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Mechanical properties of old concrete—UHPFC interface

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ABSTRACT: This investigation was aimed at assessing the bond strength between Ultra-High Performance Fiber Concrete (UHPFC) as a repair material and Normal Concrete (NC) substrate as a mature concrete in existing structures. Splitting tensile strength and slant shear tests were performed to quantify the bond strength in indirect tension and shear, respectively. The correlation between splitting tensile strength and slant shear was assessed. It is found that UHPFC gives high bond strength at the early age of the repair process, and interacts strongly with the surface of the substrate; as a result, the failure occurred mostly in the substrate. A good correlation was obtained between the slant shear strength and the splitting tensile strength.

1 INTRODUCTION

In this modern era, a highly developed infrastructure is vital for economic growth and prosperity of mankind. In many nations throughout the world, a lot of structures that constitute the whole infrastructures, especially those made of reinforced concrete, have suffered severe degradation which for some cases commenced shortly after construction due to the combined effects of aggressive environments such as freeze–thaw cycles, deicing salts, marine exposure and significantly increasing live loads. Hence, some of the most important challenges faced by today's civil engineers are to save, retrofit and maintain these deteriorated structures. Implementation and development of new, efficient, as well cost-effective rehabilitation and repair methods are required to extend the useful service life of the deteriorated structures (Green, Bisby, Beaudoin, & Labossière, 2000).

The extremely low permeability of UHPFC which concurs with their outstanding mechanical properties supports the main idea of using UHPFC to rehabilitate and strengthen the zones where the concrete structures are exposed to high mechanical loading and severe environmental exposures. All other parts of the structures remain in normal structural concrete as these parts are subjected to relatively reasonable exposure (Brühwiler & Denarié, 2008; Brühwiler, Denarié, & Habel, 2005).

In the field of rehabilitation and strengthening, the bond strength between the new repair material and old concrete generally presents a weak link in the repaired structures (Momayez, Ehsani, Ramezanianpour, & Rajaie, 2005). Good bond is one of the main requirements for successful repair (Gorst & Clark, 2003). UHPFC could be used as a repair material as it has strong mechanical bond, which is formed between the UHPFC as an overlay material and the substrate material (Sarkar, 2010) and (Harris, Sarkar, & Ahlborn, 2011).

The main purpose of this paper to evaluate the bond strength between UHPFC as the repair material and normal concrete (NC) substrate as old concrete using the splitting tensile test and slant shear test to quantify the bond strength in indirect tension and shear, respectively, also to examine if there is a correlation between the splitting tensile strength and slant shear strength.

2 EXPERIMENTAL PROGRAMME

2.1 *Normal concrete substrate and UHPFC properties*

The mix design of the NC used in this study ensures an average characteristic compressive strength of 45 MPa is achieved at 28 days. The NC used contains Type-I ordinary Portland cement, river sand with fineness modulus of 2.4, coarse aggregate (granite) with a maximum size of 12.5 mm, a water-to-cement ratio of 0.5 and a slump value of between 150–180 mm. The mix proportions of the NC substrate are presented in Table 1. The control specimens used consists of (i) 100 mm diameter by 200 mm high cylinder for the splitting indirect tensile strength test and (ii) 100 mm × 100 mm × 300 mm tall prism for uniaxial compressive strength test. The NC was tested for 28 days strength and experimental results showed that the NC has an average splitting tensile strength and compressive strength of 2.75 MPa and 38 MPa, respectively.

The mix proportions of the UHPFC which was used as a repair material are given in Table 2. The UHPFC contains Type-I Portland cement, densified silica fume, well graded sieved and dried mining sand, high strength micro-steel fiber and polycarboxylate ether based (PCE) superplasticizer. The steel fiber used has a fiber length and fiber diameter of 10 mm and 0.2 mm, respectively, and the steel fiber has ultimate tensile strength of 2500 MPa. The UHPFC achieved an average 28 days cube compressive strength, $f_{cu} = 170$ MPa.

2.2 *Specimens preparation*

Each of the tested specimens comprised of two different materials, being the NC as a substrate and UHPFC as a repair material. The fresh NC was covered and left to set in the respective moulds for 24 hours after casting. After 24 hours the NC specimens were demoulded and were cleaned and cured for another two days in a water curing tank. At the age of three days, the NC substrate specimens were taken out from the water tank for surface preparation. In this study, the experimental parameter is the surface texture of the substrate. Five different types of surfaces were prepared, which are (i) as cast, without roughening (AC), (ii) sand blasted (SB), (iii) wire brushed (WB), (iv) drilled holes (DR) and (v) grooved (GR).

Figure 1 shows the different surfaces of the NC substrate specimens after undergoing surface preparation. These specimens represent the first-half of the substrate for the slant shear test. Prior to casting the UHPFC onto this roughened NC surface, the NC specimens were further cured in a water tank until the age of 28 days since the casting date. At the age of 28 days, the NC substrate specimens were left to dry for two months.

Before casting the UHPFC, the surfaces of the NC substrate specimens were moistened for 10 minutes and wiped dry with a damped cloth. The NC substrate specimens were then placed into steel moulds with the slant side facing upward. Mixing of the UHPFC was carrying out using a pan type mixer. The moulds were then filled with the UHPFC.

Figure 2 shows the complete composite specimens for the split cylinder strength test and slant shear strength test. The composite specimens were steam cured for 48 hours at a temperature of 90°C. After the steam curing, it was cured in a water tank. The splitting tensile and slant shear tests were performed on the 3rd and 7th day after casting the composite specimens.

2.3 *Splitting tensile test*

The splitting tensile test, as an indirect tension test, was conducted to determine the bond strength between the NC substrate and UHPFC, according to ASTM C496. In this test procedure, UHPFC was cast and bonded to the NC substrate specimens to form a composite cylinder (100 mm diameter and 200 mm height) as shown in Figure 2a.

Table 1. NC substrate mix design.

Item	Mass (kg/m^3)	Remark
OPC	400	Type I
Coarse Aggregate	930	Max 12.5 mm
Fine Aggregate	873	
Water	200	
Superplasticizer	4	

Table 2. UHPFC mixture proportions.

Item	Mass (kg/m^3)
OPC	768
Silica Fume	192
Sieved Sand	1140
Micro-Steel Fiber	157
Superplasticizer	40
Free Water	144

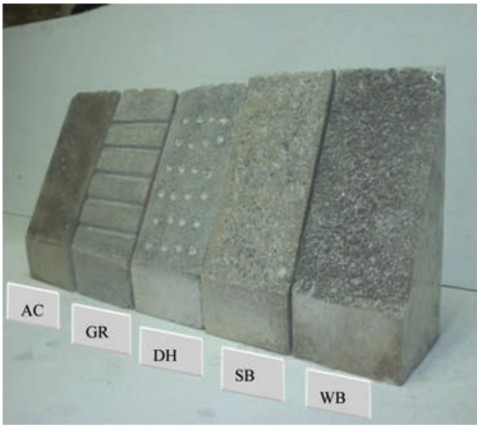

Figure 1. Slant shear test specimens with the different surface textures.

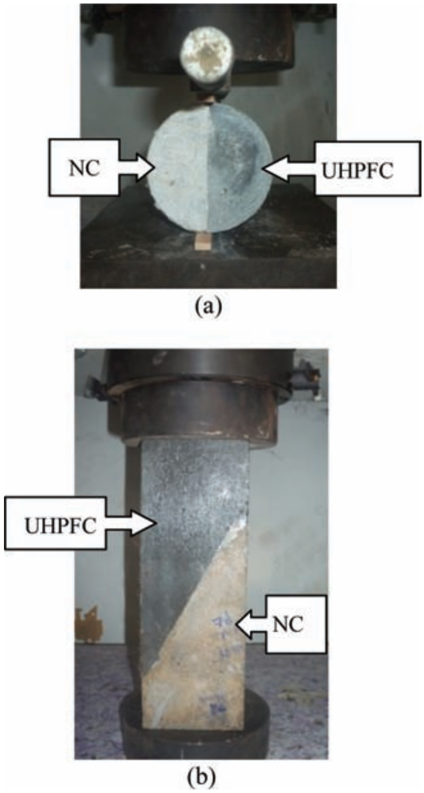

Figure 2. (a) Split cylinder specimen and (b) Slant shear test specimen.

2.4 *Slant shear test*

The slant shear test was used in this study to determine the bond strength between the NC substrate and the UHPFC, according to ASTM C 882. Following this test procedure, UHPFC was cast and bonded to the NC substrate specimens on a slant plane inclined vertically at a 30° angle to form composite prism specimens (100 mm × 100 mm × 300 mm) (Figure 2a.).

3 DISCUSSION OF RESULTS

3.1 *Split tensile test*

The splitting tensile test provides a measure of the indirect tensile capacity of the composite interface. The splitting tensile strength was calculated using the following equation:

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

where T is the splitting tensile strength (in MPa); P is the maximum experimental force (in kN); and A is the total area of the bonded plane (in mm^2) which is taken as 200 mm × 100 mm = 20,000 mm^2.

The splitting tensile strength test results are summarized in Table 3. As shown in Figure 3, the failure modes generally can be categorized into three types; Type A is a pure interfacial failure; Type B is an interfacial failure with partial substrate failure and Type C is substratum failure. The test results show that the bond strength result from UHPFC generally was very good, since most failure occurred in the NC substrate.

According to Sprinkel & Ozyildirim (2000), the interfacial bond strength test results may be classified as follows (Table 3):

As shown in Table 4, all the surfaced prepared specimens fall in the category of "excellent bond," where the average splitting tensile strength (T_{av}) was the highest for the samples with sand-blasted surface preparation. The samples with as cast (AC) surface exhibit the lowest bond strength among the test where its average splitting tensile strength was 1.67 and 1.82 MPa at 3rd and 7th days, respectively.

3.2 *Slant shear test*

Where the interface is subjected to the shear stress or the combination of shear stress and compression forces, the slant shear test is the most appropriate test for such bond assessments. Over the year, this test method has become the most widely accepted method and has been adopted by a number of international codes. The bond strength based on the slant shear test was calculated by dividing the maximum load by the bond area which can be expressed as:

$$S = \frac{P}{A_L} \quad (2)$$

Where S is the bond strength (in MPa); P is the maximum force recorded (in kN), and A_L is the area of the slant surface (in mm^2). In this case, the slant surface area is taken as 100 × 100 /sin 30° = 20,000 mm^2.

Table 3. Classification of bond strength.

Bond Quality	Bond Strength (MPa)
Excellent	≥ 2.1
Very Good	1.7–2.1
Good	1.4–1.7
Fair	0.7–1.4
Poor	0–0.7

Figure 3. Types of split tensile failure.

Table 4. Split tensile strength and failure type of composite NC and UHPFC specimens.

Surface preparation	Sample no.	Max. Force (kN)	T (MPa)	Average T_{av} (MPa)	S.D. (MPa)	Failure Mode	Max. Force (kN)	T (MPa)	Average T_{av} (MPa)	S.D. (MPa)	Failure Mode
		Test results at 3 days					*Test results at 7 days*				
As cast surface	AC1	56.95	1.81			A	58.756	1.87			A
	AC2	48.714	1.55	1.67	0.13	A	61.28	1.95	1.82	0.16	B
	AC3	52.057	1.66		[7.88]	A	51.796	1.65		[8.57]	A
Grooved surface	G1	96.43	3.07			C	98.67	3.14			C
	G2	85.70	2.73	3.03	0.29	C	90.074	2.87	3.14	0.26	C
	G3	103.75	3.30		[9.53]	C	106.61	3.40		[8.40]	C
Drill holes surface	DH1	78.13	2.49			B	73.875	2.35			C
	DH2	88.44	2.82	2.46	0.37	B	60.906	1.94	2.28	0.31	B
	DH3	65.05	2.07		[15.18]	B	79.875	2.54		[13.55]	C
Sandblast surface	SB1	105.28	3.35			C	103.88	3.31			C
	SB2	120.59	3.84	3.55	0.26	C	130.5	4.16	3.53	0.55	C
	SB3	108.49	3.46		[7.25]	C	98.371	3.13		[15.49]	C
Wire brush surface	WB1	70.60	2.25			C	62.5	1.99			B
	WB2	66.02	2.10	2.32	0.27	B	81.324	2.59	2.33	0.31	C
	WB3	82.251	2.62		[11.47]	C	76.029	2.42		[13.25]	C

T = Splitting tensile strength; S.D. = standard deviation; [ ] = Coefficient of variation

The experimental slant shear strength test results are presented in Table 5. Figure 4 shows the failure modes for the slant shear specimens which can be categorized into four types, that Type A is the interfacial bond failure; Type B is the interfacial failure and substrate cracks or small parts broken; Type C is the interfacial failure and substrate fracture, and Type D is the substratum failure. As shown in Table 5, the average slant shear test was the highest in samples with sand blasted substrate S_{av} = 17.18 and 17.17 MPa at 3rd and 7th days, respectively.

The ACI Concrete Repair Guide specifies the acceptable bond strength for repair work shall be within the ranges of 6.9–12 MPa for slant shear strength at test ages 7 days (Chynoweth et al., 1996). This guideline is particularly useful for the selection of appropriate repair material. The test results surpass the required bond strength at 7 days, specified by this ACI guideline due to the higher bond between the NC and UHPFC which has been fully cured via accelerating steam curing method. Comparison shows that most of the slant shear strengths at 3rd and 7th days are within or greater the minimum range stipulated the ACI requirement at 7th day.

3.3 *Correlation between the slant shear strength and splitting tensile strength*

From Figure 5 and Figure 6, a good correlation between the slant shear test results and the splitting tensile test results could be observed, since the relationship between the slant shear strength and the splitting tensile strength is strongly correlated

Table 5. Slant shear strength and failure type of composite NC and UHPFC specimens.

Surface treatment	Sample no.	Max. Force (kN)	(S) Shear sterss (MPa)	Average shear stress (MPa)	S.D. (MPa)	Failure Mode	Max. Force (kN)	(S) Shear sterss) (MPa	Average shear stress (MPa)	S.D. (MPa)	Failure Mode
		Test results at 3 days					*Test results at 7 days*				
As cast surface	AC1	193.6	9.68	8.18	1.36	B	144.1	7.21	8.47	1.24	A
	AC2	157.1	7.86		[16.66]	B	170.3	8.52		[14.65]	B
	AC3	140.27	7.01			A	193.7	9.69			B
Grooved surface	G1	284.91	14.25	13.87	1.07	C	296.69	14.83	13.89	1.45	C
	G2	294.06	14.70		[7.71]	D	292.22	14.61		[10.41]	C
	G3	253.30	12.67			C	244.52	12.23			C
Drill holes surface	DH1	235.68	11.78	11.03	1.14	C	241.94	12.10	11.10	0.99	C
	DH2	194.38	9.72		[10.34]	B	202.34	10.12		[8.92]	B
	DH3	231.80	11.59			C	221.83	11.09			B
Sandblast surface	SB1	335.91	16.80	17.18	0.54	D	322.66	16.13	17.17	1.21	D
	SB2	351.13	17.56		[3.13]	D	370.06	18.50		[7.06]	D
	SB3	236.91	11.85			D	337.61	16.88			D
Wire brush surface	WB1	225.94	11.30	11.44	0.82	C	209.72	10.49	11.65	1.38	B
	WB2	246.38	12.32		[7.18]	C	263.34	13.17		[11.81]	C
	WB3	213.87	10.69			B	225.91	11.30			C

S.D. = Standard deviation, [ ] = Coefficient of variation, A = Interface failure, B = Interface failure and substrate cracks, C = Interface failure and substrate fracture, D = Substratum failure

Figure 4. Types of slant shear failure.

by a linear relationship at all test ages, where $R^2 = 0.9742$ and 0.9625 for testing ages of 3 and 7 days, respectively.

4 CONCLUSIONS

This paper reports the experimental results of the bond behaviour between normal concrete (NC) which is the substrate and UHPFC as a repair material using the slant shear test and splitting test to quantify the bond strength in shear and indirect tension, respectively. In the study, the NC and UHPFC used achieved 28 day compressive strength of 45 MPa and 170 MPa, respectively. The experimental parameter was the surface texture of the substrate. Five different types of surface preparations were used which are; (i) as cast without roughening, (ii) sand blasted, (iii) wire brushed, drilled holes and grooved surfaces. The following conclusions are drawn the experimental study.

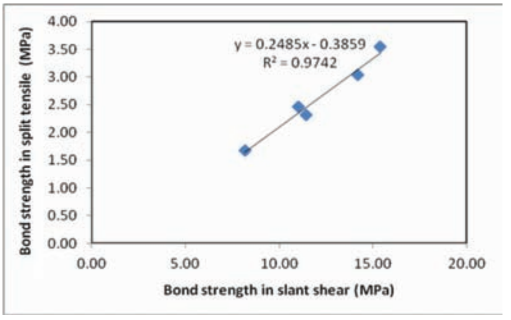

Figure 5. Correlation between slant shear test and split tensile test results at 3 days.

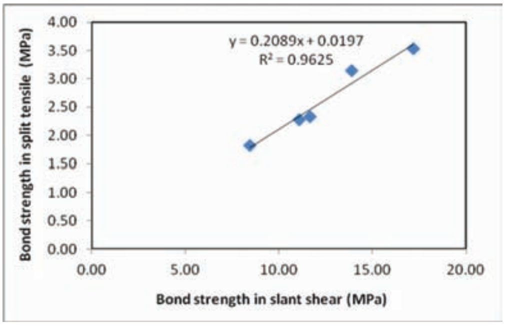

Figure 6. Correlation between slant shear test and split tensile test results at 7 days.

i. The result of the split cylinder test shows that the UHPFC overlays have "*excellent bond quality*" with the NC substrates as per the quantitative requirement. Since most of the failure modes in the split cylinder test wre through the NC substrate specimen, this indicates the bond strength between UHPFC and NC substrate is stronger than the cracking strength of the NC substrate.
ii. The results of the slant shear test show that the bond strength was very high since the interface failure occurred after the NC substrate exhibited damage. In some cases, the failure occurred only in the NC substrate and no separation between the NC substrate and the UHPFC which indicates the superior bond behaviour of the UHPFC.
iii. The results showed that there is a good correlation between the slant shear test results and the splitting tensile test results.
iv. Without sufficient statistical supporting evidence on the bond behaviour and types of surface preparation of the NC substrate, it is recommended (for the time being) that all the NC substrate surfaces shall be sand blasted prior to overlaying the UHPFC as a repair material.

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