Interface Shear Resistance of Ultra-High Performance Concrete (UHPC)

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Abstract:

In recent years, the use of Ultra-High Performance Concrete (UHPC) in bridge construction has been growing significantly. UHPC is considered an ideal material for bridge connections due to its excellent early-age mechanical properties, exceptional durability, and high workability. The objective of this paper is to evaluate the interface shear resistance of UHPC as it is considered a key property in the performance of connections between precast concrete deck panels and bridge girders. Interface shear resistance is evaluated experimentally for a commercial UHPC through two laboratory testing methods. Direct shear test is conducted to evaluate interface shear resistance of monolithic UHPC. Slant shear test is conducted to evaluate interface shear resistance of UHPC cast against hardened conventional concrete with three surface textures: smooth, shallow grooved, and deep grooved. Test results are compared to those predicted using the models obtained from literature and bridge design specifications.

Keywords: UHPC, Interface Shear, Direct Shear Test, Slant Shear Test, Bridge Connection.

1. Introduction

Accelerated Bridge Construction (ABC) projects usually use prefabricated bridge components and field-cast connections made of cementitious grout/concrete. The performance of these connections has a major effect on the constructability, durability and economy of ABC projects. The exceptional high early strength and durability properties of UHPC made it an ideal material field-cast connections. Several UHPC field-cast connections were developed, tested, and implemented in bridge construction (Graybeal 2014). Figure 1 shows examples of these connections. Also, several researchers developed simplified UHPC connections to extend spacing between connectors and minimize conflicts between deck and girder reinforcement (Badie, et al. 2018, Abo El-Khier, et al. 2018). The interface shear resistance of UHPC is a critical design criterion in these connections as it transfers shear forces between prefabricated components to achieve the composite action. Current AASHTO LRFD provisions for predicting interface shear resistance were developed for only conventional concrete (CC). Using UHPC in bridge construction requires investigating its interface shear resistance when cast monolithically and against conventional concrete with different surface preparations. Therefore, literature review and experimental investigation were conducted and presented in this paper to evaluate the interface shear resistance of monolithic UHPC and UHPC cast against hardened CC.

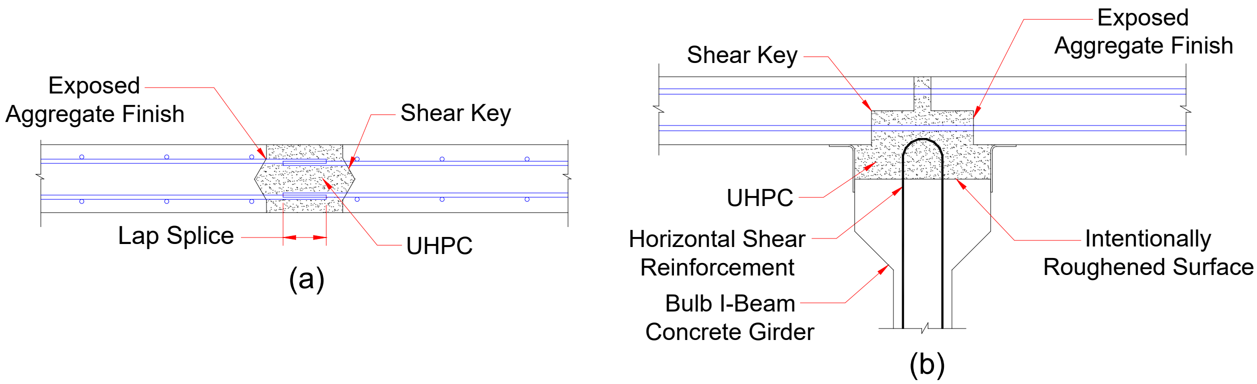


Figure 1: Examples of UHPC Field-Cast Bridge Connections: (a) Deck Panel-to-Panel Connection, and (b) Deck Panel-to-Girder Connection (Graybeal 2014).

2. Literature Review

2.1. Interface Shear Resistance of Monolithic UHPC

Crane (2010) evaluated the interface shear resistance of monolithic UHPC through performing push-off test on L-shape specimens and compared the results with ACI 318 (2008) and AASHTO LRFD (2007) equations of concrete interface shear. Two parameters were investigated including un-cracked and pre-cracked interfaces, and reinforcement ratios of 0 and 0.5%. The obtained interface shear resistance was significantly higher than that predicted for monolithic concrete in all cases. Adding transverse reinforcement across the interface plane changes the behavior to be more ductile than unreinforced planes. Average interface shear resistance was found to be 1.9, 2.6, 2.7 and 4.0 ksi (13.1, 17.9, 18.6, and 27.6 MPa) for pre-cracked monolithic with 0% reinforcement ratio, pre-cracked monolithic with 0.5% reinforcement ratio, un-cracked monolithic with 0% reinforcement ratio, and un-cracked monolithic with 0.5% reinforcement ratio specimens respectively. Another vertical push-off test was conducted to investigate the shear performance of construction joints using UHPC (Jang, et al. 2017). A monolithic 26.0 ksi (179 MPa) UHPC L-shape specimen achieved interface shear resistance of 2.7 ksi (18.6 MPa) and is considered a reference for other types of roughened or grooved interfaces.

A direct shear test was conducted on UHPC using monolithic L-shape specimens by applying vertical loads at the critical shear plane (Maroliya 2012). The interface shear resistance was obtained for different steel fiber percentages; 0%, 1.5%, 2%, and 2.5%, and different curing conditions. The plain UHPC samples exhibited brittle failure at the maximum applied load. The 2% fiber specimens gave the highest shear strength with an average value of 2 ksi (13.8 MPa) under normal curing conditions.

Small and large-scale specimens were fabricated and tested to evaluate the direct shear strength of UHPC (Haber, et al. 2017). A prismatic beam specimen with 2 in. (51 cm) square cross-section exhibited double shear failure mode after being tested at different compressive strengths of UHPC. The large-scale specimens consisted of two precast slabs with shear lugs filled with cast-in-place UHPC. The obtained direct shear strength varied between 4 and 8 ksi (27.6 and 55.2 MPa) which is significantly higher that indicated in previous researchers.

Figure 2 plots the average direct shear strength of UHPC as a function of its compressive strength obtained from the literature (Haber, et al. 2017). The exponential trend line indicates that the direct shear strength of UHPC increases with the increase in the compressive strength. However, the correlation between the two parameters is considered low, which could be attributed to the small size of specimens and its effect on scatter of test results.

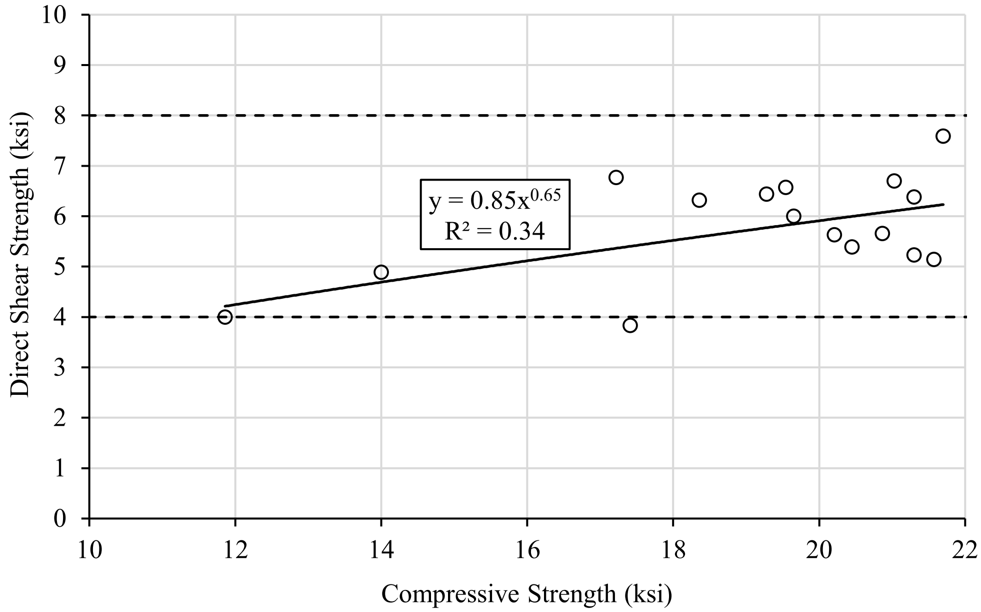


Figure 2. UHPC Direct Shear Strength as Function of its Compressive Strength (1 ksi = 6.9 MPa).

2.2. Interface Shear Resistance of UHPC cast on Hardened Conventional Concrete (CC-UHPC)

Slant shear test and L-shape push-off test are the most common testing techniques to evaluate the interface shear resistance between UHPC and hardened concrete without transverse reinforcement. Slant Shear test is conducted to evaluate the bond strength over the interface plane between two different types of materials. The type and dimensions of slant shear specimens and interface angle changes according to applied codes. Several parameters influence slant shear bond capacity such as interface plane angle and surface texture. ASTM C882/C882M for slant shear test is performed on 3 in. by 6 in. (7.5 cm by 15 cm) cylindrical specimen with an interface plane angle of 60° with the horizontal axis. ASTM C882/C882M is mainly for determining the bond strength of adding a layer of epoxy-resin-base material between two mortar sections. The composite specimens are tested according to ASTM C39 for concrete compressive strength testing.

However, Rangaraju et al. (2013) and Harris et al. (2011) followed the ASTM C882/C882M composite specimen dimensions, Harris et al. (2011) used conventional concrete instead of mortar which was used by Rangaraju et al. (2013). Different prismatic slant shear specimen dimensions were tested by Tayeh et al (2012), Muñnoz (2012), Aaleti and Sritharan (2017). Different interface plane angles with horizontal axis were investigated; 55°, 60°, and 70° (Muñnoz 2012) and 53.1° (Aaleti and Sritharan 2017). Of those tested, the sandblasted interface texture gives the highest interface shear resistance.

The data collected from the literature was divided into three categories according to the surface texture: sandblasted, brushed, and grooved. The shear stress and normal stress at the interface plane were calculated by dividing the applied load components based on the interface angle by the interface surface area for each specimen and plotted as shown in Figure 3. The effect of UHPC and CC compressive strength are not significant based on linear regression analysis with interface shear resistance for each of them separately. The parameters of the shear friction model (i.e. cohesion coefficient (c) and friction coefficient (μ)) were obtained for each surface texture and compared against those of AASHTO LRFD for CC with intentionally roughened surface as shown in Table 1. The comparison indicated that UHPC cohesion coefficient (c) is significantly higher than that for CC, while UHPC friction coefficient (μ) for brushed and grooved surfaces is very close to that of CC. The high coefficients of determination (R^2) of the developed models indicated strong correlations between the shear and normal stresses of UHPC for different surface textures.

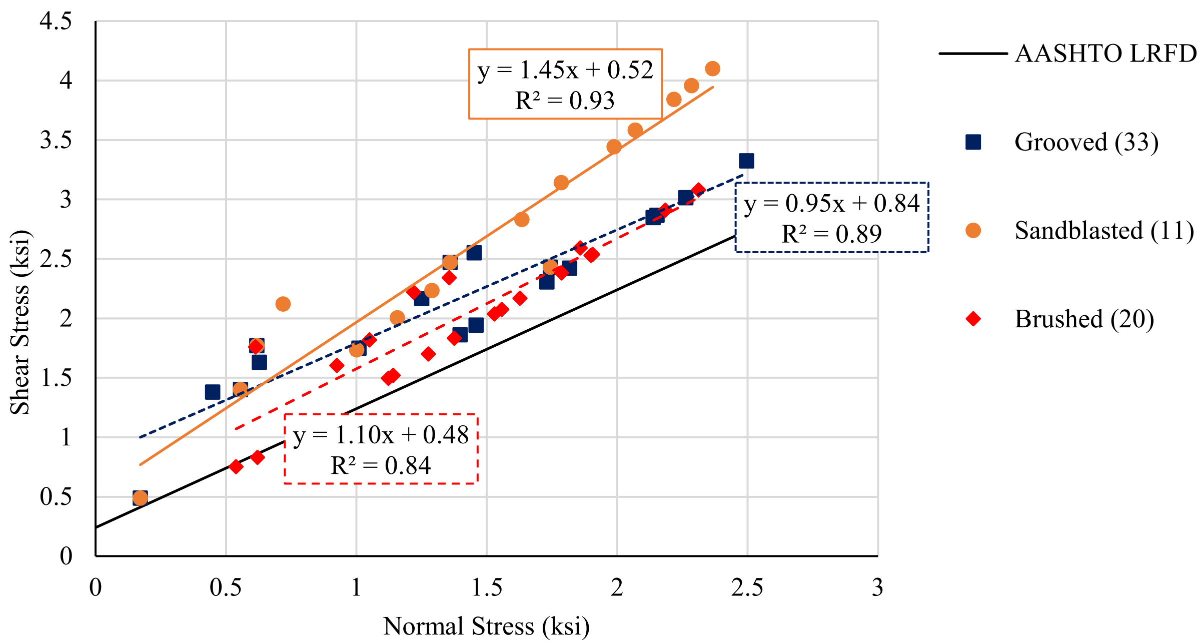


Figure 3. Interface Shear Resistance of CC-UHPC with Different Surface Textures (1 ksi = 6.9 MPa).

Table 1. CC-UHPC Cohesion and Friction Coefficients of Different Interface Surface Textures

Surface Texture	UHPC Cohesion Coefficient (c)	UHPC Friction Coefficients (μ)	R^2
Sandblasted	0.52	1.45	0.93
Brushed	0.48	1.10	0.84
Grooved	0.84	0.95	0.89
AASHTO LRFD	**0.24**	**1.0**	**NA**

3. Testing Methods

The experimental program presented below evaluates the interface shear resistance of monolithic UHPC and CC-UHPC. A commercially available UHPC was used to conduct the experimental program with 2% steel fiber content by volume.

3.1. Direct Shear Test

A direct shear test was conducted to evaluate the interface shear resistance of monolithic UHPC. Based on Haber, et al. (2017), 2x2x6 in. (5.08x5.08x15.24 cm) prismatic specimens were cut from a longer specimen cast from one end to align the fibers with the specimen length. A displacement-controlled loading with a rate of 0.05 in./min (0.13 cm/min) was used to develop double shear failure in the cross section as shown in Figure 4.

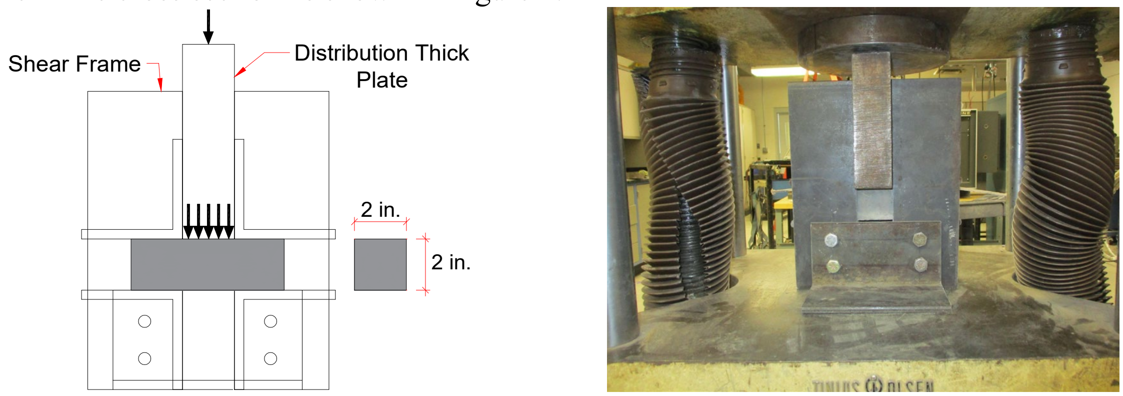
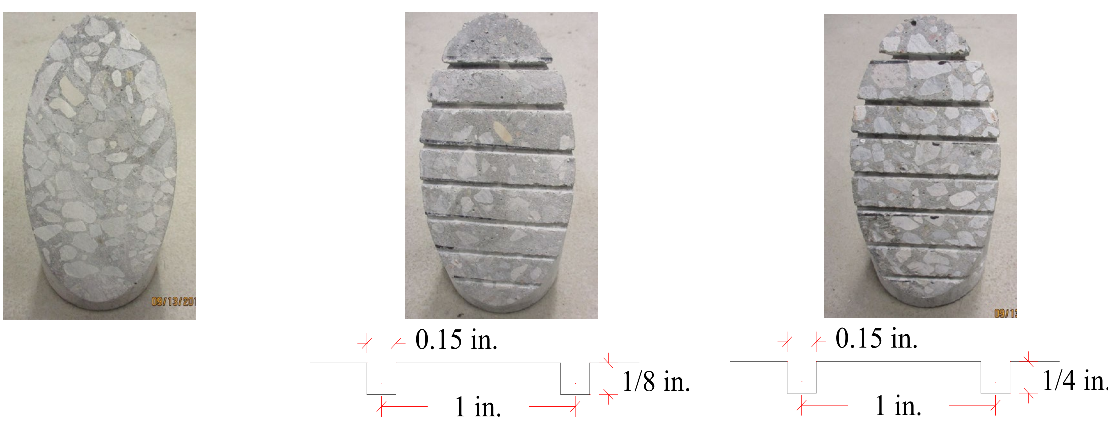


Figure 4. Direct Shear Test Setup (1 in. = 2.54 cm).

3.2. Slant Shear Test

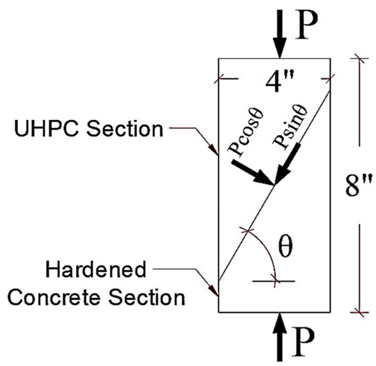
A slant shear test based on ASTM C882/C882M was performed to evaluate the interface shear resistance of CC-UHPC. A 4 in. by 8 in. (10.2 cm by 20.3 cm) cylinder section was used instead of 3 in. by 6 in. (7.6 cm by 15.2 cm) cylinder section to allow the use of conventional concrete as a substrate. Hardened CC cylinders were saw cut diagonally at 60° angle with the horizontal axis. The compressive strength of hardened concrete at 28 days was 8 ksi (55.3 MPa), which represents the common compressive strength of precast concrete girders. Figure 5 shows three different textures applied to interface shear surface; smooth, shallow grooved (1/8 in. (0.32 cm) depth), and deep grooved (1/4 in. (0.64 cm) depth).



(a) **(b)** **(c)**

Figure 5. Interface Textures of Hardened Conventional Concrete; (a) Smooth, (b) Shallow Grooved, and (c) Deep Grooved (1in. = 2.54 cm).

The interface surface was pre-wetted directly before casting UHPC. The composite section specimens were placed in a curing room of 73°F (23°C) temperature and fully humid environment till the day of testing. Both ends of composite section specimen were ground prior to being tested under a compression load rate of 300 lb/min (1.33 KN/min) till failure as shown in Figure 6.



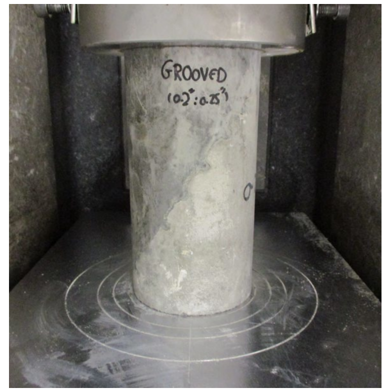


Figure 6. Slant Shear Test Specimen Dimensions and Test Setup (1 in. = 2.54 cm).

4. Results

4.1. Direct Shear Test

The direct shear strength was obtained for 15 UHPC specimens (five groups of 3 specimens each) with different compressive strengths. All the specimens exhibited double shear failure as shown in Figure 7. The obtained direct shear strengths were calculated by dividing the applied load by the double shear areas. The average direct shear strength of three specimens ranged from 4.16 to 5.95 ksi (28.7 to 41 MPa) as the average compressive strength of UHPC ranged from 11.8 to 23.4 ksi (81.4 to 161.3 MPa).

Figure 7. Double Shear Failure Mode of Direct Shear Test Specimens.

4.2. Slant Shear Test

A total of 18 slant shear specimens were tested at 28 and 56 days after casting the UHPC portion. CC had an average compressive strength of 8 ksi (55.2 MPa) and UHPC had a compressive strength of 23.4 and 27.2 ksi (161.3 and 187.5 MPa) respectively. Different failure modes were observed for different surface textures as shown in Figure 8. All specimens with smooth surface had bond failure as shown in Figure 8a. Most specimens with shallow grooved surface had bond failure with fractured CC as shown in Figure 8b. All specimens with deep grooved surface had failure in the CC portion as shown in Figure 8c. The interface shear resistance and normal stress were calculated by dividing the applied load components based on the interface angle as shown in Figure 6 by the interface surface area (25.1 in.^{2} (162.1 cm^2). Figure 9 shows the average interface shear resistance of three identical specimens at 28 and 56 days for each surface texture. This figure indicates that there is no significant difference in the interface shear resistance of UHPC cast against hardened CC with different surface textures.

(a) **(b)** **(c)**

Figure 8. Slant Shear Specimen Failure Modes; a) Bond Failure, b) Bond Failure and CC Fracture, and c) CC Failure.

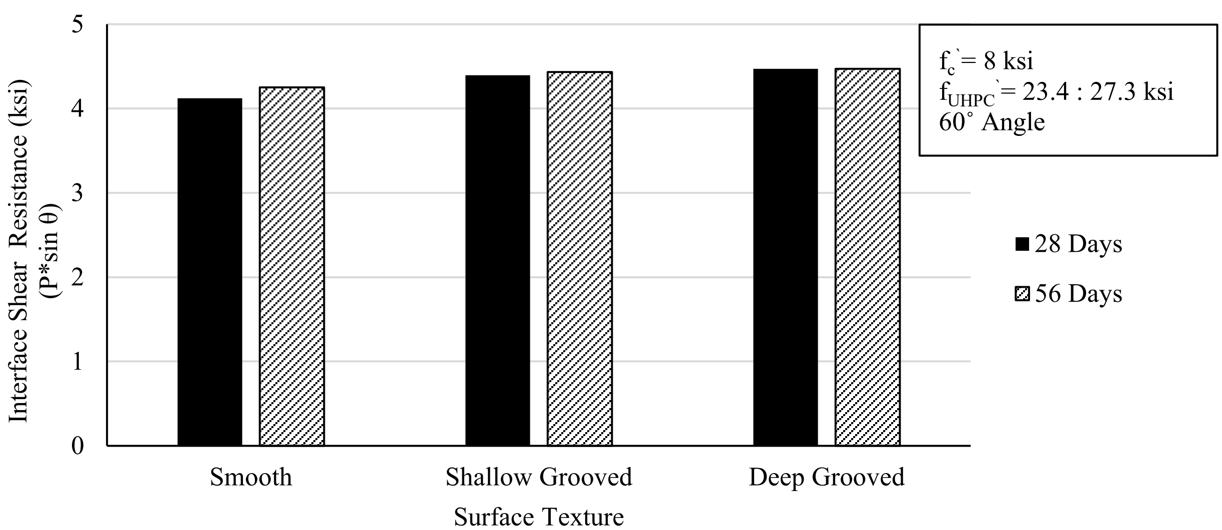


Figure 9. Interface Shear Resistance of CC-UHPC at 28 and 56 Days for Different Surface Textures (1 ksi = 6.9 MPa).

5. Discussion

5.1. Direct Shear Test

The obtained direct shear strengths are varying between from 4.16 to 5.95 ksi (28.7 to 41 MPa) which lies on the same range of results presented in Haber, et al. 2017. Figure 10 shows the obtained average shear strengths and the strengths obtained from the literature review. The obtained direct shear strengths are two or more times higher than some of the literature review results (Crane 2010, Maroliya 2012, and Jang, et al. 2017). The weak correlation between shear strength and compression strength might be attributed to the small size of the specimens used. Also, the applied load paths inside the specimen affect the obtained shear strengths as these paths act through compression struts towards the supports. So, the obtained shear strengths need to be corrected.

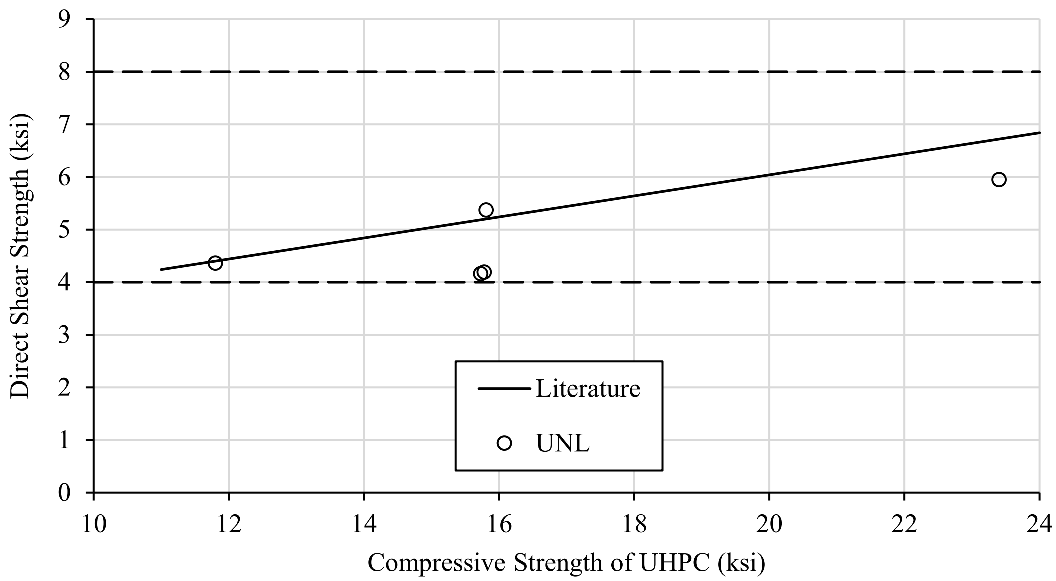


Figure 10. Results of Direct Shear Test and their Comparison to the Literature (1 ksi = 6.9 MPa).

5.2. Slant Shear Test

The deep grooved interface surface achieved slightly higher interface shear resistance than smooth and shallow grooved interface surface for 8 ksi CC and 24 ksi UHPC. This conclusion might change when different compressive strengths are used. Figure 11 plots the slant shear test results against the relations developed from the literature. The plot shows that interface shear resistance of all tested specimens is very close to predicted values for sandblasted surface texture and higher than those of grooved interface.

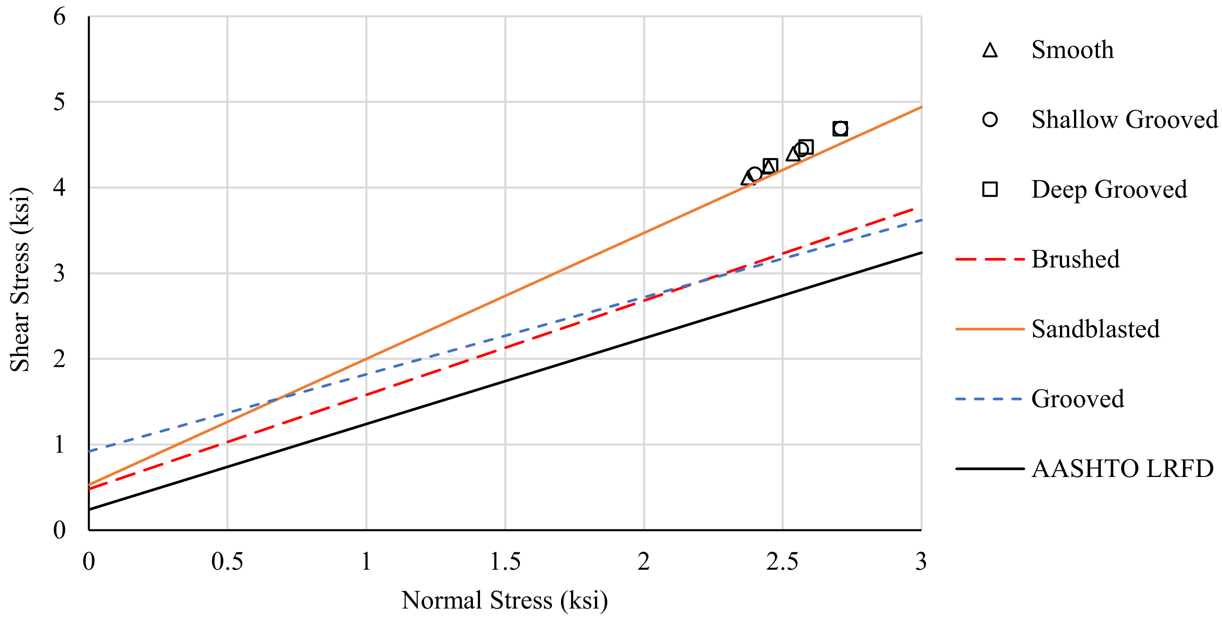


Figure 11. Results of Slant Shear Test and their Comparison to the Literature (1 ksi = 6.9 MPa).

6. Conclusions

The literature review and experimental investigation conducted to evaluate the interface shear resistance of monolithic UHPC and UHPC cast on hardened conventional concrete have shown the following conclusions:

1. The direct shear strength of monolithic UHPC ranges from 4 to 8 ksi (27.6 to 55.2 MPa) depending on its compressive strength. The small size of the specimens used in this test and the effect of uncertain load path could be reasons for the high scatter in the test data.
2. Interface shear resistance of UHPC cast on hardened conventional concrete (CC-UHPC) can be modeled using the current AASHTO LRFD shear friction model. However, different cohesion and friction coefficients should be used for different surface textures.
3. The deep grooved interface surface (1/4 in. (0.64 cm) deep grooves) resulted in conventional concrete failure rather than bond failure. Therefore, the compressive strength of conventional concrete is a key parameter in predicting the interface shear resistance of CC-UHPC with roughened interface surface.

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