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Evaluation of Bond Strength between Ultra-High-Performance Concrete and Normal Strength Concrete: An Overview

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ABSTRACT

Ultra-high-performance concrete (UHPC) is an advanced, durable cementitious material with excellent mechanical properties, which makes it an appropriate material for strengthening, repair, and retrofitting of damaged concrete structures. The UHPC as a repair material on normal strength concrete (NSC) depends on the quality of the bond strength at the interface. The interface behavior of UHPC-NSC concrete has a significant impact on its overall durability performance. This paper reviews the studies conducted on the bond strength at the concrete interface to determine the effectiveness of different bond strength testing techniques. The review has shown that the bond strength is commonly evaluated through splitting tensile, slant shear, direct shear, pull-off, bi-surface shear, and third-point flexural tests. Slant shear and splitting tensile test methods are the most common techniques used to evaluate the performance of bond strength between UHPC and NSC. splitting tensile tests, stress is directly applied at the concrete interface, while in the slant shear test, the interface surface is subjected to combined compressive stress and shear stress. Thus, Splitting tensile tests produces more accurate results than the slant shear test. Bi-surface shear and third-point flexural tests are easy to conduct and give a result similar to splitting and direct shear tests. However, further investigations are required on the reliability of the test methods under different conditions. In terms of failure modes, splitting tensile tests produces a more consistent result compared to the pull-off test.

Keywords: Bond strength; Bonding test technique; Normal strength concrete; Ultra-high-performance concrete;

INTRODUCTION

The damage of a reinforced concrete structure such as a bridge is a severe problem for society and a considerable challenge for engineers (Li and Burgueño, 2019). The infrastructure system is the key to the social and economic development of modern society. Bridges, as part of them, have an essential role since their inefficiency, or damage has critical and sometimes irreversible negative consequences on the nation and economy (Sousa et al. 2020; Gong and Jacobsen 2019). The structural damage of concrete occurs for different reasons, including physical, chemical, or mechanical actions. The error in design, calculation, and construction practice, undesired increase in load, change of service conditions, spalling and cracking of concrete due to aggressive environment, deterioration due to corrosion of steel rebar, and other chemical attacks are the leading causes of concrete damages (Bahraq et al. 2019). The durability and load-carrying capacity of such infrastructures will severely decrease and requires urgent attention. The conventional method used to repair, strengthened or retrofit damage concrete is either (1) steel jacketing, (2) carbon fiber-reinforced polymer (CFRP) wrapping, or (3) Concrete jacketing (Jiang et al. 2016; Sezen and Miller 2011; Rocca et al. 2007; Petrou et al. 2008). The idea of repairing structural elements with UHPC is more efficient and is significant in increasing the durability and performance of the damaged structure (Rodrigues et al. 2018; Ruano et al. 2015).

UHPC is an advanced construction material with mechanical and durability properties far exceeding those of NSC. UHPC has a compressive strength of 120 MPa to 240 MPa and sustains tensile strength of 6 MPa to 10 MPa. UHPC provides superior properties such as low fatigue loss, high resistance to chemical attack, high impermeability, high flowability, high energy absorption, and high tensile strength (Farzad et al. 2019c; Shafieifar et al. 2017).

The effectiveness of UHPC-NSC composite concrete depends on how close it behaves as monolithic concrete (Ali Dadvar et al., 2020). The response of its interface connection influences the overall structural and durability performance of the composite concrete. There is excellent compatibility between NSC and UHPC in terms of bond strength. Many works in the literature show that the bond between NSC and UHPC is sturdy and durable. Aaleti and Sritharan (2019) conducted analytical and experimental studies to understand the influence of NSC, interface roughness, and the curing condition on the shear transfer behavior across the interface between NSC and UHPC. The result shows that, regardless of the concrete strength, with a minimum of 3mm roughness, the shear transfer over the interface is adequate for overlay application. Yin et al. (2019) developed numerical techniques using an equivalent beam element at the interface between the NSC and UHPC to predict the structural response of the composite considering bond strength at interface. Qin et al. (2019) conducted an interfacial fracture toughness test to study the effect of the shrinkage reducing admixture (SRA) on the strength of a new-to-old concrete interface; the result shows that the bond strength decreases with increasing moisture penetration.

Recently, there is an increasing number of bridges that will soon need retrofitting or even replacement due to environmental effect or because their design lifespan is approaching (Farzad et al. 2019a; Aaleti & Sritharan 2019; Farzad et al. 2019b). Furthermore, with increasing application of ultra-high performance concrete as a strengthening and repair material (Beschi et al. 2011, Farhat et al. 2007; Habelet al. 2006), there is a growing challenge of bond strength testing technique between the NSC and UHPC. This paper reviews different bond strength testing techniques with the emphasis on the bond strength, surface preparations, and failure modes. The paper aims to account for the state of understanding and identify the effectiveness and accuracy of each testing method.

SUBSTRATE SURFACE PREPARATION

Surface preparation is key to effective bond strength between UHPC and NSC. This review reveals that there are twelve different surface preparation techniques commonly used, namely mechanical connector (MC), bonding agent (BA), rough + drilled hole (RD), high rough (HR), rough + groove (RG), smooth (SM), sandblasting (SB), post-installed rebar (PR), wire brush (WB), grooving (GR), sawed (SW), chips (CH), and drilled hole (DH). This conforms with the study performed by (Abu-Tair et al. 1996; Júlio et al. 2004; Júlio et al. 2005; Santos et al. 2007). Fig.1 shows the different types of surface treatments used for the slant shear test.

TECHNIQUES FOR TESTING BOND STRENGTH

Studies show that there are various test methods used to analyze the bond strength between the two materials (Harris et al. 2011; Momayez et al. 2005). In this review article, six different bonding strength testing techniques were reviewed, namely, slant shear test, splitting tensile test, pull-off test, direct shear test, bi-surface tensile test, and third-point flexural test. The quality of a bond is assessed based on the value of the bond strength obtained during testing and the failure mode. The quantitative bond quality is presented in Table 1.

FAILURE MODE

Based on the reviewed articles, three different failure modes were observed from different bond strength testing techniques. Moreover, it conformed with other studies, which show that the failure mode is classified into three categories: (1) purely interface failure (B), which is observed at the bond line while the bond surface remains smooth. It indicates a weak bond between the NSC and UHPC. (2) partial interface failure (B/C), which is seen at substrate concrete, and part of the bond line. It indicates a moderate bond strength between NSC and UHPC. (3) complete NSC substrate failure (C) which is mainly observed at the substrate close to the bond interface, which indicates a strong bond between the two concrete. (Harris et al. 2011; Momayez et al. 2005).

SPLITTING TENSILE TEST

The splitting tensile test is conducted to evaluate the bond strength between normal strength and ultra-high-performance concrete, and the load is applied on the composite line until a failure occurs. The test is usually conducted at 7, 28, and 90 days according to ASTM C496. The splitting tensile strength is evaluated using Equation (1)

$$T = \frac{1}{\pi} \times \frac{2P}{LD} \quad (1)$$

T = the splitting tensile strength (MPa);
P = maximum applied load (N);
L = length of specimen (mm);
D = diameter of specimen (mm)

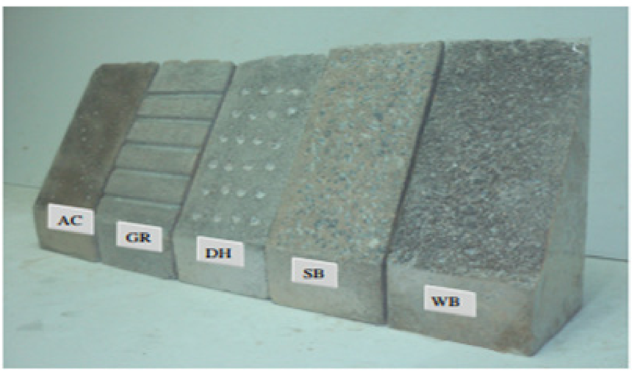

FIGURE 1. Slant shear test specimens with five different surface textures (Tayeh et al. 2012)

TABLE 1. Quantitative bond quality in terms of tensile bond strength (Sprinkel & Ozyildirim 2000)

Bond strength (MPa)	Bond Quality
≥ 2.1	Excellent
1.7-2.1	Very Good
1.4-1.7	Good
0.7-1.4	Pair
0 - 0.7	Poor

Zhang et al. (2020a) investigated the bond characteristics between the NSC substrate and the UHPC layer. The authors conducted a splitting tensile test and evaluated the interfacial bond strength and failure mode. The result obtained from the experiment exceeds the minimum requirement by ACI 546-06. Partial interface and complete substrate failure were observed on surfaces prepared using three different techniques, as shown in Table 2, indicating a strong bond between UHPC and NSC.

Sabah et al. (2019b) investigated the durability performance of the interfacial bond between the normal strength concrete as old and new green university saint Malaysia reinforced concrete (GUSMRC) as a repair material under the effect of elevated temperature of (100, 200, 300, 400, and 500 ^{0}C). The bond strength decreased with increasing temperature. The failure mode observed indicated a strong bong between GUSMRC and NSC.

Sabah et al (2019b) investigated the interfacial bond strength between a newly developed GUSMRC as a repair material and normal strength concrete as a substrate using the splitting tensile test. From the splitting test result, splitting strength with sandblasting is higher by 8.3, 20.7, and 18.5% than with the grooving at 7, 28, and 90days, respectively.

Baharuddin et al. (2016) investigated and compared the interfacial bond characteristics between fire-damaged reinforced concrete RC substrate and ultra-high-performance fiber-reinforced concrete (UHPFRC) as a repair material using splitting tensile test. The authors prepared 15 fire-damaged RC specimens subjected to three different surface moisture conditions, namely, air dry, saturated surface dry (SSD), and wet five samples each. The results obtained by the authors indicate that surface moisture conditions significantly influence bond strength. There is a weak bond between UHPFRC and NSC due to fire damage and inadequate surface preparations.

Hong and Kang (2015) investigated the interface bond strength of the UHPC-NSC by considering the effects of surface condition (surface roughness and moisture content of UHPC), and curing method (temperature and relative humidity of the specimens). The result of splitting tensile test at seven days shows a good quality bond strength between UHPC and NSC.

Tayeh et al. (2014) investigated the properties of the interfacial transition zone between normal concrete (NC) substrate as old concrete and ultra-high performance fiber-reinforced concrete (UHPFC) as a repair material. The authors performed splitting tensile test to quantify the bond strength in indirect tension, at 3, 7, and 28days. The bond strength at 28days achieved a minimum requirement by the American concrete institute (ACI). The substrate failure in the split tensile test is the primary mode of failure experienced by the specimens.

Carbonell et al. (2014) evaluated the bond characteristics between UHPC and NSC under varying stress configuration and environmental conditions. The authors conducted a splitting tensile test to determine the bond performance under severe conditions 0, 300, 600, and 900 of freeze-thaw cycles. Splitting tensile test result shows an increase in bond strength with increasing age of concrete, and excellent bond strength was achieved at 185days.

Tayeh et al. (2013a) investigated the interfacial bond characteristics between UHPFRC as a repair material and NSC as old concrete. Splitting tensile tests indicated that the substrate surface preparation has a significant influence on the mechanical bond strength, as shown in Table 2.

Tayeh et al. (2013b) investigated the relationship between the performance of bond strength between UHFPRC and NSC and the substrate roughness parameter. The splitting cylinder tensile test shows that wire brush WB and sandblasting SB surface preparation increased the bond strength by 40.9 and 95.8% when compared with As Cast AC.

Tayeh et al. (2013c) evaluated the performance of bond strength between UHPFRC and NSC against salt damage. Good bond strength was observed. The complete substrate failure observed during the test indicates a strong bond between the concretes.

Tayeh et al. (2012) investigated the mechanical properties and permeability characteristics of the interface between the NSC and UHPFRC. From the splitting test results, the interfacial bond strength is even more durable than the monolithic NSC, indicating compatibility between the NSC and UHPFRC.

DISCUSSION ON SPLITTING TENSILE TEST

In this review, different authors conducted splitting tensile tests to identify the effect of different conditions of the sample specimens on the bond strength. Sabah et al. (2019b) evaluated the effect of temperature, Baharuddin et al. (2016) identified the effect of damaged concrete under different moisture surface conditions, while Carbonell et al. (2014) investigated the effect of different freeze-thaw cycles. Therefore, the test method can be used under different conditions of test specimens. The result obtained from the experiment exceeded the minimum requirement by ACI 546-06. As shown in Table 2, all three failure modes were observed, indicating its capability to identify the effect of different surface preparations. The most common failure mode observed is B/C type, failure at substrate concrete, and part of the bond line, it indicates a moderate bond strength between NSC and UHPC. Figure 2 presents splitting tensile test results with different surface preparations. The test results can differentiate the effect of surface preparation on the bond strength at the interface, with grooving surface preparation have the highest bond strength of 8.37MPa.

SLANT SHEAR TEST

The slant shear test is the most widely accepted bonding strength test method in many international codes. The bond strength is evaluated by dividing the maximum load by bond area, as shown in Eq. (2).

$$f_n = {}^{P}\!/_{A_n} \tag{2}$$

f_n is the slant shear bond strength, A_n is the area of the slant bonding plane (in mm^2), P is the failure load (in N). The composite specimen- with a slant plane inclined vertically at an angle of 30^0 is employed, as stated in ASTM C882 for a slant shear test. Table 2 provides the minimum acceptable slant-shear and direct-tensile bond strengths according to ACI Concrete Repair Guide (Chynoweth et al. 1996).

Zhang et al. (2020a) investigated the bond characteristics between the NSC substrate and the UHPC layer. The authors conducted a slant shear test and evaluated the effect of strength of NSC, age of UHPC, and surface preparation of NSC, The interfacial bond strengths of the UHPC-NSC composite samples were higher than that of the NSC-NSC sample and close to the monolithic NSC specimen. The bond strength of NSC-UHPC developed at an early age and could reach the ultimate at 28days. Excessive curing temperature (90 ^{0}C) can lead to a decrease in the bond strength due to the rapid development of UHPC shrinkage.

Farzad et al. (2019c) developed a new numerical model for predicting a load capacity of the concrete composite where the substrate NSC is jointed with overlaid UHPC. The model was validated using a slant shear test, and the accuracy of the model is within an 18% error.

Jafarinejad et al. (2019) studied the performance of bond strength between UHPC and NSC. The authors examine the bond strength using the slant shear test. The test result shows that ultimate bond strength was achieved just three days after casting UHPFRC.

Sabah et al. (2019a) investigated the durability performance of the interfacial bond between the NSC as old and new GUSMRC as a repair material under the effect of elevated temperature of (100,200,300,400, and 500 ^{0}C). The authors performed a slant shear test at 7, 28, and 90days. The slant shear test can reflect the effect of temperature on the bond strength, and excellent bond strength was achieved at 28days, as shown in Table 3.

Sabah et al (2019b) investigated the interfacial bond strength between a newly developed GUSMRC as a repair material and NSC as a substrate. The authors performed a slant shear test at 7, 28, and 90days and achieved an excellent bond strength at 28days with complete substrate failure.

Baharuddin et al. (2016) investigated and compared the interfacial bond characteristics between fire-damaged reinforced concrete RC substrate and ultra-high-performance fiber-reinforced concrete (UHPFRC) as a repair material. The authors performed a slant shear to determine the interfacial bond strength of the composite under three surface moisture conditions. The result of the slant shear test shows the influence of moisture surface conditions. Saturated surface dry produced an excellent bond strength.

Carbonell et al. (2014) evaluated the bond characteristics between UHPC and NSC. The authors performed a slant shear test under several combinations of shear stresses. The slant shear test result shows that the bond strength at 8days is higher than the substrate strength.

Tayeh et al. (2013a) investigated the interfacial bond characteristics between UHPFRC as a repair material and NSC as old concrete. The authors conducted a slant shear test and evaluated the mechanical performance of the interfacial bond strength. The slant shear result of different surface preparation meets a minimum requirement set by ACI 2006, as shown in Table 3.

Tayeh et al. (2013b) investigated the relationship between the bonding performance of UHFPRC used as a repair material using a slant shear test. Three different surface preparation methods were evaluated. The slant shear

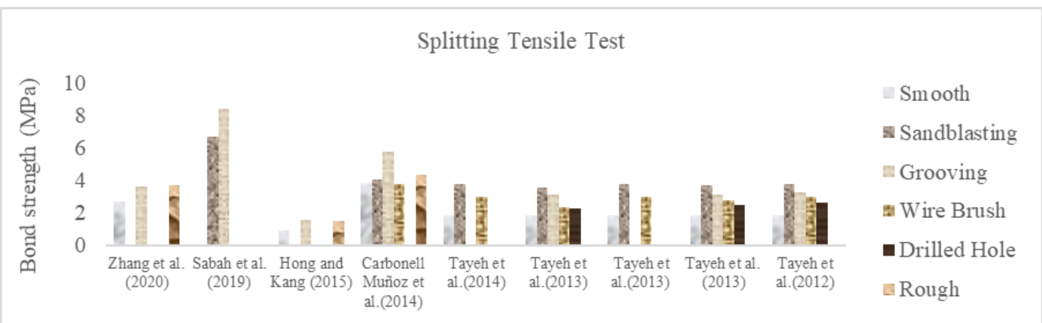

FIGURE 2. Splitting Tensile Strength of different surface preparations

TABLE 2. Summary of splitting tensile test

Study	Surface Preparation Technique	Sample Age (Day)	Bond Strength (MPa)	Failure Mode
Zhang et al. (2020a)	SM	28	2.77	B/C
	HR		3.70	C
	RD		3.73	B/C
	RG		3.65	C
Sabah et al. (2019a)	SB	28	6.69	C
	GR		8.37	B/C
Sabah et al.(2019b)	GR	28	8.37	C
	SB		6.63	C
Baharuddin, et al (2016)	SM	28	0.65	B
Hong and Kang (2015)	Gx	7	1.23	B/C
	Gy		1.57	B/C
	RO		1.51	B/C
	SM		0.94	B
Carbonell Muñoz et al. (2014)	SB	28	4.05	C
	WB		3.75	C
	GR		5.75	B/C
	SM		3.82	B/C
	CH		4.30	C
Tayeh et al. (2014)	SM	28	1.85	B/C
	WB		2.96	C
	SB		3.79	C
Tayeh et al.(2013a)	SM	28	1.82	B
	WB		2.33	B/C
	SB		3.53	B/C
	DH		2.28	B/ C
	GR		3.14	B/C
Tayeh et al.(2013b)	WB	28	2.96	C
	SM		1.85	C
	SB		3.79	B/C
Tayeh et al. (2013c)	SB	28	3.68	C
	WB		2.77	B/C
	GR		3.11	C
	DH		2.50	B/C
	SM		1.82	B
Tayeh et al. (2012)	SB	28	3.79	C
	WB		2.96	C
	GR		3.24	C
	DH		2.60	C
	SM		1.85	B

rough + drilled hole (RD), transverse grooving (Gx), longitudinal grooving (Gy), high rough (HR), rough + groove: (RG), rough (RO), smooth (SM), sandblasting (SB), wire brush (WB), grooving (GR), chips (CH), drilled hole (DH),

test result shows that wire brush WB and sandblasting SB surface preparation increases the bond strength by 41.43 and 103.6%, respectively, when compared with As Cast AC.

Tayeh et al. (2013c) evaluated the performance of bond strength between UHPFRC and NSC under the effect of salt damage. The authors conducted a slant shear test and quantified the bond strength in shear. Excellent bond quality is achieved as per the requirement of ACI 2006.

Tayeh et al. (2012) investigated the mechanical properties of the interface between the NSC and UHPFRC. The authors conducted a slant shear test to evaluate the interfacial bond strength and quantify the influence of various surface preparations. From the test results, shown in Table 3, the interfacial bond strength is even more durable than the monolithic NSC, indicating compatibility between the NSC and UHPFRC.

DISCUSSION ON SLANT SHEAR TEST

Table 3 presents a summary of the slant test conducted by different authors. The values of the bond strength obtained is higher when compared with the other testing methods, and this is due to the testing procedure. The interface of the specimens is subjected to combined shear stress and compressive stress, making the test results less consistent than the results obtained from the splitting tensile test. All three failure modes were observed. The most common failure mode observed is type C; the failure is mainly observed at the substrate close to the bond interface, which indicates a strong bond between the two concrete. Figure 3 presents the slant shear test results with different surface

TABLE 3. Summary of slant shear test

Study	Surface Preparation Technique	Sample Age (Day)	Bond Strength (MPa)	Failure Mode
Zhang et al. (2020a)	SM	28	13.93	B/C
	HR		24.59	C
	RD		25.10	C
	RG		25.39	C
Farzad et al. (2019)	SM	28	21.80	B
Jafarinejad et al. (2019)	SB		29.40	C
	GR		19.60	B
	WB		13.50	B
	SM		11.50	B
Sabah et al. (2019a)	GR	28	23.90	C
	SB		35.20	B/C
Sabah et al.(2019b)	SB	28	35.20	C
Baharuddin et al. (2016)	SM	28	3.25	B
	GR		23.90	C
Carbonell Muñoz et al.(2014)	SB	28	21.70	C
	WB		16.10	C
	GR		17.50	C
	RO		17.00	C
Tayeh et al.(2013a)	SM	28	8.47	B
	WB		11.65	B/C
	SB		17.17	C
	DH		11.10	B/C
	GR		13.89	B/C
Tayeh et al.(2013b)	SB	28	17.81	C
	WB		12.75	B/C
	SM		08.68	B
Tayeh et al.(2013c)	SB	28	17.74	C
	WB		12.15	B/C
	GR		13.63	B/C
	DH		11.99	B/C
	SM		08.39	B
Tayeh et al. (2012)	SB	28	17.81	C
	WB		12.75	B/C
	GR		13.92	B/C
	DH		12.27	B/C
	SM		08.68	B

rough + drilled hole (RD), high rough (HR), smooth (SM), sandblasting (SB), rough (RO), wire brush (WB), grooving (GR), drilled hole (DH),

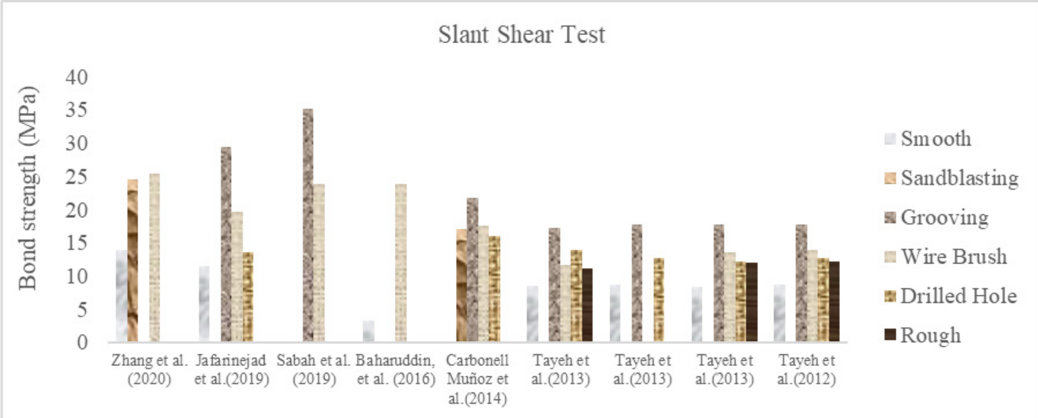

FIGURE 3. Slant Shear Strength of different surface preparations

preparations. The test results can differentiate the effect of surface preparation on the bond strength at the interface, with sandblasting surface preparation having the highest bond strength of 35.2MPa.

DIRECT SHEAR TEST

This method provides broad information on bond strength, but it is not widely used in the past because of some technical difficulties in the experimental setup. The technique is commonly used in Rock mechanics based on the procedure provided by ASTM D5607 can also be carried out based on (Leichnitz 1985; Saiang et al. 2005). In the direct shear test, normal and shear stresses are applied to the composite interface, making the normal stress at a fixed value while gradually increasing the shear stress. The relationship between the shear strength τ of the composite concrete, the adhesion stress C, the internal friction angle ϕ, and the normal stress σ_N is obtained from Eq. (3).

$$\tau = C + \tan(\phi).\sigma_N \tag{3}$$

Zhang et al. (2020a) investigated the bond characteristics between the NSC substrate and the UHPC layer. The authors conducted a direct shear test to evaluate the bond strength in shear. The interfacial bond strengths of the UHPC-NSC composite samples were higher than that of the NSC-NSC sample and close to the monolithic NSC specimen.

Zhang et al. (2020b) investigated the shear properties of the UHPC-NSC interface. The authors conducted a double-sided direct shear test and determined the shear failure mode of the UHPC-NSC interface. The UHPC-NSC interface exhibited a desirable bond behavior. In most of the specimens, the failure mode is either partial interface failure and partial NSC failure or complete NS, as shown in Table 4. The shear strength of UHPC-NSC can reach up to 90% of its ultimate shear strength at the age of 7days. The steam curing of UHPC can reduce the shear strength of the UHPC-NSC interface by 12.9%. The addition of the expansion agent on UHPC slowed down the development of shear capacity at the interface.

Farzad et al. (2019c) conducted a direct shear test to validate the numerical model developed to predict the load capacity of the concrete composite structure where the substrate NSC is repaired with overlaid UHPC. The accuracy of the numerical model is within an 18% error.

Jafarinejad et al. (2019) studied the performance of bond strength between UHPC and NSC. The authors examined the bond strength using direct shear and evaluate the effectiveness of four different substrate surface preparation, as shown in Table 4. The ultimate bond strength was achieved just three days after casting UHPFRC.

Hong and Kang (2015) investigated the interface bond strength of the UHPC-NSC. The direct shear test shows that increasing the temperature during UHPC curing decreases the bond strength between the concretes.

DISCUSSION ON DIRECT SHEAR TEST

The direct shear test is used to determine the bond strength between UHPC and NSC. The test offers the most conservative measured bond strength because of the absence of influence caused by friction or other stresses in the other test methods. Table 4 presents the result of the direct shear test. The result obtained from the experiment exceeded the minimum requirement by ACI 546-06. All three-failure mode was observed. The predominant failure mode observed under the direct shear test is B/C type, failure at substrate concrete, and part of the bond line. These indicate a moderate bond strength between NSC and UHPC.

BI-SURFACE SHEAR TEST

The bi-surface shear test is easy to construct, and it does not require any special equipment to perform; the standard cubic specimens used for the experiment is built based on ASTM C39. The added UHPC and NSC are 1/3 and 2/3, respectively. The bond strength can be calculated from Eq. (4).

TABLE 4. Summary of Direct shear test

Study	Surface Preparation Technique	Sample Age (Day)	Bond Strength (MPa)	Failure Mode
Zhang et al. (2020a)	SM	28	2.18	B/C
	RO		2.76	C
	RD		2.45	B/C
	RG		2.54	C
Zhang et al. (2020b)	SM	28	4.24	B/C
	RO		6.55	C
	GR		5.95	B/C
	DH		5.50	B/C
	PR		6.12	B/C
Farzad et al. (2019)	SM	28	6.20	B
Jafarinejad et al. (2019)	SB	28	7.81	C
Hong and Kang. (2015)	GR	7	7.20	B/C
	RO		4.46	B/C
	SM		1.61	B

rough (RO), post-installed rebar (PR), smooth (SM), sandblasting (SB), grooving (GR), drilled hole (DH),

$$\tau = \frac{P}{2bd} \quad (4)$$

where τ: bond strength, P: failure load for specimen, b: width of the cube cross-section, d: depth of the cube cross-section.

Valikhani et al. (2020) investigated the bond strength between UHPC and NSC with different surface preparation. The authors conducted a bi-surface shear test on thirty (30) samples with different surface preparation, including roughness degree, mechanical connector, and a bonding agent. The bi-surface shear test results show that with or without a mechanical connector, provided there is adequate roughness; the failure mode can transfer into the substrate concrete, indicating a strong bond existing between the NSC and UHPC.

DISCUSSION ON BI-SURFACE SHEAR TEST

The bi-surface shear test is used to evaluate the performance of the bond under direct shear. The difference between the bi-surface and direct shear test is that, in the bi-surface test, the standard test specimens are $153mm^3$, according to ASTM C39. However, there is a need to compare the results with other published results to verify its compatibility. All three-failure modes were observed, and the value of bond strength reflects the result obtained from other bonding test methods.

THIRD-POINT FLEXURAL TEST

The third point flexural test is used to evaluate the bond strength of a composite joint that is purely in tension using a procedure described in ASTM C78.

Farzad et al. (2019c) developed a new numerical approach of predicting a load capacity of the concrete composite structure where the substrate NSC is jointed with overlaid UHPC at the interface between the two concrete. The modeling technique used the interface plane between the concrete layers.

To validate the model, the authors conducted a third-point flexural test on a series of composite specimens to characterize the bond performance between UHPC and NSC. The accuracy of the proposed model is within 18% error when the bond is in shear tension compared to the Tie model of more than 150%.

Sabah et al. (2019a) investigated the durability performance of the interfacial bond between the NSC as old, and GUSMRC under a severe condition of high temperature. The test result shows excellent bond strength between GUSMRC and damaged substrate concrete shown in Table 5.

Li and Rangaraju (2016) investigated the performance of bond strength between UHPC and precast NSC. The authors perform a third-point flexural to assess the influence of different degrees of surface roughness. The third point flexural test happens to be more convenient and realistic for the bond test, and 10 seconds of sandblasting are enough to achieve a required bond strength between UHPC and NSC just seven days after casting the UHPC.

DISCUSSION ON THIRD-POINT FLEXURAL TEST

The third-point flexural test which evaluates the performance of bond in flexural tension is not widely used, as shown in Table 5. This is because the technique is recently developed and not been used to study the performance of the bond strength. Only two failure modes were observed: (B) and (C). The bond strength value is sensitive to different surface preparations. One advantage of bi-surface shear and third-point flexural is that the test set up is easy and requires no special equipment. However, there is a need to further investigate the method through many experimental results under different conditions to check the reliability of the test result. Irrespective of the bond strength testing technique, and surface preparation, except for a smooth surface, all the bond strength meets the minimum requirement set by ACI.

PULL-OFF TEST

The pull-off test is used to estimate the bond strength of composite concrete under pure tension and is carried out according to ASTM C1583. The method is straightforward, and many researchers widely use it. The tensile strength of the bond can be estimated by Eq. (5).

$$P = F/A \quad (5)$$

P is the bond or tensional strength of the specimens, F is the maximal tensional force, A is the cross-sectional area of the specimens.

Jafarinejad et al. (2019) studied the performance of bond strength between UHPC and NSC. The authors examined the bond strength using the pull-off test. Weak bond strength was observed by using wire surface preparation.

Sabah et al. (2019a) investigated the durability performance of the interfacial bond between the NSC as old, and GUSMRC as a repair material under the effect of elevated temperature, only pure substrate failure was observed using Pull-off test as shown in Table 7.

Sabah et al (2019b) investigated the interfacial bond strength between a newly developed GUSMRC as a repair material and NSC as a substrate. The pull-off strength is good, according to Table 6, and complete substrate failure was observed.

Carbonell et al. (2014) evaluated the bond characteristics between UHPC and NSC. They conducted a pull-off test and measured the bond strength. The bond performance exceeds the recommended capacity required by ACI 2006.

Tayeh et al. (2014) investigated the bond strength between UHPC and NSC using the Pull-off test. The test results revealed that all failures occurred in the substrate, regardless of the substrate surface roughness.

DISCUSSION ON PULL-OFF TEST

Table 7 presented a pull-off test result with bond strength values and failure modes. The result obtained from the experiment exceeded the minimum requirement by ACI 546-06, except for two results from Jafarinejad et al. (2019), this is due to the effect of surface preparation. Therefore, the test method is highly sensitive to surface preparations.

TABLE 5. Summary of Bi-surface and Third-point flexural test

Study	Surface Preparation Technique	Sample Age (Day)	Bi-surface (MPa)	Third-point flexural (MPa)	Failure Mode
Valikhani et al. (2020)	SM	28	2.80		B
	SB		6.30		C
	SB + MC		7.40		C
	SM + BA		2.40		B/C
	SB + BA		3.20		B/C
Farzad et al. (2019c)	SM	28		2.80	B
Sabah et al. (2019a)	SB			5.52	C
	GR			5.86	C
Li and Rangaraju et al. (2016)	SB	28		6.80	C
	SM			4.40	B
	SW			6.20	B

mechanical connector (MC), bonding agent (BA), groove (GR), sandblasting (SB), smooth (SM), sawed (SW),

TABLE 6. Minimum acceptable slant-shear and direct tensile bond strengths test according to ACI Concrete Repair Guide(Chynoweth et al. 1996)

Experiment	Days	Bond strength (MPa)
Slant shear	1	2.76–6.9
	7	6.9–12.41
	28	12.41–20.68
Direct shear (Pull-off Test)	1	0.5–1.0
	7	1.0–1.7
	28	1.7–2.1

TABLE 7. Summary of Pull-off Test

Study	Surface Preparation Technique	Sample Age (Day)	Bond Strength (MPa)	Failure Mode
Jafarinejad et al. (2019)	SB	28	3.67	C
	GR		2.72	B
	WB		0.55	B
	SM		0.59	B
Sabah et al. (2019a)	SB	28	3.57	C
	GR		3.08	C
Sabah et al. (2019b)	SB	28	2.57	C
	GR		2.31	C
Carbonell Muñoz et al. (2014)	SB	28	2.30	C
	WB		2.20	C
	GR		2.60	C
	RO		2.40	C
Tayeh et al. (2014)	SM	28	2.30	C
	WB		2.32	C
	SB		2.34	C
Tayeh et al. (2013)	SB	28	2.34	C
	WB		2.32	C
	SM		2.30	C

CONCLUSIONS

Many authors adopt various types of bond strength testing techniques to evaluate bond strength between the UHPC and NSC. From the papers reviewed, the typical test method used to assess the bond performance between substrate NSC and UHPC is the slant shear test and splitting tensile test.

The effectiveness and accuracy of slant shear, splitting tensile, pull-off, direct shear, bi-surface shear, and third-point flexural tests on the bond strength are reviewed. Splitting tensile tests provides more accurate results than the slant shear test. The direct shear test offers broad information on bond strength. However, it is not commonly used due to its technical difficulties because, initially, it was not meant for concrete but applied in rock mechanics. From the result, only two failure modes were observed from the pull-off test method. Bi-surface shear test and third-point flexural tests are easy to conduct and give a result similar to splitting and direct shear. However, further investigation is required on the reliability of the test method under different conditions.

DECLARATION OF COMPETING INTEREST

None.

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