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Evaluation of bonding performance of ultra high-performance concrete with fly ash content as overlay on normal strength concrete.

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Abstract. Ultra High-Performance Concrete (UHPC) has good mechanical strength and durability, so it can be the solution for an overlay material for old materials that need to be renewed. The problem with using UHPC as a construction material is the high price and sustainability, so a partial replacement for cement is required to reduce production costs, energy consumption, and CO_2 gas emissions. Bonding performance is an important parameter and must be considered when applying UHPC as an overlay material. The bonding performance test of the UHPC consists of three tests: the slant shear test, splitting tensile, and direct tensile/pull-off test. The results of this study were compared with the standards of ACI 546R-14 and M.M. Sprinkel & C. Ozyildirim. Based on the test results, replacing 40% of cement with fly ash on UHPC is good to use as an overlay because it meets applicable standards. The test results showed an increase of 27% in the slant shear test and 37% in the splitting tensile test compared to the existing standard. Replacing cement with fly ash in UHPC can also increase workability, reducing the need for superplasticizers, reducing UHPC production costs by 18.4%, energy consumption, and CO_2 emission problems.

1. Introduction

UHPC is concrete with compressive strength of more than or equal to 150MPa[1,2]. UHPC with compressive strength ranging from 130-150MPa is considered a lowered bound UHPC[1]. Four factors that decide the compressive strength of UHPC are the reduction of porosity, improvement of microstructure, increase in homogeneity, and increase in toughness[3]. UHPC is produced using a low w/b ratio, not using coarse aggregate, and supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granular blast furnace slag [4]. Adding a superplasticizer to UHPC reduces the w/b ratio, and the addition of steel fibers with a tensile strength of 200-2600 MPa prevents the development of cracks in the UHPC[5].

Bridge repair problems have become a problem for bridge owners. One of the solutions to this problem can be fixed by using a 25–52-mm or 1–2-inch thick UHPC overlay[6]. UHPC can potentially be a material solution for bridge repair because of its ability to withstand the frost effect, alkali-silica reaction, and abrasion[7]. According to the research of Ahmed J et al., bridge repair methods with overlay can use high-performance concrete (HPC), low-slump concrete (LSC), latex-modified concrete (LMC), and polymerbased concrete (PBC). These materials have drawbacks in the form of longevity, availability of materials, and price when compared to UHPC with a thickness of 25 mm [7].

With its excellent mechanical properties, UHPC is very suitable for use as a bridge overlay. On the other hand, the bonding performance between UHPC and NSC must meet some requirements. Some research evaluates the bond capability of UHPC and NSC. Harris et al. tested the bond capability by testing the material with slant shear, splitting tensile, and pull-off test to review the bond characteristics between UHPC and NSC, such as surface roughness, moisture degree, and the age of UHPC[8,9]. In conclusion, the bond performance between 2 materials performs well using UHPC. Hussein et al. performed a direct tensile test according to ASTM standards to determine the cohesion between UHPC-NSC with different NSC surface treatments[10]. Although several studies that focus on the bonding performance of UHPC-NSC have been conducted, the problems with UHPC are the high cost of its production and sustainability. For those reasons, further research is needed on the production of UHPC, which is cheap and environmentally friendly but has a strong bond performance.

Most of the construction work carried out is in the form of structural repairs[11]. UHPC is a material that can be used as a solution for repair methods due to its high strength and durability[11]. The high cost and its sustainability issues are the reasons why UHPC is not commonly used in the construction industry. The high price is caused by its constituent materials: cement, silica fume (SF), silica sand, superplasticizer, and fibers[12]. The replacement of cement with fly ash can be used. Fly ash is a waste from the combustion of steam power plants. According to the research of Bahedh et al., replacing cement with fly ash with a ratio of 0-40% can increase workability and compressive strength at 28 days [13]. According to Shah et al. research, adding fly ash up to 70% can increase workability, reducing the need for superplasticizer to acquire the desired flowability[12].

The replacement of cement with fly with ash can also be the solution to environmental issues. The production of UHPC has some problems in the form of high cement demand, high energy, and high CO_2 emissions[14]. According to Korpa et al., researching the hydration of UHPC, the low water content of UHPC causes a large amount of cement to remain unhydrated and be a filler UHPC[15], in which only around 30-40% of cement is hydrated, and the rest become a filler[14]. Therefore, replacing cement with fly ash as a filler can reduce the high use of energy and CO_2 emissions[16].

This study aims to test the mixture of UHPC containing 40% fly ash as an overlay whose bond performance is tested, and the result is compared to ACI 546-14[17] and M.M. Sprinkel & C. Ozyildirim[18]. The testing methods that were conducted are compressive, slant shear, splitting tensile, and direct tensile/pull-off. Factors affecting bond performance are roughness degree, moisture degree, and age of UHPC were analyzed for their influence.

2. Materials and Method

2.1. Mix proportion of material

2.1.1. NSC (substrate). NSC with a compressive strength of 40 MPa was made using Ordinary Portland Cement (OPC) sourced from PT. Solusi Bangun Indonesia with Specific Gravity (Gs) 3.11 and pH 11.8, coarse aggregate with a maximum diameter of 20 mm, and fine aggregate with a fineness modulus (FM) 2.9. The mix proportion can be seen in Table 2. NSC compressive strength was tested with cylindrical concrete with a diameter of 10 cm and a height of 20 cm based on the ASTM C39 standard [19].

2.1.2. UHPC. UHPC was made using OPC with Gs 3.11 and pH 11.8, fly ash used in this study was sourced from PLTU Paiton with X-ray Fluorescence (XRF) results shown Table 3, Silica Fume sourced from PT. SIKA Indonesia with Gs 2.14 and pH 6.54, Fine Sand with FM 3.01 and Gs 2.61, Steel Fiber with a diameter of 0.22 mm, length of 13 mm, Aspect Ratio 59 mm, and Tensile Strength 2500 MPa, and Sika® ViscoCrete-1003® superplasticizer. The mix proportion can be seen in Table 1. UHPC compressive strength tested with 50x50x50 mm cube mortar based on ASTM C109 standard [20].

Table 1. Mix proportion of UHPC.

	Water (kg/m^3)	OPC (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Fine Sand (kg/m^3)	Steel fiber (kg/m^3)	Superplasticizer (kg/m^3)
FA0	157.5	1050	0	210	1150	21	21.1
FA10	157.5	945	105	210	1150	21	19.0
FA20	157.5	840	210	210	1150	21	16.9
FA30	157.5	735	315	210	1150	21	14.8
FA40	157.5	630	420	210	1150	21	12.7

Table 2. Mix proportion of NSC.

Water (kg/m^3)	OPC (kg/m^3)	Coarse Aggregate (< 20 mm) (kg/m^3)	Fine Aggregate (kg/m^3)
0.4	470	1060	710

Table 3. Chemical composition of fly ash.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO_2	P_2O_5	SO_3	LOI
Fly ash Paiton, %	36.57	19.06	11.32	19.5	6.21	2.45	1.35	0.75	0.15	0.21	1.3	0.63

2.2. Specimens Preparation

As previously mentioned, in existing studies, some parameters affect bonding performance, as shown in Table 4. The NSC samples were made with a cylindrical shape with a diameter of 10 cm, height of 20 cm, and a beam measuring 10x15x60 cm. NSC samples were kept in saturated lime water for 28 days. After 28 days, the NSC will be prepared according to Figure 1, the NSC samples' surfaces were treated according to Figure 2. Once the NSC samples were ready, they were cured at room temperature 32±2°C for 28 days. NSC samples were treated according to 3 types of moisture. Air surface dry is a condition where the NSC substrate is in a completely dry condition. Air surface wet is where the NSC substrate is in a thoroughly wet condition. Saturated surface dry is a condition where NSC is wet, but the surface condition is dry. After that, the NSC samples were re-entered into the mold to pour UHPC overlays. Twenty-four hours after UHPC pouring, the mold was dismantled, and UHPC-NSC specimens were kept forseven7 days and 28 days in saturated lime water before being tested.

Table 4. Parameter of NSC surface and UHPC age for bond performance testing.

Parameter	Detail
Roughness degree	Smooth (Sm)
	Wired-brushed (WB)
	drilled hole (DH)
Moisture degree	Dry
	Wet
	Saturated-Surface-Dry (SSD)
Age of UHPC	7 Days
	28 Days

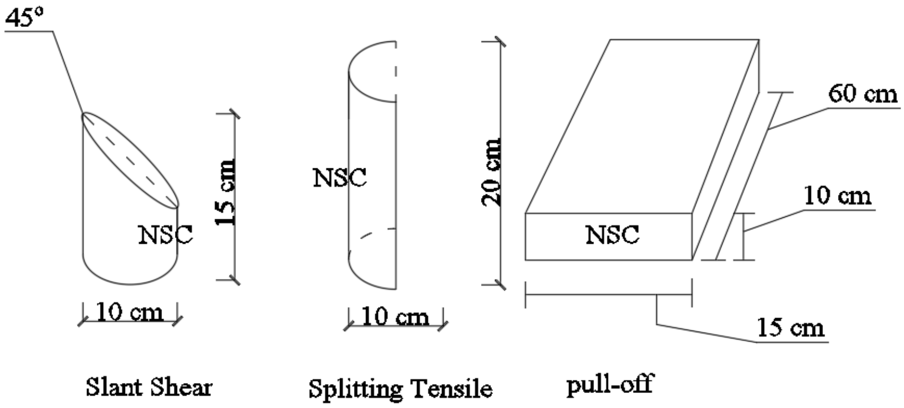

Figure 1. Preparation scheme of UHPC-NSC.

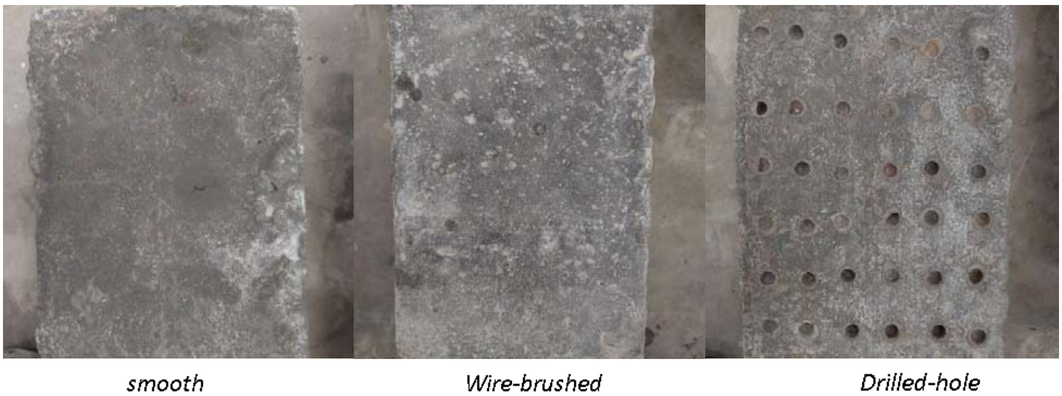

Figure 2. Roughness degree NSC.

2.3. Bond Strength Test

2.3.1. Slant Shear Test, according to ASTM C882 [21], the slant shear test was performed using a combination of compressive and shear stress. UHPC-NSC specimen testing was tested the same as cylinder compressive strength testing using a compressive strength machine such as Figure 3. The resulting compressive strength obtained can be converted into slant shear bond strength (f_n) using the equation as follows:

$$f_n = \frac{p}{A_n} \quad (1)$$

Where P is the Failure Load (N) and A_n is the area of the inclined plane (mm^2).

2.3.2. Splitting Tensile Test. Tensile strength is one of the essential things in bonding performance. The tensile strength of UHPC-NSC can be tested by splitting tensile test or what is commonly called indirect tensile test. According to ASTM C496 [22], the splitting tensile test is carried out by pressing the long part of the cylinder with bearing strips placed through the cylinder so that the spread of force from the compressive strength machine is evenly distributed, as in Figure 3. The load rate used for splitting tensile tests is 0.7-1.4 kN/s. The results obtained can be converted into splitting tensile bond strength (f_{sp}) using the equation as follows:

$$f_{sp} = \frac{2p}{\pi A_{sp}} \quad (2)$$

Where P is the Failure Load (N), and A_{sp} is the connection area (mm^2).

2.3.3. Direct tensile/pull-off test. A direct tensile/pull-off test is a test that has a conservative method due to the absence of friction force and other forces at the time of testing. According to ASTM C1583[23], the pull-off test was carried out by preparing a substrate that had been core-drilled with a diameter of 5 cm and 10 mm deep or more and then attached to a steel disk using an epoxy-resin-hardener. After the epoxy-resin-hardener is applied, tensile stress is applied to the steel disk until a failure occurs, as in Figure 3. The load rate used for pull-off testing is 5±2 Psi/s. Pull-off bond strength (f_t) can be calculated by using the equation as follows:

$$f_t = \frac{p}{A_t} \quad (3)$$

Where P is the Failure Load (kN) and At is the connection area (mm^2).

Slant-shear *Splitting Tensile* *Pull-off*

Figure 3. Slant shear, splitting tensile, and direct tensile/pull-off test.

2.4. Bonding Strength Standard

Based on the concrete repair method according to ACI 546R-14 [17], there is a minimum strength standard of slant shear test and direct tensile/pull-off test, which can be seen in Table 5. Bond quality evaluation of splitting tensile test and direct tensile based on M.M. Sprinkel & C. Ozyildirim [18] standard is presented in Table 6. The performance of a UHPC overlay layer against NSC is said to be successful if it has met the minimum standard required by the specified standards.

Table 5. Standard bond strength for slant-shear and direct-tensile bond strength [17].

	Bond Strength (MPa)		
	1 Day	7 Days	28 Days
Slant Shear	2.8-6.9	6.9-12	14-21
Direct Tensile	0.5-1	1-1.7	1.7-2.1

Table 6. Bond quality of splitting tensile and direct tensile test [18].

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

2.5. Failure Modes

The test of bonding performance in Figure 4 depicts three different failure modes. (a) Pure Interface Failure is a failure that occurs at the connection point. The surfaces of both materials remain smooth, and there is no cracking or fracturing in both material. (b) Partial interface failure is a failure that occurs in a combination of NSC failures that occur in the transition zone, and UHPC is still attached to the NSC. (c) Complete NSC substrate failure is a failure that occurs in the NSC section that has a fracture, and the UHPC-NSC material is still not separated.

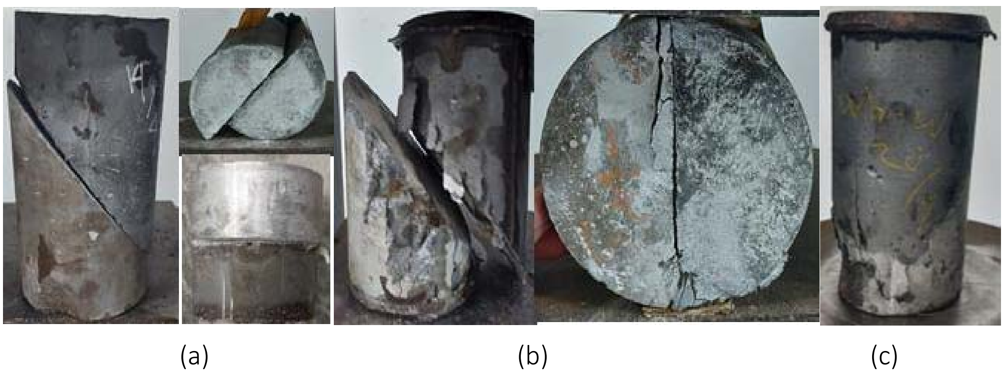

Figure 4. Failure modes: (a)B: Pure bonding failure(bond); (b)B/C: Partial bonding failure(bond-concrete); (c)C: NSC failure (concrete).

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3. Results and Discussion

3.1. Effect of cement substitution to fly ash

3.1.1. Compressive Strength. Evaluation of the compressive strength of UHPC with cement replacement with fly ash ranging from 0% to 40% is performed. Based on Figure 5, we can see the result of the compressive strength of the UHPC. Compared to FA0, the compressive strength on FA10, FA20, FA30, and FA40 decreased on day 7. This is due to the less reactive nature of fly ash, so it takes longer to reach the optimum compressive strength, so it can be seen that the compressive strength on days 28 and 56 has increased by 28%.

3.1.2 Cost Reduction. The cost of the materials utilized in UHPC was decreased by 4.6%, 9.2%, 13.8%, and 18.4%, respectively, for FA10, FA20, FA30, and FA40. The price change was observed to be quite significant due to the reduced use of cement and superplasticizers. The calculation of UHPC production costs per 1 m^3 can be seen in Table 7. The replacement of cement with fly ash can reduce CO_2 gas emissions and high energy use[16]. A mixture proportion of FA40 with cement replacement with fly ash by up to 40% can reduce CO_2 emissions and significant energy use.

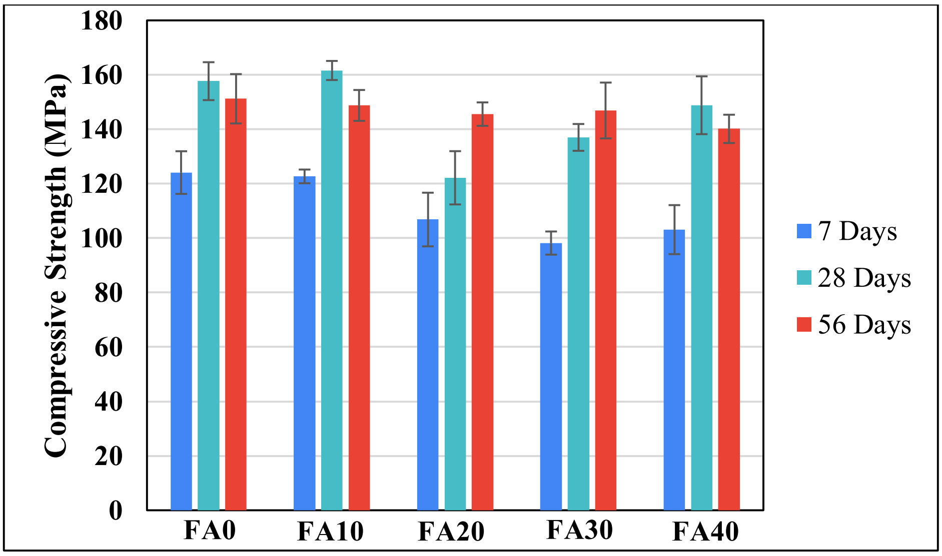

Figure 5. UHPC compressive strength.

Table 7. UHPC Production Cost per 1 m^3.

			Price/m^3 (IDR)				
Materials	Price/kg (IDR)		FA0	FA10	FA20	FA30	FA40
Cement	1.400	kg	1.470.000	1.323.000	1.176.000	1.029.000	882.000
Silica Fume	15.000	kg	3.150.000	3.150.000	3.150.000	3.150.000	3.150.000
Fine Sand	500	kg	575.000	575.000	575.000	575.000	575.000
Steel Fibre	37.620	kg	790.020	790.020	790.020	790.020	790.020
Superplasticizer	113.902	kg	2.403.327	2.164.133	1.924.940	1.685..746	1.446.552
	Total		8.388.347	8.002.153	7.615.960	7.229.766	6.843.572

3.2. Slant Shear Test Result

3.2.1. Failure modes. Table 8 lists several categories of failures for the slant shear test. The type of failure that occurs in 94% of slant shear test specimens is B/C and C. Except for Sm-Dry-7 conditions that experience failure type B. This is due to the absence of an interlocking system between UHPC-NSC under Sm-Dry conditions. On the other hand, WB and DH conditions have an interlocking system that strengthens bonding. Failure C occurs because the NSC disintegrates before the connection fails, indicating high bond strength.

3.2.2. Test result. The average slant shear test results are summarized in Table 8 and Figure 6, showing the effect of roughness degree, moisture degree, and Age of UHPC on bonding performance. 83% of specimens met the standards of ACI546R-14[17] even 78% of specimens met the 28-day bonding strength standard at seven days of age. The highest slant shear test results for bonding performance were in the DH-SSD-28 condition. WB and Wet conditions also had good results, with only a 10% difference in bonding strength between Wet and SSD and 18% between WB and DH. For Sm and Dry conditions, bonding strength obtained is relatively low, with a difference of 37% between Sm and WB, 50% between Sm and DH, 27% between Dry and Wet, and 32% between Dry and SSD. This is due to the condition of the DH surface, which provides an interlocking effect, and also the condition of the SSD, which prevents the transfer of water to the NSC from the UHPC so as not to reduce the water content of the UHPC and prevent poor hydration which can weaken the bonding performance of the UHPC-NSC. The UHPC age factor experienced an increase in bonding strength but was not significant, precisely 13%. This makes UHPC suitable as an overlay because it has a high bonding performance at an early age.

3.3. Splitting Test Result

3.3.1. Failure modes. Table 8 summarizes the various types of failures for splitting tensile tests. B/C and B failure types are 78% and 22% of the splitting tensile test specimens, respectively. This is because the splitting tensile test focuses on the indirect tensile stress method, so the failure is joint-centered.

3.3.2. Test result. The average splitting tensile test results summarized in Table 8 and Figure 7 show the effect of roughness degree, moisture degree, and Age of UHPC on bonding performance. In the splitting tensile test, 89% of the results were in the excellent category, and 11% of the results were in a good category, according to M.M. Sprinkel & C. Ozyildirim [18]. This is because 11% of the result is Sm-Dry conditions where the interlocking system is weak. There was a significant increase in bonding strength between WB, DH, Wet, and SSD conditions. This is due to the strong interlocking properties in these conditions. The difference in bonding strength of Sm conditions against WB and DH experienced a 30% and 26% increase. The bonding strength obtained improved by 34% and 37% for Wet and SSD conditions compared to Dry conditions. The bonding strength obtained for the UHPC age factor has increased by 10%. The UHPC has a high initial compressive strength. Hence the difference between bonding performance at 7 and 28 days is negligible.

3.4 Direct Tensile/pull-off Test Result

3.4.1. Failure modes. The type of failure in the pull-off test is the failure of the epoxy-resin-hardener connection with the steel disk, as shown in Figure 9. This is due to the lower tensile strength of the epoxy-resin-hardener than the UHPC-NSC bond strength so that the connection is loosened first. This causes the pull-off test results to be not good.

3.4.2. Test Result. The average pull-off test results are summarized in Table 8 and Figure 8, which show the effects of roughness degree, moisture degree, and UHPC age on bonding performance. The bonding strength results obtained are not good, do not meet the ACI standard 546R-14[17], and are classified as poor and fair according to M.M. Sprinkel & C. Ozyildirim [18] at 7 and 28 days. This phenomenon happened due to the weak epoxy-resin-hardener connection on the steel disk. Weakness of the epoxy-resin bond due to the presence of dust on the surface of the NSC [24].

Table 8. UHPC-NSC bond performance test result.

Sample	Slant Shear			Splitting Tensile			Pull-off		
	f_n (MPa)	stdev	failure mode	f_{sp} (MPa)	stdev	failure mode	f_t (MPa)	stdev	failure mode
Sm-Dry-7	3.20	0.87	B	1.61	0.04	B/C	0.46	0.21	Epoxy
Sm-Dry-28	9.61	0.16	B/C	1.79	0.20	B/C	1.06	0.01	Epoxy
Sm-Wet-7	13.57	2.99	B/C	3.37	0.25	B	0.51	0.25	Epoxy
Sm-Wet-28	14.09	0.39	C	4.22	0.32	B/C	1.69	0.14	Epoxy
Sm-SSD-7	15.91	0.94	C	3.80	0.34	B/C	0.26	0.04	Epoxy
Sm-SSD-28	15.24	0.43	C	3.41	0.22	B/C	1.67	0.08	Epoxy
WB-Dry-7	19.18	3.39	B/C	3.48	0.76	B	0.49	0.02	Epoxy
WB-Dry-28	18.14	0.31	C	3.16	0.15	B/C	1.52	0.18	Epoxy
WB-Wet-7	21.13	1.76	C	4.50	0.31	B/C	0.47	0.19	Epoxy
WB-Wet-28	17.46	0.08	C	4.55	0.00	B/C	1.49	0.07	Epoxy
WB-SSD-7	20.65	0.71	C	4.83	0.12	B/C	0.85	0.23	Epoxy
WB-SSD-28	18.50	0.18	C	4.96	0.10	B/C	1.25	0.02	Epoxy
DH-Dry-7	17.61	0.12	B/C	3.23	0.55	B	0.54	0.25	Epoxy
DH-Dry-28	19.43	0.32	B/C	3.37	0.29	B/C	1.22	0.03	Epoxy
DH-Wet-7	20.51	2.10	C	3.92	0.19	B	0.71	0.20	Epoxy
DH-Wet-28	27.53	1.21	C	4.55	0.00	B/C	1.34	0.33	Epoxy
DH-SSD-7	26.25	1.54	C	4.06	0.65	B/C	0.56	0.02	Epoxy
DH-SSD-28	28.89	2.50	C	4.96	0.10	B/C	1.12	0.29	Epoxy

Each test specimen is given a notation in the form of moisture degree (Dry, Wet, and SSD), roughness degree (Sm = Smooth, WB = Wired-brushed, DH = Drilled Hole), and UHPC age (7, 28). (B = Pure bonding failure (bond), B/C = Partial interface failure (bond and concrete), and C = NSC failure (concrete).

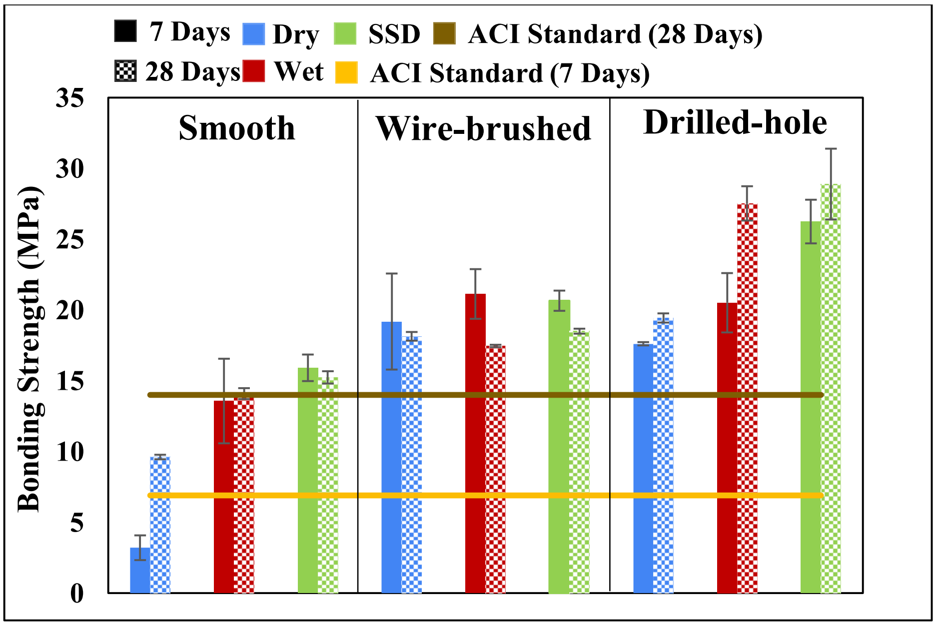

Figure 6. Slant shear test result.

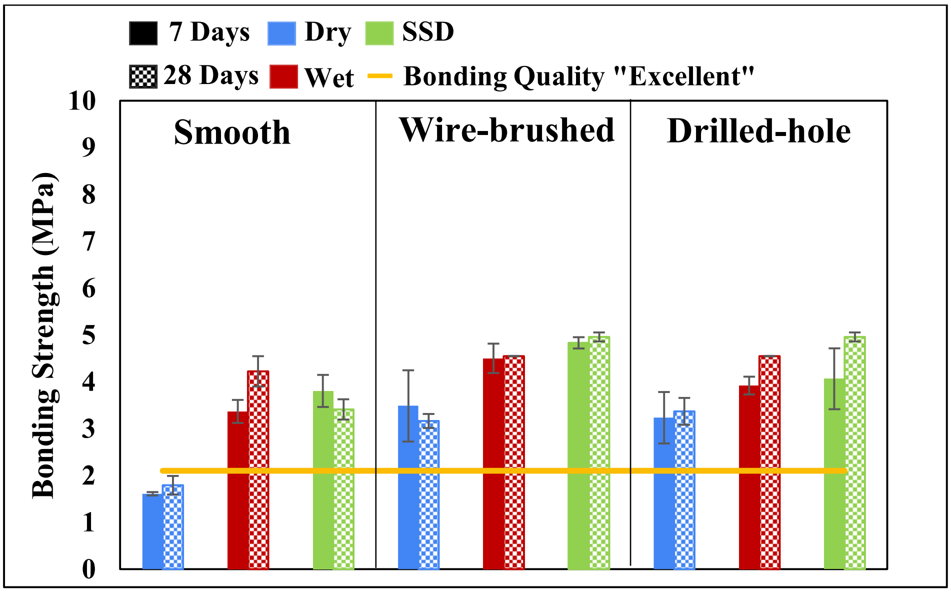

Figure 7. Splitting tensile test result.

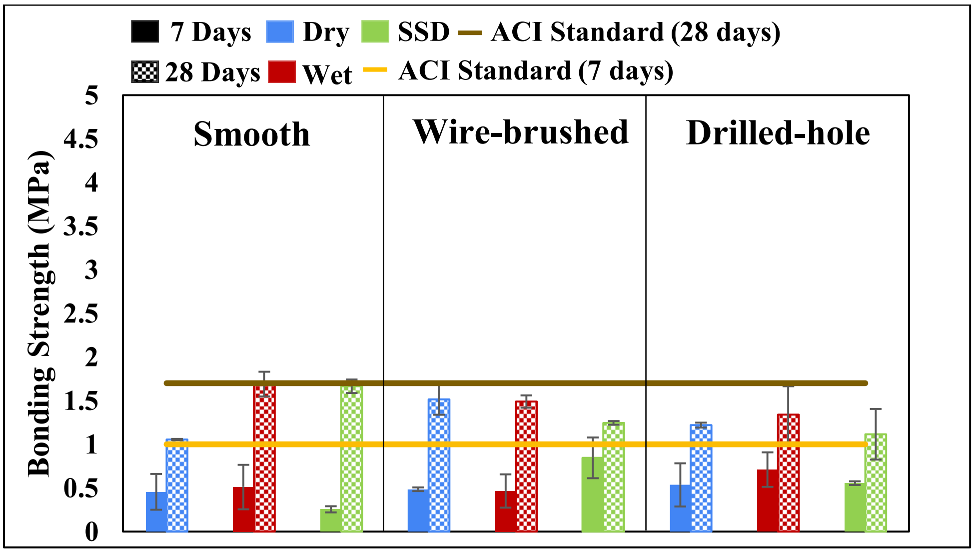

Figure 8. Pull-off test result.

Figure 9. Epoxy failure at steel disk.

4. Conclusion

The manufacture of UHPC with partial replacement of cement by fly ash was carried out to determine its effect on overlay on NSC in terms of bond performance: slant shear test, splitting tensile test, and pull-off test. From the discussion of the test results, the conclusions obtained are as follows:

1. This research was carried out by making UHPC with a water to binder ratio of 0.15, a replacement of 40% of cement with fly ash, the addition of 2% steel fiber, and the addition of 20% silica fume. The results showed that the compressive strength of mortar was 103.12 MPa, 148.82 MPa, and 144.14 MPa at 7, 28, and 56 days, respectively. There was a decrease in the compressive strength of mortar using a replacement rate of 40% cement with fly ash at the ages of 7, 28, and 56 by 16.89%, 5.6%, and 6.3% when compared to the mixture without cement replacement. The decrease in strength was caused by the slow hydration process of the material and the pozzolanic reaction due to the high amount of fly ash.
2. With reduced use of cement and superplasticizers, the impact of partial replacement of cement by fly ash can significantly reduce production costs. In terms of reducing production costs for UHPC, the cost reduction is 18.4% by replacing 40% cement with fly ash compared to the mixture without cement replacement.
3. Roughness degree, moisture degree, and age of UHPC significantly affect the bond performance of UHPC-NSC. DH and WB are surface conditions that give the strongest bond, while Sm has the weakest bond. The increase in bond strength from Sm to WB and DH conditions was 28% and 37%, respectively. Wet and SSD are humidity conditions with the most robust adhesion, while Dry conditions are the weakest bonding. The increase in bond strength from Dry to Wet and SSD conditions was 30% and 28%, respectively. Bonding performance at the age of 28 days increased by 12% compared to the age of 7 days due to the saturated lime water curing process, which prevents shrinkage and increases the compressive strength of UHPC.
4. The bond strength of UHPC-NSC with a cement replacement rate of 40% with fly ash is very strong. 83% of the results met the minimum bond strength standard, and 89% were categorized as "Excellent" based on the bond quality standards. In fact, in DH-SSD-7, DH-SSD-28, and DH-Wet-28, the bond strength exceeded the minimum requirements of 25%, 37.6%, and 31.1%.
5. 94% of the failures that occurred in the slant-shear test were B/C and C. This was due to the bonding strength exceeding the NSC compressive strength. The high bonding strength is caused by good interlocking properties in WB, DH, Wet, and SSD conditions. This is an indication that the UHPC overlay has excellent bonding performance.
6. This study's limitation is the epoxy-resin-hardener's inability to adhere properly to the steel disk. Hence, the direct tensile/pull-off test results obtained are not good.

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