical steps used by other researchers (Graybeal, 2013; Wille and boisvert-Cotulio, 2013). The steps are as follows: (1) mix sand/aggregate and silica fume for 5 min, (2) add cement and supplemental material and mix for an additional 5 min, (3) add 1/3 of the HRWR to the water, (4) add the water-HRWR mixture within 1 min after pouring is started, (5) add the remaining HRWR within 1 min after pouring is started, (6) increase mixing speed, (7) add fibers if applicable, (8) mix until fluidity is optimized (between 5–10 min). As it can be seen, the mixing process took a long time and one can reasonably assume that fibers were well-mixed in the process. In addition, we used a vertical mixer which is the standard mixer for UHPC.

2.2 Pullout tests of proprietary and non-proprietary UHPC

For this project, a proprietary UHPC from a major manufacturer in the United States is used. This type of proprietary UHPC is typically used in bridge closure pours in ABC applications. As noted above, the non-proprietary UHPC was developed at Idaho State University (Shokrgozar, 2023).

3 Material property tests and pullout specimens

To determine material properties, UHPC concrete samples were cast in accordance with ASTM C1856/C1856M, *Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete* (ASTM, 2017). UHPC was mixed in the laboratory with a vertical mixer. 51 mm × 51 mm × 51 mm (2 in. × 2 in. × 2 in.) cubes were cast for determining the compressive strength of the UHPC. 78 mm (3 in.) diameter by 152 mm (6 in.) cylinders were cast for determining the split tensile strength. The samples were removed from their respective molds after 24 h of casting and were moist cured in lime-saturated water for 28 days and removed afterwards for testing. Compressive strength tests were performed in accordance with ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in Cube Specimens* (ASTM Standard, 2020). The split tensile test was done in accordance with ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* (ASTM Standard, 2017). The flow table test of UHPC mixes were done in accordance with ASTM C1856/C1856M, *Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete* (ASTM Standard, 2017).

Pullout test specimens were prepared to determine the ultimate force and bond-slip relationship between bar and UHPC with the bars having typical embedment length used in closure pour connection. Figure 2A shows the cross-section of two side-by-side Deck Bulb-T girders. Figure 2B shows the close-up view of the closure pour connection between the two girders. Figure 2C shows the the pullout specimen that represents the bottom half of the closure pour connection. The goal was to determine the pullout behavior of a 19 mm diameter (No. 6 or 0.75 in. diameter) transverse bar (the middle bar) in presence of two opposing transverse bars. To make the bond-slip behavior more realistic when it comes to concrete confinement,

TABLE 2 Fine aggregate gradation specifications.

Sieve size	Diameter in. (mm)	Percent passing (ASTM C144)	Percent passing (modified A&A curve)
No. 4	0.187 (4.76)	100	100
No. 8	0.0937 (2.38)	95 to 100	100
No. 16	0.0469 (1.19)	70 to 100	99
No. 30	0.0234 (0.595)	40 to 75	61
No. 50	0.0117 (0.297)	20 to 40	33
No. 100	0.0058 (0.149)	10 to 25	12
No. 200	0.0029 (0.074)	0 to 10	0

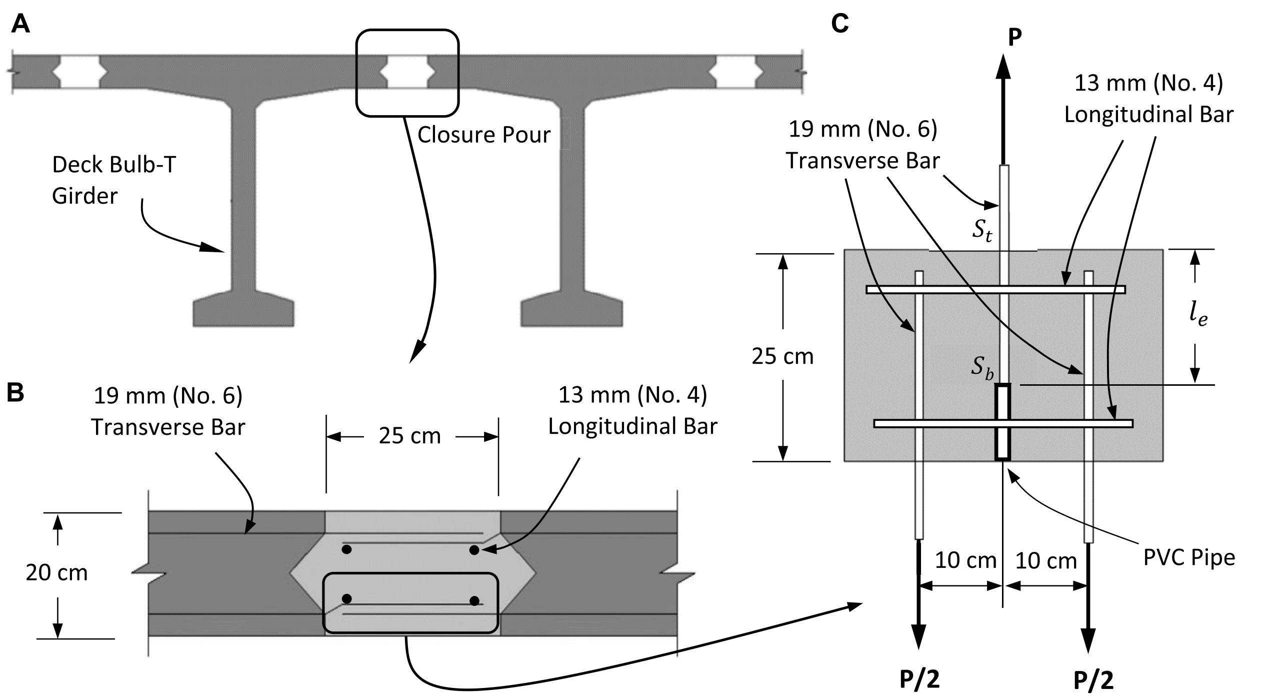

FIGURE 2
(A) Cross-section of two girders, **(B)** closure pour connection, and **(C)** pullout specimen schematic (1 mm = 0.0394 in.).

13 mm diameter (No. 4 or 0.5 in. diameter) longitudinal bars were also included as shown in Figure 2C. The bars were ASTM A615 Grade 60 with yield and ultimate strength values of 60 ksi (414 MPa) and 90 ksi (621 MPa), respectively. The size of pullout specimen was 381 mm × 254 mm × 102 mm (15 in. × 10 in. × 4 in.). Specimens with the top bar (the bar under consideration) embedment lengths, l_e, of 127 mm (5 in.), 178 mm (7 in.), and 229 mm (9 in.) were prepared. Note that in bridge closure pours, the embedment lengths are typically 25 mm (1 in.) less than the closure pour width. Many states in the United States use either 152 mm (6 in.) or 203 mm (8 in.) closure pours, requiring 127 mm (5 in.) or 178 mm (7 in.) bar embedment lengths. Idaho Transportation Department uses a 265 mm (10 in.) closure pour, requiring a 229 mm (9 in.) embedment length. Thus, the range of embedment lengths chosen for this study.

The top bar embedment length was achieved by using the PVC pipe extending from the bottom of the bar to the bottom of the specimen. Experimentally, the bond-slip of the top bar was measured at two locations: (1) at the top where the bar immediately exits the specimen, and (2) at the bottom of the bar (by inserting a displacement sensor inside the PVC pipe). The displacements (slips) at these locations are denoted by S_t and S_b in Figure 2C. The 13 mm bars used as longitudinal reinforcement was placed at 25 mm (1 in.) from both top and bottom of the mold. The specimens were cured for 28 days prior to testing.

The specimen and the locations of the displacement sensors (linear potentiometers) are shown in Figures 3A, B. It should be noted that placement of bars in specimen is symmetrical. That is, the transvers bars were placed in the middle the specimen with centers located 5 cm (2 in.) from each side. There is one displacement sensor at the bottom measuring the bar bottom slip (i.e., S_b, in Figure 2C) relative to the bottom surface of specimen. On the top there are two displacement sensors measuring the top slip (i.e., S_t, in Figure 2C) with respect to the top of the specimen. The two top displacements were averaged to remove any rotations. Figure 4 shows the pullout test setup (Aryal, 2022).

As shown in Figure 4, a displacement-controlled servo-hydraulic actuator was used to apply the load to the specimens. A 1000 kN (225 kips) capacity load cell was connected to the head of the actuator. The loading rate of 0.5 mm/min was used by the actuator to pull the specimen. Displacements were measured at the top and bottom of the top bar. These displacements were measured with the help of 102 mm (4 in.) stroke potentiometers. Force and displacement data were collected from the pullout tests.

4 Experimental results

Table 3 shows the results of the standard tests on both the proprietary and the non-proprietary specimens. As it can be seen, both UHPC materials have similar material properties, with proprietary UHPC having slightly higher strength values.

The specimens cast from proprietary UHPC were designated as P5-A, P5-B, P5-C, P7-A, P7-B, P9-A, P9-B, and P9-C. The specimens cast from non-proprietary UHPC were designated as NP5-A, NP5-B, NP7-A, NP7-B, NP9-A, and NP9-B. The specimens were named based on their UHPC mix and bar embedment length. For example, P5-A stands for pullout specimen made from proprietary UHPC with 5 in. (127 mm) embedment length, sample A. Data was collected up to the point of failure which was defined by either concrete failure or fracture of the upper bar. Table 4 summarizes the results of the pullout tests.

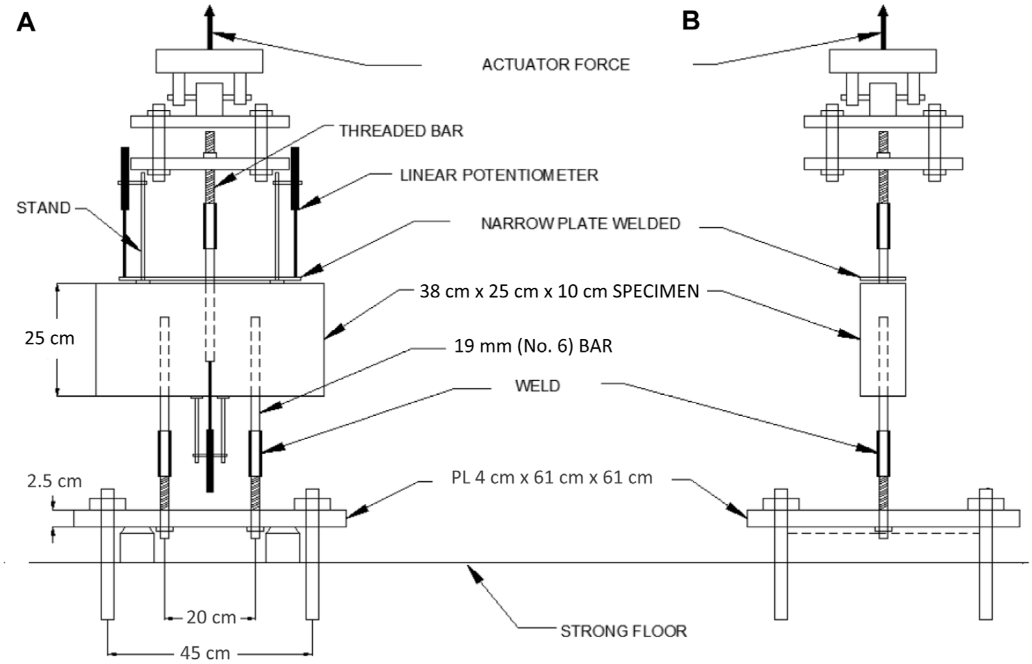

FIGURE 3
Specimen **(A)** front view, and **(B)** side view (1 cm = 0.394 in.).

FIGURE 4
Pullout test setup.

The results show that for proprietary specimens, concrete failed for specimens with smaller embedment, whereas bar broke for specimens with larger embedment. For non-proprietary specimens, concrete failed for all embedment lengths. Concrete cracking first initiated at the top surface and propagated vertically and horizontally across the specimen. The upper bar displacement (slip) at top (S_t) was more than the displacement at the bottom (S_b). Figures 5, 6 show the force versus displacement of proprietary and non-proprietary pullout

TABLE 3 Test results.

Mix	1-day compressive strength MPa (ksi)	7-day compressive strength MPa (ksi)	14-day compressive strength MPa (ksi)	28-day compressive strength MPa (ksi)	7-day split tensile strength MPa (ksi)	28-day split tensile strength MPa (ksi)	Flow mm (in.)
Proprietary	55 (8.0)	104 (15.1)	124 (18.0)	138 (20.0)	18 (2.7)	20 (2.9)	254 (10)
Non-proprietary	49 (7.1)	92 (13.3)	111 (16.0)	125 (18.1)	17 (2.5)	18 (2.7)	241 (9.5)

TABLE 4 Ultimate force for proprietary and non-proprietary specimens.

Specimen	Ultimate force kN (kips)	Remark	Specimen	Ultimate force kN (kips)	Remark
P5-A	115 (25.8)	Concrete failed	NP5-A	76 (17.1)	Concrete failed
P5-B	118 (26.5)	Concrete failed	NP5-B	77 (17.4)	Concrete failed
P5-C	82 (18.4)	Concrete failed	–	–	–
P7-A	136 (30.5)	Bar fractured	NP7-A	109 (24.5)	Concrete failed
P7-B	127 (28.6)	Concrete failed	NP7-B	101 (22.8)	Concrete failed
P9-A	144 (32.3)	Bar fractured	NP9-A	135 (30.4)	Concrete failed
P9-B	132 (29.7)	Bar fractured	NP9-B	141 (31.7)	Concrete failed
P9-C	116 (26.0)	Bar fractured	–	–	–

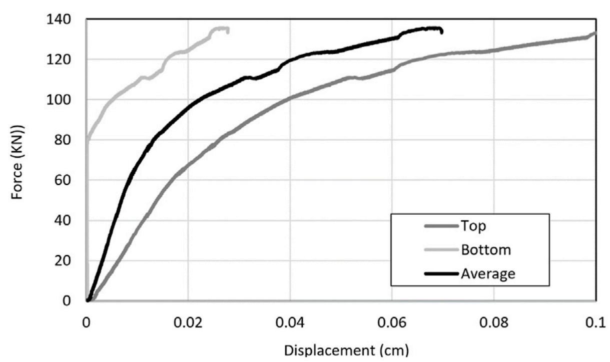

FIGURE 5
Force versus displacement (slip) for specimen P7-A.

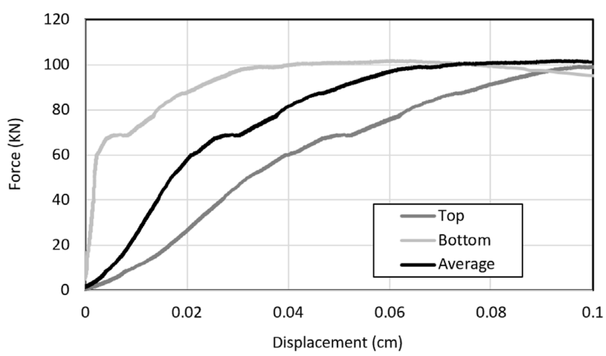

FIGURE 6
Force versus displacement (slip) for specimen NP7-B.

specimens for specimens P7-A (proprietary UHPC with 178 mm or 7 in. embedment) and NP7-B (non-proprietary with 178 mm or 7 in. embedment), respectively. The displacement at top of the bar is more than the displacement at the bottom which makes sense because the top of the bar is the loaded side and bottom of the bar is the unloaded side. After transferring the load from the bar to concrete through mechanical interlocking, adhesion, and friction, the displacement of the unloaded side becomes smaller than the loaded side. The curve labeled as "Top" is the average of the displacement values collected from left and right potentiometers located at the top of the specimen. See Figure 3A. After reaching the ultimate load, the test was concluded. For graphs for all force versus displacement data for all the embedment lengths considered, please refer to the thesis by Aryal (2022).

Table 5 shows the comparison of average ultimate force, average slip at ultimate force, and average ultimate shear stress for proprietary and non-proprietary UHPC.

From Table 5, it is clear that although bars with larger embedment lengths result in larger ultimate forces, the bond shear stresses as obtained by Eq. 1 (i.e., normalized values) are closer to one another. Figure 7 shows the graph of the average shear stress versus slip for all proprietary and non-proprietary specimens having embedment lengths of 127 mm (5 in.), 178 mm (7 in.), and 229 mm (9 in.); i.e., for use with typical closure pour widths of between 152 mm (6 in.) to 254 mm (10 in.). Figure 7 shows that the non-proprietary UHPC has a smaller initial slope and behaves somewhat more ductile. On Figure 7, the limit of the working shear stresses measured in a bridge in Idaho is also shown (Ebrahimpour et al., 2020). As a part of the research by

TABLE 5 Comparison between proprietary and non-proprietary UHPC.

Specimen	Average ultimate force kN (kips)	Average ultimate shear stress MPa (ksi)	Average slip at ultimate force cm (in)
Proprietary, 127 mm (5 in.)	104.9 (23.6)	13.72 (1.99)	0.068 (0.027)
Non-proprietary, 127 mm (5 in.)	77.0 (17.3)	10.13 (1.47)	0.170 (0.067)
Proprietary, 178 mm (7 in.)	131.7 (29.6)	12.34 (1.79)	0.043 (0.017)
Non-proprietary, 178 mm (7 in.)	105.4 (23.7)	9.93 (1.44)	0.119 (0.047)
Proprietary, 229 mm (9 in.)	130.3 (29.3)	9.51 (1.38)	0.053 (0.021)
Non-proprietary, 229 mm (9 in.)	138.0 (31.0)	10.06 (1.46)	0.124 (0.049)

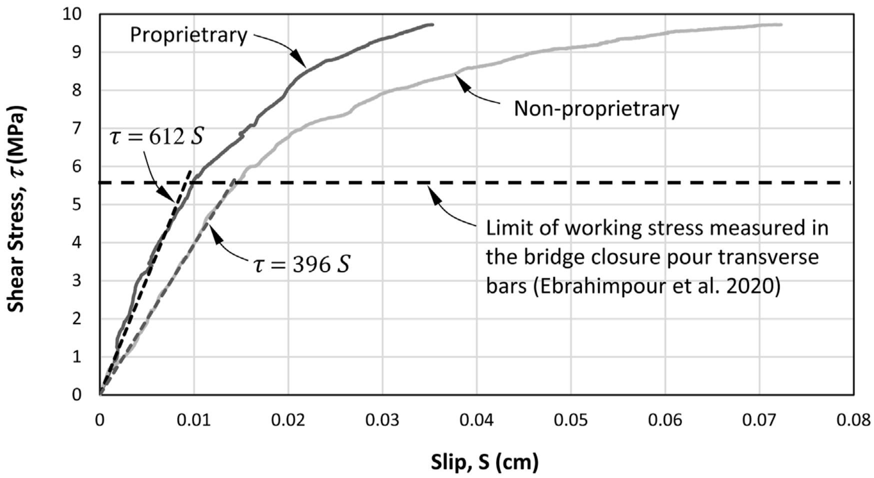

FIGURE 7
Average stress versus slip for all proprietary and non-proprietary specimens having embedment lengths of 127 mm (5 in), 178 mm (7 in), and 229 mm (9 in).

Ebrahimpour et al. (2020) the transverse bars in four closure pour connections of the bridge were instrumented with strain gages. This working shear stress limit is approximately 5.5 MPa (0.8 ksi). Since both curves in Figure 7 behave somewhat linearly in this range, fitted lines are also shown in Figure 7 in the linear regions which may be used in computer modeling of the closure pour UHPC. In both fitted line equations shown in Figure 7, the shear stress, τ, is in MPa and the bond slip, S, is in cm.

As seen in Figure 7, the bar slip in non-proprietary UHPC is slightly more at the working stress level of 5.5 MPa. This difference is less than 0.005 cm or 0.05 mm which is smaller than bond slip of about 0.1 mm at the same bond stress measured by Rao et al. (2007). Having noted this, the extra slip in non-proprietary UHPC and its effect on deck transverse deflection needs to be further investigated.

5 Summary, conclusion and recommendations for future work

One of the advantages of using non-proprietary is its cost. The material cost of the non-proprietary UHPC is less than the proprietary UHPC. Another consideration of using non-proprietary UHPC is being able to use local materials (e.g., aggregates and cement) and domestic fibers. Such materials make the use of non-proprietary UHPC more appealing since its use will not be affected by supply-chain and it is also more environmentally friendly. In addition, with the use of the non-preoperatory UHPC, the added cost of an on-site engineer can be eliminated. With proper guidance, this responsibility can be given to the department of transportation bridge project manager and the on-site inspector.

Through laboratory experimentation, it was seen that the material properties of non-proprietary UHPC are comparable to proprietary UHPC. These included compressive strength, tensile strength, and flow table tests. The bond-slip response of the proprietary and non-proprietary UHPC were also similar. However, on average, the non-proprietary UHPC exhibits more bond-slip than the proprietary UHPC. Simplified linear equations are suggested in the linear range of bond shear stress versus slip.

More work needs to be done in determining whether the developed UHPC satisfies all the design requirements. Some future work may include: (1) environmental durability, including freeze-thaw, chloride ion penetration, and carbonation with comparisons made with proprietary UHPC, (2) the effect of the additional bond-slip in non-proprietary UHPC in relation to allowable deflection of the deck, and (3) the effect of fiber size on bond-slip behavior of reinforcing bar in UHPC.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

AS: Data curation, Investigation, Methodology, Supervision, Writing–original draft. BA: Data curation, Methodology, Writing–review and editing. AE: Funding acquisition, Supervision, Writing–review and editing. MM: Supervision, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors are thankful to Jared Cantrell, the laboratory manager at Idaho State University, for his help in the lab. The authors are also grateful to Pocatello Ready Mix and Cannon Builders for their generous material donations to complete this project.

Conflict of interest

Author AS was employed by Tindal Engineering Corporation. Author BA was employed by David Evans and Associates.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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