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Review Article

Factors Affecting the Bond Between Substrate-Overlay Material. A Review

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Abstract

Repair is a common method for restoring deteriorated structures. A strong bond between the substrate-overlay is critical to concrete restorations. The interface layer between substrate-overlay effects the strength and durability of a composite system. This interface layer is influenced by the mechanical load and chemical properties of the composition of the substrate and repair material. Because of these interactions, the bond strength between the substrate- overlay concrete is critical. Factors influencing bond strength are surface roughness, micro fractures, compaction, curing, workability, and other environmental factors. Several tests are available to examine the bonding behaviour of substrate-overlay concrete. However, there is no specific way to determine bond strength.
This paper outlines the various approaches and strategies by researchers to assess bond strength. Due to its simplicity, most researchers utilised slant shear test, split tensile test, and pull off test and avoided the mixed test method due to its complexity. According to literature, concrete repair is the best method, and higher strength concrete is used to produce better shear outcomes; conventional concrete is more cost-effective than higher strength concrete.

Keywords: Binder; Grooved effect; Overlay strength; Repair concrete; Substrate layer; Surface roughness

1. Introduction

The demand for concrete building repair and protection has increased rapidly in recent years. According to estimates, most national building budgets in many countries are spent on repairing old infrastructure. The leading cause of premature deterioration of concrete structures is mechanical and chemical forces like corrosion of steel reinforcement, which is frequently combined with the poor cover depth and the resulting cracking, spalling, and delamination of the concrete. The costs of poorly designed or executed repairs can be significantly higher. This cost highlights the importance of correct design principles for concrete repair projects, including repair material selection and material application processes. Many concrete repair projects involve the removal of degraded concrete from the existing structure and the subsequent placement of a bonded overlay. Various variables, such as insufficient bond strength or low crack resistance, might impact the endurance and, thus, the performance of concrete overlays.

In the rehabilitation and strengthening of deteriorated structures, the bond strength between substrate - overlay is often a weak point in the composite structures; a good bond is one of the most critical parameters for a repair. The bond strength depends on the interface surface behaviour mechanism; the bonding mechanism has been shown in figure 1. The bond strength of the interface mainly depends on the physical and chemical properties [1] and the composition [2] of both substrate-overlay material. It depends on factors like surface condition, surface type, and the substrate-overlay material properties with environmental conditions. The interface layer forms an ITZ similar to the ITZ in concrete in terms of its microstructure and shape caused by the aggregate and cement reaction.

But there are some problems with large-scale bond strength tests, such as it is hard to find out where the bond start fails; which is not enough to describe the failure reasons [3],[4]. The bond strength depends on the two main types of concrete overlays: bonded or not bonded.

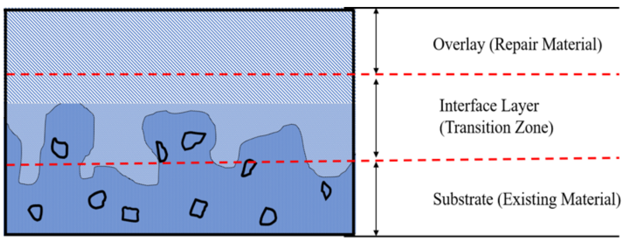

Fig. 1. Model of surface repair system [5]

In unbonded concrete overlays, there is no bond between the concrete substrate-overlay concrete. An interface layer usually is used to keep the two layers of concrete to sticking together. Bonded concrete overlays are made of two layers of concrete that are connected and work as monolithic members. For monolithic action, there must be a complete bond between the substrate-overlay concrete. Most of the time, bond strength is measured by the tensile strength across the interface plane. But bond strength in shear may also be considered because of loading conditions. The researchers used numerous methods to increase bond strength, including improvement of mechanical interlocking by surface roughness [6], development of stable repair materials [7], increasing the compressive strength of overlay concrete, using unique cementitious-based composite materials, employing bonding agents [8], including ECC [9],[10], UHPC [11], and sand concrete [12], increasing

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workability of overlay concrete, using supplementary cementitious materials [13], by the addition of nanomaterials [14],[15],etc. ACI 546.3R-14 [16] recommends the list for choosing a suitable repair material.

Table 1. Types of common tests used for the testing bond substrate - overlay concrete

Author	Type of test	Specimen geometry	Substrate concrete		Repair concrete		Surface preparation	Adhesive type	Failure type
			Material used	CS(MPa)	Material used	CS(MPa)			
[7]	Four-point bending	100×100×500 split into 100×100×250	HPFRM or SCC (Without SRA)	47.6 to 48.2	HPFRM or SCC (With SRA)	32.9 GPa to 32.8 GPa	(a) Smooth surface (b) Grid pattern		Interface failure
[8]	SST	φ= 150 α= 30° h= 300 , φ = 75 30° h= 150 , 100x100×400, 200x200×100	NC	25	SCC adding latex and polypropylene fiber	35	(a) HB (b) GS (c) Mechanical brushed	latex paint, EBA, and cement mortar	No interface failure with EBA
[12]	(i) Third-point flexural (ii) DST (iii) SST	(i) 150×150×500 (ii)50×150×150 (iii)75×150 α= 42°	NC	48	UHPC	174	(a) Screed (b) Troweled (c) No preparation	Dry Wet	Within the substrate, along with the bond interface, Mixed failure
[17]	(i) SST (ii) POT	(i)102×76×394 with α=60° and 70° (ii)100×100×400 and 40×40×160	NC	54.3	UHPC	154.7	(a) Smooth (b) Chipped (c) SB (d) Grooved (e) Roughened (f) Brushed		Cohesive and mixed failure
[18]	SST finite element analysis software LUSAS	400x100x100 α = 60° and 30°	NC	75	UHPC with and without silica fume	150 and 120	Saw cut surface		Cohesive failure
[19]	(i) POT (ii) splitting prism (iii) BSST	(i) 150×150×150 φ =150 (ii) 100×150, h= 150 (iii) 150×50, h= 150	NC	35	SF MCM AMCM with SBR	36 35 38	(a) Low roughness by steel wire (b) High roughness	K100 polymer adhesive	Shear-compression failure in SST
[20]	(i) SST (ii) STT (iii) POT	(i) 100×100×300 (ii) φ = 100 h= 200 (iii)300×300×70	GUSMRC	152.82	NC	49.20	(a) GS (b) SB	EBA	Substrate failure
[21]	STT	100×100×100 100×100×400 φ = 160, h= 320	NC (With glass)	28 to 55	Sand concrete (With glass)	49.21 36 to 50	LRG, HRG, DH, HRGDH		Interface failure Mixed failure
[22]	Modified -SST	150×150×600 α= 30° B_h= 170	Reinforced concrete	35.5		HS 32.5 W 37.4	(a) HS (b) W	HS W	SST-cohesive failures, M-SST-adhesive failures
[23]	(i) SST (ii) STT (iii) DTT	(i)150x150x300, 100x100x300 and 100x100x400 (ii)100×100×300 (iii)100×100×300	NC50 NC40 NC30	53.0 42.2 31.9	UHPC	92.8 to 123.6	(a) Smooth (b) WB (c) Low/High rough (d) Rough + Drilled/ Grooved	ASD ASW SSD EBA	Interface failure, Partial interface failure, Substrate failure
[24]	New frustum specimens Flexural bending specimens	**Specimen Frustum** φ=360, t=150 & 50 Prism (i) 160×40×40 (ii) 140×40×40 **Repair materials** Frustum: φ= 150	NC	80.8 (120 days)	PC SAC MPC	(i) 66.1(PC) (ii) 69.1(SAC) (iii) 61.8(MPC)	(a) Polished (b) Wetted		All specimens separated into two parts along with the interface

[25]	(i) SST (ii) DST	&100, h = 20 & 20, α=5° Prism: (i)100×40×40 (ii)60×40×40 (i)90×90×400 α =15° φ= 100 with α =30°, 37.5°, 45° (ii)outer φ =142 inner φ =10 with h=380	NC	35.61 (120 days)	RC	45.52	HCS		Monolithic behaviour
[26]	(i) STT (ii) SST	(i) φ =100 h=200 α = 30° (ii)100x100x 300	NC	45	UHPFC	170	(a) DH (b) WB (c) GS (d) SB		Failure at the interface, substrate fracture, and substratum failure
[27]	(i) STT (ii) SST	(i) 150×150×75 (ii)150×150×300 α = 30°	NC50	61.4	SCC 50	61.4	(a) Hammers chipping (b) Scattering gravels		Interface failure, Cohesive failure
[28]	Quasi-static slant shear bond behaviour split Hopkinson pressure bar	φ =70.4 ,α = 30°,40°, B_h=144	NC30	55.2 (90 days)	NC40	61.9 to 62.8	(a) For 30° VD = 1.2 & 2.4 (b) For 40° VD = 1.2 & 2.4		Interface failure
[29]	SST	150×150×450 α = 30°	NC	52.7 (56 days)	RAC 0%,20%,50 % and 100%	(28 days) NAC - 50.0 RAC20 - 47.5 RAC50- 46.1 RAC100 - 42.7	(a) Smooth surface (b) Rough (steel brush and needle gun)	SSD	Adhesive failure Localized failure
[30]	(i) STT (ii) Double shear test	(i)75×150×150 (ii)50×150×150	NC30	45.26	RPC	With Steel fiber 99.89	(a) Brushing (b) Chipping (c) Milling		Shear failure typical brittle failure
[31]	SST	50×50×125 α = 30°	PCC	35.9	Geopolymer mortars	38.5 to 62	Rugged fracture surface		Prisms failed in the monolithic mode
[32]	(i) DTT (ii) LCB test (iii) SST	(i) φ=100,h=200 (ii) 100x100 (iii) φ= 100x200 α = 30°	CC AC	CC 53.62 (90days) AC 11.38 (60days)	SCHPC	SCHPC 101.96 (60days)	(a) cement pasted (b) Bush-hammering (c) Extending Bituminous emulsion	HBM X60	Cohesive, mixed and adhesive failure
[33]	(i) POT (ii) SST	(i) 200×200×200, φ=75 (ii) 200×200×400, α = 30°	NC	50	RM	50	(a) Steel Brush, (b) Partially Chipped (c) SB	Cyclohexylamine epoxy	Interface failure
[34]	(i) SST (ii) POT	(i) 4x8 inch B_h=2inch, α = 45°, 8x4 inch B_h= 1inch, α = 33.75° 13.5x4 inch, B_h= 1.92inch, α =22.5°	CC	35.78	RM	25.44 to 33.71	(a) No treatment (b) SB	EBA	Interface failure

		(ii)6 x 6 x 24 inch							
[35]	BSST	38 (t)×51 (w)× 153 (l)	NC	35	UHPC	150	(a) No treatment (b) Rough SB	Sikadur 31, Hi-Mod gel	Cohesive, adhesive, and mixed failure
[36]	Push-off test (L shape)	254×546×127	NC	35	RC	35	No treatment		At connectors failure
[37]	POT	300×650×80	C16, C35 and C55		SFRC	C20, C25, C35, C45, C55, C60	(a) Rough machine used (b) Compressed air jet	EBA	At the top of old concrete, just below the bond adhesive
[38]	(i) STT (ii) SST	(i) φ = 100, h=200 40×40×160 (ii) 75x150 α= 30°	SCRM		Fiber reinforced SCRM	45	SB		Interface and substrate failure
[39]	(i) Shearing test (ii) STT (iii) Bending test	(i) 40 ×40 ×160 (ii)100×100×100 (iii) 100×100×400	NC	30 and 50	Repairing mortar	M5 and M10 mortar	(i) DH (ii) Brush cleaned	MKPC	Shearing failure
[40]	(i) SST (ii) Push-out (iii) DST (iv) POT	(i) 295×62 and 332×70 with α= 20°, 372×103.5,290×70, 257×62 with α= 25°, 280×75 with α= 30° (ii) 300×150×300 with α= 0° (iii) 150×50with α= 180° and 200×100 with α= 0° (iv) 35×50 and 110×50 with α= 180°	Normal Strength and High Strength Concrete	46 to 90	NC and High Strength mortar (with and without Fiber)	61 to 60(Normal Strength) 90 to 104(High Strength mortar)	SSD		Substrate failure Mixed failure
[41]	Debonding test machine-learning model	HPFRC-NC (Butterfly-shaped)	NC	16–55 in model	HPFRC	50–140 In model	(a) Mechanically roughened (b) Roughened with chemical	EBA	Interface failure
[42]	POT	600×800×100 and 500×500×70	NC	**Group A** 34.96 to 48.77 **Group B** 31.47 to 62.10	polymer-cement (PCC) repair mortars	PCC A 60 PCC B 30	(a) Polishing (b) Dry SB (c) Jack hammering (d) Brushing (e) Wet SB (f) Scarification (g) Water jetting		Superficial middle deep failure
[43]	SST	75 ×150, α = 30°	NC	10.4 to 14.3	Metakaolin added in NC		(a) Acid-etched (b) WB (c) Grooved/Grooved-WB (d) Grooved-acid etched		Interface failure
[44]	pull-off method	5×70×250	MKPC	58.5	MKPC with binder	51.3 to 56.8	U shape cutting through cutting surface	Rapid-setting adhesive	Partial and substrate failure
[45]	(i) SST (ii) Pull-off method	(i)100×100×100 (ii)200×300×4000	OPC		OPC with binder		(a) Mortar binder (b) U-type expansive binder (c) Fly ash binder		Near to interface and substrate failure

[46]	BSST	50×150×150 100×150×150	NC	40/50	NC	40/50	(a) Shot blasting (b) WB (c) No treatment (d) Dry surface (e) Saturated substrate	EBA	Adhesive failure At the interface Cohesive failure Mixed failure
[47]	Modified FIB shear test (model)	150×150×150 with half substrate and half overlay	NC	20,30,50	NC	25 and 40	SB	Saturated Surface Dry 30min, 24h, and Oven-dried	Close to the interface

While selecting repair measures, two things should be considered:

a. The behaviour of substrate-overlay concrete
b. The cost and efficiency of the repair materials because unsuitable repair materials lead to a higher cost than reconstruction [48].

Interface layer bonding depends on various factors like, workability [8],[47–49], surface roughness [50–53], bonding agent [54], surface moisture condition [55],[56], overlay materials strength [4],[21],[47] [57], age of concrete [46],[58], specimen size [49],[59-60], micro-cracking [47],[61], shrinkage of concrete [62],[63], cohesion in the substrate concrete[64],[65], aggregate interlock [66],[67], and other time-dependent factors [19],[68]. Some factors have been shown in figure 2 that describes the relationship of bond strength and with its degree of influence. From table 1, it can be concluded that most of the researchers used SST, STT followed by POT. SST is chiefly used to test the bond strength of substrate-overlay concrete because of the simplicity of the test. WB surface roughness technique is easy and have been used by many researchers. It is an easy and suitable surface technique. The interface failure is observed in most of the cases due to, the lack of EBA.

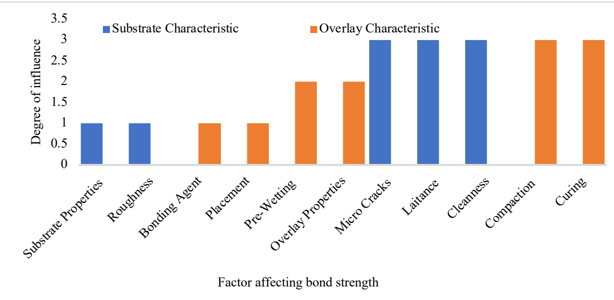


Fig. 2 Factors that Influencing the bond strength [69]

1.1 Workability

High workable repair material as overlay reduces the bond strength, especially for rough substrate surfaces; because, it can fill the substrate's pores, which creates low porous interfacial zone between substrate-overlay concrete. In comparison, low workable repair materials may be incapable of filling voids created by rough surfaces and making pores in the interfacial area. However, care should be taken as more workable repair materials may draw more water, which may lead to shrinkage of repair materials and stress concentration, and cause cracks at the interface zone. In addition, if the polymer-based coating is used in substrate-overlay concrete, can weaken the bond strength because it has a low w/b ratio [49]. The pozzolan with cement slurry in overlay concrete make it more rigid and leads to increase in stresses in the interface and decrease in bond strength. Also, higher use of water reduces the effectiveness of polymer-based adhesives [70].

Diab et al.[8] used SCC and noted the effect of flow diameter on SSBS. By increasing flow diameter from 640 to 810 mm, 28-day SSBS increased from 11.4 to 15.4 MPa (+35%). It could be due to the filling effect caused by the larger flow diameter. Compared to low workable overlay concrete, high workable concrete showed good bond strength [47]. Marchment et al. [71] explained that using additives would help cement particles to spread out more evenly, making the bond area easier to work.

1.2 Compressive Strength of the overlay

The CS plays an important role in bonding substrate-overlay concrete. Some authors claimed that increasing CS of overlay concrete increases bond strength [8], while another observed opposite result due to the difference in stiffness between the overlay and substrate concrete, which caused shear stresses at the interface [49],[72]. The interface shear bond strength is strongly related to the overlay compressive strength, with a ratio of roughly 0.1 [57].

Diab et al. [8] tested the effect of SSC as an overlay at 25, 35, 37, and 42 MPa CS by keeping base concrete at 25 MPa CS. They noted that the CS of overlay concrete significantly affects SSBS. For instance, when the CS of overlay SCC was 25 MPa, the SSBS was only 7.74 MPa. When this overlay CS increased to 35 MPa, a 70% increase in SSBS was observed. However, it was also observed that no significant improvement was observed beyond the overlay CS of 35 MPa, which may be due to cracks that may occur in low CS base concrete. An increase in bond strength with an increase in CS of overlay concrete was also reported by other researchers [4],[21],[47],[57]. Yildirim et al. [62] found a linear relationship between CS of overlay concrete and SSBS. The adhesive failure mode can be changed to cohesive failure mode by increasing the CS of overlay concrete. Sometimes, the higher CS leads to low shrinkage [73]; because, higher strength concrete swells more than normal concrete at relative humidity greater than 70%.

The increase in bond strength by increasing CS of overlay concrete may not always be true. Mohammadi et al. [49] used SF and MK in overlay concrete to test their CS. When MK was from 0 to 10% and SF was 0-15% by weight of cement, 28 days CS increased by increasing pozzolana content. However, when these types of concrete were used as overlay concrete, bond strength decreased by increasing pozzolana content. Kristiawan et al. [74] described the relationship between the SST and CS of concrete linear, as shown in figure 3. At the early age, modified PVA mortar did not adhere enough to the substrate concrete. After a suitable gap interval, the modified PVA mortar reaches to maximum cement hydration and develops a suitable bond to the substrate concrete and leads to higher SSBS.

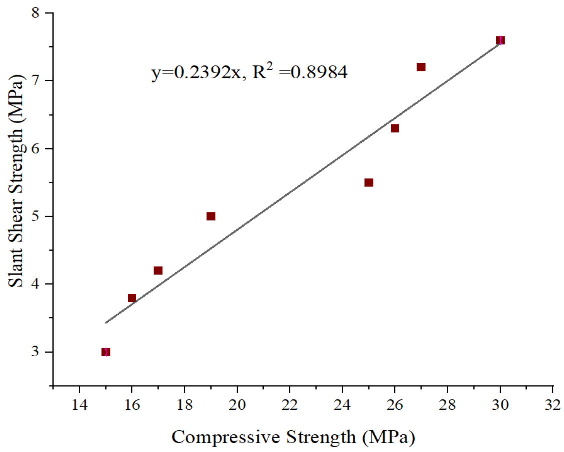


Fig. 3. The relation between slant shear strength and CS [74]

The substrate concrete properties affect the bonding behaviour of composite members. CS of overlay concrete affects the behaviour of substrate concrete. For low strength (25 MPa) overlay concrete, the impact of substrate concrete strength on shear bond strength is minimal; due to, the substrate moisture condition and overlay workability. The OTZ has a larger porosity on higher water-content substrates, which weaken the substrate-overlay relationship. However, bond strength increases with high overlay strength (40 MPa) [47]. Ali et al. [65] determine the effect of NC and HSC as substrate, with UHPC as an overlay. With HSC, direct tensile bond strength increased by 9.5% compared with NC strength. It indicates that the strength of the substrate concrete influences the bond strength.

1.3 Surface roughness of base concrete

The roughness of substrate surface increased the bond strength and can change adhesive failure to cohesive failure. To overcome this effect, various researchers found that concrete-to-concrete interface strength improved with increase in surface roughness [50–52]. In the bonding, the interface surface roughness is crucial for composite action and horizontal shear transfer. Thus, roughen of the surface is highly recommended [75],[76].

Many techniques can be used for substrate surface preparation, including SB, wire-brushing, sand-water blasting, grinding, chipping, water jetting, pneumatic hammering, milling, and hydro-demolition. The main difficulty in adopting sand and water blasting is their high cost. Wire brushing, as-cast and shot blasting surface treatment were carried out for bi-surface shear test to observe the bond strength and it was found that, shot-blasting surface treatment showed the highest bond strength [46]. The higher bond strength was due to more irregular pattern which leads to perfect bonding as compared to as-cast or brush treatment.

The effect of several surface roughness on bond strength has been compared in table 2. The surface preparation techniques should be chosen according to the strength of concrete. High-impact energy can cause micro-cracks in the concrete substrate. It is recommended to use less aggressive surface treatments on low mechanical strength concrete and more aggressive surface treatments on high mechanical strength concrete. For example, water jetting and jack-hammering can cause irregular substrate surfaces and weaken the ITZ [77]. It has been reported that the shear bond strength observed for water jetted surfaces was greater than 3 MPa [78]. For the interface between an NSC substrate and a UHPC overlay, the water-jet interface and the 10 mm-bubble groove interfaces are effective and suitable. The 25 mm-bubble groove interface can be considered the best solution for connecting a UHPC substrate to an NSC overlay; while, the water-jet interface has poor shear performance [79]. According to Abo Sabah et al. [80], SB surface treatment showed better strength, because of higher pressure application in treatment, it removed the loose particles. So, SB is required for better adhesion between UHPC and NC [35].The index of concrete surface preparation given by the ICRI [81] has been shown in table 3.

Table 2. The effect of several types of surface roughness on bond strength is compared

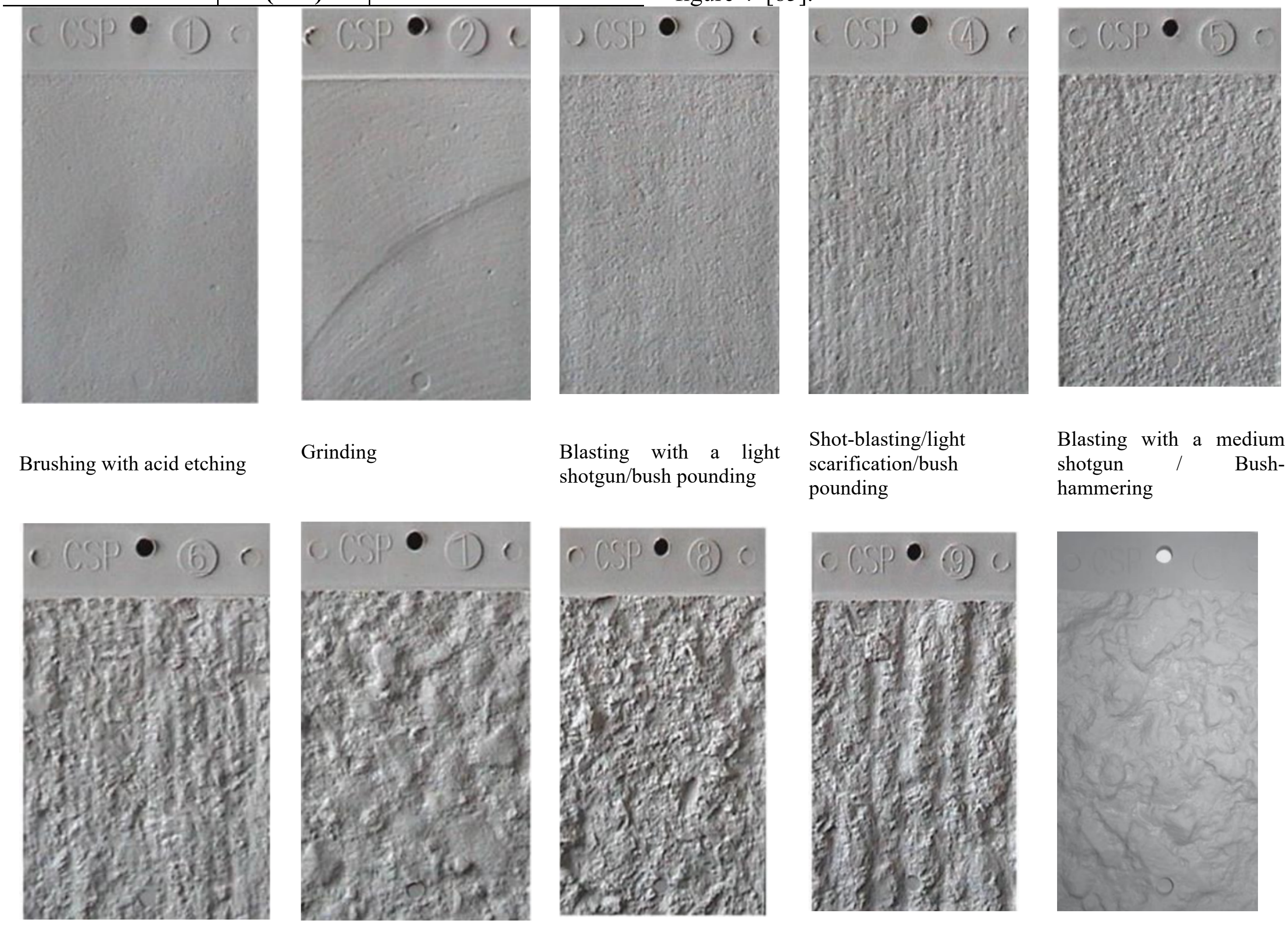
Methods used for surface roughness	SST	POT	STT	Flexural test	Double-sided DST	References
As-cast, R, DH, G, post-installed rebar					AC < DH < G < post-installed rebar < R	[4]
AC, DH, WB, GS, SB	AC < DH < WB < GS < SB		AC < DH < WB < GS < SB			[6]
AC, R, WB, SC, SB, G			AC < SB < WB = SC < G			[17]
WB, HCS, SC, HDC			WB < HCS < SC	HD < SC		[21]
AC, WB, SC, SB	AC < SC < WB < SB	SC < WB < SB				[33]
AC, WB, SHB					AC < WB < SHB	[46]

Therefore, more aggressive techniques should be avoided with large-size coarse aggregates on substrate concrete. When the surface was changed from smooth to rough, the bond strength was increased. Zhang et al. [82] discovered the bond strength between the asphalt layer and the existing cement slab. It was found that the rough surface showed better results than the original smooth surface. However, when the surface was changed from rough to very rough, no increase in bond strength was noted [83]. Kamada [84] observed no significant differences between smooth and rough surfaces for substrate or the overlay concrete. It indicates no increase in bond strength due to the damaged substrate surface.

Table 3. ICRI substrate surface classification

Surface treatment	**Depth (mm)**	**ICRI profile**
Grooved	n/a	n/a
Smooth	0.6	1,2
Brushed	0.73	1,3
Chipped	0.92	n/a
Sandblasted	0.96	4,5
Rough	2.18	Aggregate exposure > 8,9

ICRI gives various surface profiles from CSP 1 (almost flat) to 10 (very rough). These profile have been shown in figure 4 [85].



Brushing with acid etching | Grinding | Blasting with a light shotgun/bush pounding | Shot-blasting/light scarification/bush pounding | Blasting with a medium shotgun / Bush-hammering

Scarification on a moderate scale | Blast using abrasive material | Scabbled | Scarification to an extreme | Concrete blasting with a handheld blast proceeded by abrasive blasting

Fig. 4. Surface profiles from CSP1 to CSP 10

Diab et al. [14] used hand brush and mechanical roughness. For the surface preparation, 3mm (wide) x 3mm (deep) and 6mm (wide) x 6mm (deep) groove used. On existing concrete with grooves of 6mm (wide) x 6mm (deep), the highest SSBS was found, followed by mechanical wire brush and grooves of 3mm (wide) x 3mm (deep). The maximum SSBS was achieved with grooves of 6 mm width and height. Shear strength also improved by up to 137% for wire brush treatment and 217% for needle gunned treatment [86]. The DTT strength with epoxy and mortar applied by wire brushing decreased up to 8% and 23% respectively. Under the tensile load, the monolithic specimen is not suitable for reaching the level of strength. [87]

Magbool, Hassan M., and Tayeh [88] have used the brushed surface and found that POT and SST increased by 4% and 23%, respectively. Jafarinejad et al. [66] found that the bond strength obtained for the SB and groove surface showed a higher value between conventional and overlay concrete. After an SB treatment, good adhesive characteristics were observed, but low adhesive properties were measured after a dispersion emulsion treatment [89]. The improvement in bond strength by SST and STT with different surface roughness has been shown in figure 5.

Figure 6 shows higher bond strength with the SB surface, and it indicates that the shear strength of an interface is most affected by its roughness. After treatment, the interface shear load-carrying efficiency improved by 63.2 %. Omar et al. [58] used grooved and rough surfaces and found that flexural strength was between 32-52% for grooved surfaces. All the above mechanical and chemical methods for substrate surface preparation may cause damage to concrete substrate and its durability. They may be expensive and difficult to use because of their chemical composition [90]. To overcome these issues, Zhang et al.

[27] spread gravels of different sizes on the surface of the fresh concrete substrate. The STT showed that spreading aggregates of 5-10 mm increased the tensile bond strength by 29%. The SSBS was improved up to 107% when 5-20 mm aggregates were used.

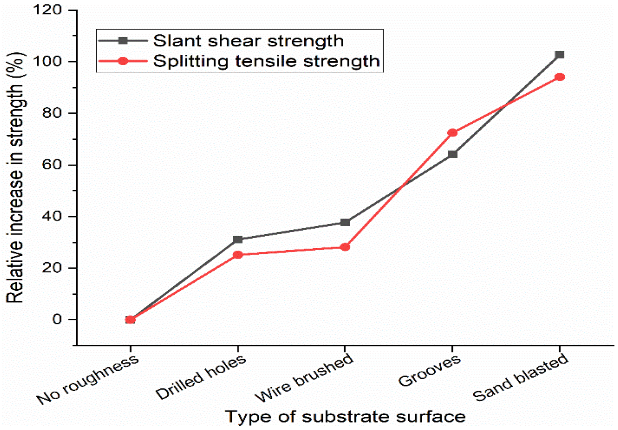


Fig. 5. Relative increment in strength by different substrate surface [6]

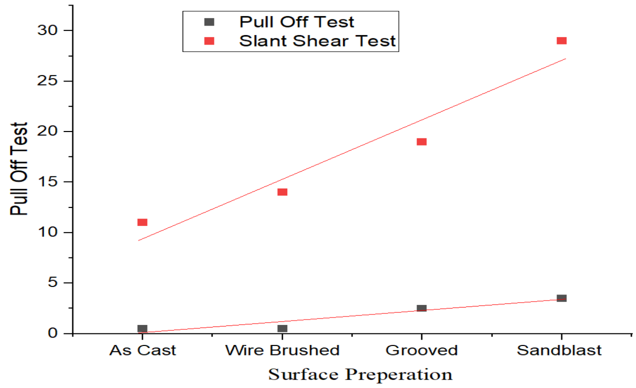


Fig. 6. Effect of substrate surface roughness on bond strength [66]

1.4 Grooved effect

The grooving plays an important role in the interlocking because the interface bond strength highly depends on surface preparation [91]. The interfacial groove improves bonding by increasing the mechanical interlocking [92],[93]. Using mechanical interlocking bond strength was 26% and 60% increases according to Zareiyan et al. [94] and Marchment et al. [71], respectively.

The results of Diab et al. [8] were in good agreement with ACI 546, according to which deeper roughening enhances the strength of the bond between substrate-overlay concrete. When the aggregate size was like the groove, the SSBS decreased. Momayes et al.[19] also observed similar results, i.e. for 3-4mm groove size SSBs was lesser than that for 7-8mm groove size. Sahab et al. [20] used GUSMRC as an overlay material by grooving and SB surface treatment. It was observed that SB surface treatment performed better than grooving. Al-rousan et al. [95] found that the bond strength increased by 66–133% using epoxy in the groove.

The bond strength depends on the groove pattern, core depth into the substrate, core diameter, maximum peak-to-valley height, load eccentricity, and loading rate [96]. Santos et al.[97] recommend the maximum peak-to-valley height, overall roughness height, and maximum valley depth. Improving the roughness of the interface between cementitious grout and standard concrete is a good way to increase the performance of the interface [98],[99].The greater the roughness of the interface, the larger the interface area and the more tack coat consumed. The interlocking effect created by a rough concrete substrate led to higher mechanical performance [100].

1.5 Substrate surface moisture

From the literature, it can be concluded that the substrate surface moisture reduces the bond strength. the AASHTO-AGC-ARTBA Joint Committee recommended a dry substrate surface, except on hot and dry summer days [46],[58]. The Canadian Standards Association A23.1 suggested wetting the substrate surface for at least 24 hours before casting overlay concrete. Omar et al. [58] found the effect of surface moisture on flexural strength and stated that SSD performed better than the other. Van Der Putten et al. [101] did not recommend the moisture surface because a well-roughened surface shows higher bond strength than the moisture surfaces. Dry surfaces show poor bond strength because the water from overlay concrete is absorbed by the substrate concrete, reducing the w/c in overlay concrete. However, with a wet surface, the water creates a layer on the substrate and prevents substrate - overlay concrete bonding. This type of problem decreased the strength. Ali et al. [65] performed four tests: DTT, bi-shear test, POT, and SST to investigate the bond strength of dry and SSD effects between normal concrete and UHPC overlay. In the POT, the SSD interface performed poorly (-2.8%) compared to the dry interface. Improvement in bond strength of the SSD interface was 2.3%, 22.7%, and 3% in case of testing by SST, bi-shear, and DTT, respectively.

When the double-sided direct shear test was used to investigate the strength of the NSC-UHPC interface, the highest strength was observed with SSD, followed by wet surface and dry surface [4]. Saturated surface wet conditions showed better bond strength than SSD conditions; due to, the moisture content of the substrate's interior layer and surface will affect bond strength development [1]. The dry surface may cause a more severe loss in bond strength at the NSC-UHPC interface than at the NSC-NSC interface. This is because UHPC has very low water, insufficient for complete cement hydration. When dry substrate concrete absorbs water from UHPC, it reduces water in UHPC next to the interface and, as a result, hydration product reduces at the interface. According to the study by Santos et al.[46], the bi-surface shear strength was enhanced when the substrate surface was dry compared with SSD. Using the SST, dry surface specimens had stronger bond strength than wet surface specimens. The ideal moisture content required to improve bond strength is impossible due to substrate material properties [65].

Beushausen et al. [47] established that pre-wetting the substrate surface had no effect on bond strength and probably reduced the bond strength. Maximum bond strength is achieved in SST than in the DST. The DST bond strength increased by 105% when roughened by chipping with 24hrs pre-wetting and 32.5% in SST [102]. The dry and pre-wet surface results also depend on the test method used. For instance, Julio et al. [33] observed that a pre-wet surface gave higher SSBS than a dry surface. However, lower pull-off strength was obtained with a pre-wet surface compared with a dry surface. Previously, Ali et al. [65] also highlighted that the bond strength of dry and pre-wet surfaces depends on the test method used. Figure 7 shows the positive and negative effect of pre-wetting and bonding agent effects on strength reported by various researchers from 1919 to 2012. Humidity, temperature, and evaporation rate can affect the requirement for pre-wetting. Preparation of the substrate, including profiling and cleaning, can affect the bonding agent's performance. These variables are difficult to regulate and measure, even in a laboratory.

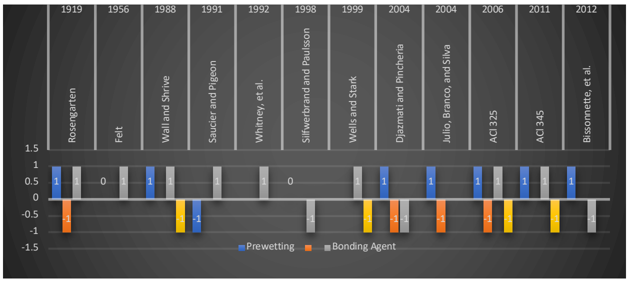


Fig. 7. Pre-treatment's effect on strength and durability by the various researchers [103]

Saturated dry surfaces help to improve bond strength [4],[58], but few studies observed the negative effect of Saturated dry surfaces on bond strength[47-48],[104] as shown in figure 8.

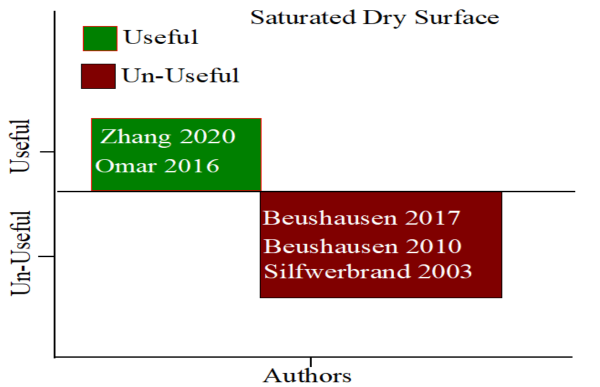


Fig. 8. Saturated dry surface recommended by authors

Useful: -

(i) Saturated dry surface is useful due to the mechanical interlocking and adsorption theories that define the substrate-overlay bonding behaviour.
(ii) The surface preparation technique creates mechanical interlocking at the microscopic level [105]. The surface porosity of the interface layer is creating a strong connection via a tangle of the hydrates.
(iii) Thermodynamic adsorption theory stated that the bonding of substrate-overlay concrete is connected through the hydrogen liaison, chemical bonding and mainly by van der Waal forces.

Un useful:

(i) Firstly, free water on the substrate surface will increase the water-cement ratio (w/c) of the overlay mix, reducing the strength of the thin layer of overlay above the interface.
(ii) Secondly, a dry concrete substrate called "thirsty," limit the overlay concrete moisture required for complete cement hydration to proceed.

1.6 The age difference between substrate-overlay concrete

The bond strength mainly depends on the overlay strength. The time gap between substrate-overlay castings affects the bond strength. The bond behaviour between substrate-overlay concrete varies with age because the shrinkage, strength, and stiffness properties vary with time. A 3-hour and 48-hour casting period of overlay reduced the interface bond strength by 30% and 40%, respectively [106]. Diab et al.[8], Mirmoghtadaei et al. [43] and He et al. [107] investigated the impact of the age of the interface on the SSBS. Zhang et al. [23] stated that SSBS and DTT strength showed similar behaviour with UHPC overlay bonding at 1,2,3,7,28,90, and 180 d; but, the STT strength changed dramatically at 2 and 3 d. This similarity in the strength of the interfacial bond significantly depends on the growth of the UHPC overlay material properties. The age of the UHPC and the curing condition have a negligible effect on the interfacial bonding performance. From the figure 9, it can be observed that SST and DTT bond strength also achieved similar strength about 86.6% at 28 d; because, the interface bond strength was mainly developed during the curing days in UHPC overlay. Higher roughness with smaller age of substrate concrete enhances the bond strength, because at the smaller age of substrate concrete, the effect of roughness on the bonding property of the substrate-overlay concrete structure is more significant than substrate concrete age [108].

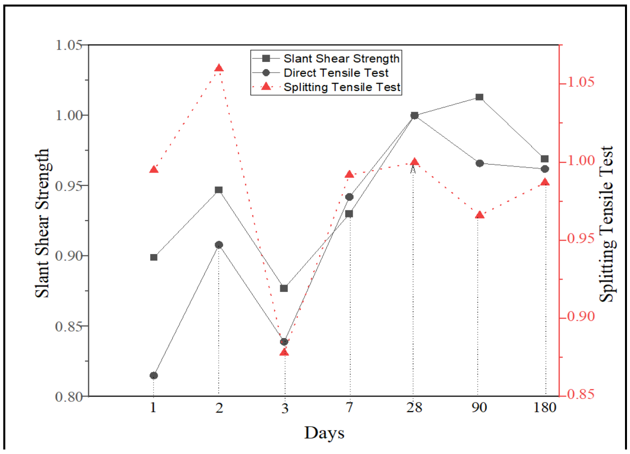


Fig. 9. Interface strength vs. time duration in days [23]

1.7 Bonding agent

The bonding agent is widely used as a repair material nowadays, but some researchers believe that bonding agents may reduce the interface interlocking by creating an extra plane at the interface layer. Al-ostaz et al. [109] examined that cement-based bonding materials lead to a decrease in the SSBS (19.2 to 40%). However, others stated that bonding agents are good with surface preparation techniques [110] and increase the bond strength [33],[42],[46],[107],[111]. Diab et al. [8] investigated the effect of three bonding agents: cement mortar, latex paint, and epoxy adhesive on the SSBS between the substrate and the new SCC. The highest SSBS was obtained with epoxy specimens, followed by latex paint, and cement mortar. For example, the epoxy specimens did not fail at the interface surface. Epoxy resin coatings increased bond strengths in SST with 70º angle.

In SST when the interface angle was changed from 70º to 63.38º, the bond strength by cement mortar and epoxy coating decreased to 9% and 22% respectively. This shows that when there is a bond coat on the surface, the bond is more likely to break down faster [112]. Mohammadi et al. [49] used bonding slurry (cement + water + latex) and plain cement slurry as interfacial adhesives. The bond strength performance of plain cement slurry was almost double as compared with bonding slurry. The bonding agent's effect depends on surface preparation [46],[110],[113-114]. Bonding agents significantly enhanced bi-surface shear strength with the smooth surface substrate. When the substrate was shot-blasted, the bonding agent had no effect [115]. The bonding agent has even less effect on a roughened substrate surface. In addition to chemical bonding agents for coating OTZ, cement paste with SCMs was also used.

Li et al. [45] prepared 3 types of binder (plain cement paste, FA mortar, and expansive binder) in addition to no binder. The splitting tensile strength of all three types of binders was higher than no binder when coated on substrate concrete. These results showed that binder coating on substrate concrete increased bond strength as compared to no binder. The effect of binder coating may depend on the difference in CS of substrate-overlay concrete. Kuroda et al. [116] used cement paste with FA, SF, and silica powder for interface coating. It was observed that direct tensile strength for all the samples coated with SCMs, including paste, was higher than control specimens. When SF and silica powder were used in the coating, about an 80% increase in the strength was noted. It was reported that the additive used in interface coating with high SiO_2/CaO improved the bond strength. The polymers in bonding agents cover the cement particles and aggregates by forming the film, creating strong adhesion between substrate-overlay concrete. It is possible that the rubber in the concrete will make it more flexible. The bond strength values for the specimens with SBR as a bonding agent fulfilled the criteria for bond strength given by the ASTM [117],[118].

1.8 Overlay Binder

1.8.1 UHPC overlay

UHPC is a high-strength concrete created in France in the 1990s. Due to its high mechanical and durability features, it is considered the best repair material. Tayeh et al. [11] used UHPC as overlay concrete and performed POT and STT. In the POT failure, the bond strength of overlay concrete was very high.

Similarly, higher bond strength was also observed in the STT. SF creates dense ITZ in UHPC that reacts with calcium hydroxide in old concrete to generate secondary C-S-H. C-S-H creation at the interface can reduce voids and form dense, impermeable concrete. UHPC is an excellent overlay material, but its high cost may restrict its use [119].

Using locally available materials and normal curing procedures lower the cost of UHPC can be reduced. Bond strength increased with UHPC age, so normal bonding agents may not require [17]. Rith et al. [120] stated that the bond strength was lowered by utilising ultra-rapid hardening concrete as the overlay. The bonding performance of various UHPC and NSC interfaces is affected by mixing and casting procedures [79]. The interface strength increased by applying mechanical connectors between the UHPC and concrete substrates [121]. With UHPC as a repair material, the main failure observed was complete NSC failure or partial interface and partial NSC failure under a double-sided direct shear test [4]. When UHPC is mixed with NSC, a strong chemical bonding force is generated, and the UHPC effectively removes the floating pulp layer on the surface of the NSC. The removal of the floating pulp layer resulted in an improvement[122].

1.8.2 Fly ash

Emberson and Mays [123] reported that a polymer-modified cementitious material is a good repair material with higher bond strength than other repair materials. Li et al.[45] used a 2-3 mm layer of the binder with 75% cement and 25% FA and used this layer between substrate-overlay concrete. As compared with plain cement paste, bond strength improved by 48%. The enhancement in FA based binder as compared with a plain binder is due to three reasons:

(i) FA reacts with calcium hydroxide and forms C-S-H
(ii) FA fills the pores in the transition zone and enhances the density
(iii) FA helps to reduce drying shrinkage

Increasing the liquid-solid ratio reduces the binding strength of the repair material. The addition of FA to replace cement by 10% [124] and 15% [125] showed better bond behaviour by making the interracial zone very dense. The bond strength increased with cement mortar without FA. The addition of FA can effectively reduce harmful pores in the adhesive interface[126]. Li [45] replaced 40% of cement to FA in overlay concrete and noted that early age pull-off strength (28 d) was lowered as compared with plain concrete; while, it was higher in later age (1 year); due to, the slow pozzolanic reaction of concrete with FA. The addition of FA in concrete improved the microstructure of the interface with dense C-S-H; however, the bond strength was reduced by 26.7% to 54.3% when the FA content was increased from 10% to 30% respectively [127].

The bonding performance of substrate-overlay concrete could be enhanced by increasing the slag content and the FA content[128][129]. Compared to regular Portland concrete, the interface bond strength of repair concrete with alkali-activated slag/FA increased by about 62%. The strength increased first, then decreased, reaching its peak at 50% slag content [130].

1.8.3 Engineering cementitious composites

ECC can be a promising repair material with a high bond strength and substrate failure mode [9],[131]. As a repair material, Sahmaran et al. [9] developed two types of ECCs, one with FA and the other with slag. The SST and STT were performed to observe the bond strength of OTZ. For both the ECCs, SSBS at 28 d was greater than the upper range specified by ACI 546-06. ECC with slag showed 12% higher slant shear strength than ECC with FA, which was attributed to the filling effect and pozzolanic reaction of slag with calcium hydroxide at 28 d. Some point also that there was a need for surface roughness with ECC as overlay material. This result is like the UHPC overlay [17]. Lepech et al. [132] compared ECC overlay with standard overlay and found that ECC overlay saved overall life cycle energy by 14%, greenhouse gases by 32%, and costs by 40%.

1.8.4 Metakaolin

Metakaolin is the calcined form of a clay mineral kaolinite that is anhydrous. Minerals having kaolinite are referred to as China clay and kaolin and have historically been used to create porcelain. Although it's not as fine as silica fume, metakaolin has a lower particle size than cement. Metakaolin is used as a binding agent in the substrate - overlay concrete. Metakaolin shows high shrinkage, with a low sand/binder mass ratio. It is 5 to 10 times cheaper than the other binding materials [133]. According to Mirmoghtadaei et al.[43], 10% metakaolin replacement showed better bond strength.

2. Conclusions

The primary goal of this research is to analyse and evaluate various tests and procedures to determine the efficiency of the substrate repairing process using novel overlay material.

Past studies have covered the effect of various factors on interface layer bonding, workability, surface roughness, bonding agent, surface moisture condition, overlay materials strength, age of concrete, specimen size, micro-cracking, shrinkage of concrete, cohesion in the substrate concrete, aggregate interlock, and other time-dependent factors. Most past studies have focused on testing the efficiency of different test setups to determine a perfect bond.

The roughness substrate surface improves binding strength over a smooth surface.

Use of pozzolanic materials can improve the bond strength. Most researchers employed the WB surface roughness approach, which was found an easy and acceptable surface technique.

Due to its simplicity, most researchers utilised SST, STT, and POT and avoided the mixed test method due to its complexity.

Many experiments have been undertaken to measure bond strength, including pure tension (direct and indirect), pure shear, shear and tension and compression (mixed mode) tests, and bending tests. The pure tension test is the most often used and successful method for determining bond strength.

Compared to no binder, binder coating/Epoxy coating on substrate concrete increases binding strength.

Bond strength by SST is higher than BSST, and SST is primarily employed to test the bond strength of substrate-overlay concrete due to its simplicity.

Interface failure is observed in most cases due to the lack of EBA.

The above results are based on the various research observations; further research is required to explore suitable methods, materials and surface techniques.

3. Future research

- UHPC is an excellent repair material; however, its high cost hinders its wide use. Therefore, effort should be made to decrease the cost of UHPC as repair material by using local material and normal curing without heat treatment.
- The effect of surface treatment on the bonding behaviour of different tests is not clearly defined.
- The grooved study is also affected by lack of details.
- Microstructure observations of the bond interface are not studied clearly.
- The previous studies were not focused on the application methods of the different repair material.
- More sensitive profile meter devices are needed for a accurate surface model and representation.
- The damages caused by the surface treatment techniques have been not addressed clearly.
- Effect of specimen size and contact bond as the bond strength also need to be explored.

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References

1. S. Austin, P. Robins, and Y. Pan, "Tensile bond testing of concrete repairs," *Mater. Struct.*, 28(5), 1995, pp.249-259.
2. X. Zou *et al.*, "Shear bond strength in repaired concrete structures," *Constr. Build. Mater.*, 26(1), 2020, pp.1–8.
3. S. Feng, H. Xiao, R. Liu, X. Dong, Z. Liu, and H. Liu, "The influence of different bond primers on the bond strength of concrete overlays and the microstructure of the overlays transition zone," *Cem. Concr. Compos.*, 119(1), 2021, pp.1-13.
4. Y. Zhang, C. Zhang, Y. Zhu, J. Cao, and X. Shao, "An experimental study: various influence factors affecting interfacial shear performance of UHPC-NSC," *Constr. Build. Mater.*, 236(1), 2020, pp.1-15.
5. P. H. Emmons and A. M. Vaysburd, "Performance criteria for concrete repair materials, Phase 1," 1995.
6. B. A. Tayeh, B. H. Abu Bakar, and M. A. Megat Johari, "Characterization of the interfacial bond between old concrete substrate and ultra high performance fiber concrete repair composite," *Mater. Struct. Constr.*, 46(5), 2013, pp.743–753.
7. R. Qin, H. Hao, T. Rousakis, and D. Lau, "Effect of shrinkage reducing admixture on new-to-old concrete interface," *Compos. Part B Eng.*, 167(1), 2019, pp.346–355.
8. A. M. Diab, A. E. M. Abd Elmoaty, and M. R. Tag Eldin, "Slant shear bond strength between self compacting concrete and old concrete," *Constr. Build. Mater.*, 130(1), 2017, pp.73–82.
9. M. Sahmaran, H. E. Yücel, G. Yildirim, M. Al-Emam, and M. Lachemi, "Investigation of the Bond between Concrete Substrate and ECC Overlays," *J. Mater. Civ. Eng.*, 26(1), 2014, pp.167–174.
10. M. Singh, B. Saini, and H. D. Chalak, "Long term evaluation of engineered cementitious composite containing stone slurry powder," *Constr. Build. Mater.*, 264(1), 2020, pp.1-13.
11. B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and A. M. Zeyad, "Microstructural analysis of the adhesion mechanism between old concrete substrate and UHPFC," *J. Adhes. Sci. Technol.*, 28(18), 2014, pp.1846–1864.
12. M. Farzad, M. Shafieifar, and A. Azizinamini, "Experimental and numerical study on bond strength between conventional concrete and Ultra High-Performance Concrete (UHPC)," *Eng. Struct.*, 186(1), 2019, pp.297–305.
13. L. G., X. H., and X. G., "Transition zone studies of new-to-old concrete with different binders," *Cem. Concr. Compos.*, 23(4-5), 2005, pp.381–387.
14. G. Singh and B. Saini, "Nanomaterial in cement industry: a brief review," *Innov. Infrastruct. Solut.*, 7,(1), 2021, pp.45-52.
15. X. Wang, S. Dong, A. Ashour, and B. Han, "Bond of nanoinclusions reinforced concrete with old concrete: Strength, reinforcing mechanisms and prediction model," *Constr. Build. Mater.*, 283(1), 2021, pp.1-15.
16. ACI 546.3R-14, *Guide to materials selection for concrete repair*. 2004.
17. M. A. Carbonell *et al.*, "Bond performance between ultrahigh-performance concrete and normal-strength concrete," *J. Mater. Civ. Eng.*, 26(8), 2014, pp.105-111.
18. Hassan Fardoun and David Begg, "Shear strength between ultra-high-performance concrete and old concrete," Dec. 2017
19. A. Momayez, M. R. Ehsani, A. A. Ramezanianpour, and H. Rajaie, "Comparison of methods for evaluating bond strength between concrete substrate and repair materials," *Cem. Concr. Res.*, 35(4), 2005, pp.748–757.
20. S. H. Abo Sabah, M. H. Hassan, N. Muhamad Bunnori, and M. A. Megat Johari, "Bond strength of the interface between normal concrete substrate and GUSMRC repair material overlay," *Constr. Build. Mater.*, 216(1), 2019, pp.261–271.
21. K. Gadri and A. Guettala, "Evaluation of bond strength between

sand concrete as new repair material and ordinary concrete substrate (The surface roughness effect)," *Constr. Build. Mater.*, 157(1), 2017, pp.1133–1144.

22. R. Saldanha, E. Júlio, D. Dias-Da-Costa, and P. Santos, "A modified slant shear test designed to enforce adhesive failure," *Constr. Build. Mater.*, 41(1), 2013 pp.673–680.
23. Y. Zhang, P. Zhu, Z. Liao, and L. Wang, "Interfacial bond properties between normal strength concrete substrate and ultra-high performance concrete as a repair material," *Constr. Build. Mater.*235(1), 2020, pp.1-13.
24. J. Qian, C. You, Q. Wang, H. Wang, and X. Jia, "A method for assessing bond performance of cement-based repair materials," *Constr. Build. Mater.* 68(1), 2014, pp.307–313.
25. E. M. Piancastelli *et al.*, "Bond strength between old and new concretes with focus on the strengthening of reinforced concrete columns - slant shear test versus double sleeve test," *Appl. Mech. Mater.*, 864(1), 2017, pp.324–329.
26. B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Y. L. Voo, "Evaluation of bond strength between normal concrete substrate and ultra high performance fiber concrete as a repair material," *Procedia Engineering*, 54(1) 2013, pp.554–563.
27. J. Zhang, X. Ding, and Q. Zhao, "Experimental and numerical investigation of scattering gravels on the surface bond strength of self-compacting concrete," *Constr. Build. Mater.*, 145(1), 2017, pp.11–19.
28. B. Hu, Y. Li, and Y. Liu, "Dynamic slant shear bond behavior between new and old concrete," *Constr. Build. Mater.*, 238(1), 2020, pp.1-14.
29. F. Ceia, J. Raposo, M. Guerra, E. Júlio, and J. De Brito, "Shear strength of recycled aggregate concrete to natural aggregate concrete interfaces," *Constr. Build. Mater.*, 109(1), 2016 pp.139–145.
30. Y. Ju, T. Shen, and D. Wang, "Bonding behavior between reactive powder concrete and normal strength concrete," *Constr. Build. Mater,* 242(1), 2020, p. 118024, 2020, pp.1-9.
31. T. Phoo-Ngernkham, V. Sata, S. Hanjitsuwan, C. Ridtirud, S. Hatanaka, and P. Chindaprasirt, "High calcium fly ash geopolymer mortar containing Portland cement for use as repair material," *Constr. Build. Mater.*, 98(1), 2015, pp.482–488.
32. R. D. López-Carreño, P. Pujadas, S. H. P. Cavalaro, and A. Aguado, "Bond strength of whitetoppings and bonded overlays constructed with self-compacting high-performance concrete," *Constr. Build. Mater.*, 153(1), 2017, pp.835–845.
33. E. N. B. S. Júlio, F. A. B. Branco, and V. D. Silva, "Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface," *Constr. Build. Mater.*. 18(9), 2004, pp.675–681.
34. E. Gomaa, A. A. Gheni, C. Kashosi, and M. A. ElGawady, "Bond strength of eco-friendly class C fly ash-based thermally cured alkali-activated concrete to portland cement concrete," *J. Clean. Prod.*, 235(1), 2019, pp.404-416.
35. A. Valikhani, A. J. Jahromi, I. M. Mantawy, and A. Azizinamini, "Experimental evaluation of concrete-to-UHPC bond strength with correlation to surface roughness for repair application," *Constr. Build. Mater.*, 238(1), 2020, pp.1-12.
36. E. N. B. S. Júlio, D. Dias-da-Costa, F. A. B. Branco, and J. M. V. Alfaiate, "Accuracy of design code expressions for estimating longitudinal shear strength of strengthening concrete overlays," *Eng. Struct.*, 32(8), 2010, pp.2387–2393.
37. E. Bonaldo, J. A. O. Barros, and P. B. Lourenço, "Bond characterization between concrete substrate and repairing SFRC using pull-off testing," *Int. J. Adhes. Adhes.*, 25(6), 2005 pp.463–474.
38. A. Benyahia, M. Ghrici, S. Choucha, and A. Omran, "Characterization of fiber reinforced self-consolidating mortars for use in patching damaged concrete," *Lat. Am. J. Solids Struct.*, . 14(6), 2017, pp.1124–1142.
39. Yue Li, Weiliang Bai, and Tongfei Shi, "A study of the bonding performance of magnesium phosphate cement on mortar and concrete," *Constr. Build. Mater.*, 142(1), 2017 pp.459–468.
40. C. Zanotti and N. Randl, "Are concrete-concrete bond tests comparable?," *Cem. Concr. Compos.*, 99(1), 2019, pp.80–88.
41. P. Jiao, M. Roy, K. Barri, R. Zhu, I. Ray, and A. H. Alavi, "High-performance fiber reinforced concrete as a repairing material to normal concrete structures: Experiments, numerical simulations and a machine learning-based prediction model," *Constr. Build. Mater.*, 223(1), 2019, pp.1167–1181.
42. L. Courard, T. Piotrowski, and A. Garbacz, "Near-to-surface properties affecting bond strength in concrete repair," *Cem. Concr. Compos.*, 46(1), 2014, pp.73–80.
43. R. Mirmoghtadaei, M. Mohammadi, N. Ashraf Samani, and S. Mousavi, "The impact of surface preparation on the bond strength of repaired concrete by metakaolin containing concrete," *Constr. Build. Mater.*, 80(1), 2015, pp.76–83.
44. H. Kim, D. Han, K. Kim, and P. Romero, "Performance assessment of repair material for deteriorated concrete slabs using chemically bonded cement," *Constr. Build. Mater.*, 237(1), 2020, pp.1-8.
45. G. Li, "A new way to increase the long-term bond strength of new-to-old concrete by the use of fly ash," *Cem. Concr. Res.*, 33(6), 2003, pp.799–806.
46. D. S. Santos, P. M. D. Santos, and D. Dias-Da-Costa, "Effect of surface preparation and bonding agent on the concrete-to-concrete interface strength," *Constr. Build. Mater.*, 37(1), 2012, pp.102–110.
47. H. Beushausen, B. Höhlig, and M. Talotti, "The influence of substrate moisture preparation on bond strength of concrete overlays and the microstructure of the OTZ," *Cem. Concr. Res.*, 92(1), 2017, pp.84–91.
48. H. Beushausen, "The influence of concrete substrate preparation on overlay bond strength," *Mag. Concr. Res.*, 62(11), 2010, pp.845–852.
49. M. Mohammadi, R. Mir Moghtadaei, and N. Ashraf Samani, "Influence of silica fume and metakaolin with two different types of interfacial adhesives on the bond strength of repaired concrete," *Constr. Build. Mater.*, 51(1), 2014, pp.141–150.
50. Pedro Miguel Duarte Santos and and Eduardo Nuno Brito Santos Júlio, "Factors affecting bond between new and old concrete," *ACI Mater. J.*, 108(4), 2011, pp.449-456.
51. Li Bo and E. S. S. Lam, "Influence of interfacial characteristics on the shear bond behaviour between concrete and ferrocement," *Constr. Build. Mater.*, 176(1), 2018, pp.462–469.
52. W. Shi and B. Shafei, "Bond characteristics between conventional concrete and six high-performance patching materials," *Constr. Build. Mater.*, 308(1), 2021 April, p. 124898, 2021, pp.1-12.
53. J. by Norbert J. Delatte Dawn Marie Wade, and David W. Fowler, "Laboratory and field testing of concrete bond development for expedited bonded concrete overlays," *ACI Mater. J.*, 97(3), 2000, pp.1-8.
54. M. S. Essa, A. M. Abdul–Amir, and N. F. Hassan, "Effect of Adding (SBR) on Concrete Properties and Bond between Old and New Concrete," *Kufa J. Eng.*, . 4(1), 2014, pp.81–95.
55. Z. Ding, J. Wen, X. Li, and X. Yang, "Permeability of the bonding interface between strain-hardening cementitious composite and normal concrete," *AIP Adv.*,9(5), 2019, pp.1-7.
56. N. K. Baharuddin, F. M. Nazri, R. P. Jaya, and B. H. A. Bakar, "Evaluation of bond strength between fire-damaged normal concrete substance and ultra-high-performance fiber-reinforced concrete as a repair material," *World J. Eng.*, 13(5), 2016, pp.461–466.
57. H. Beushausen and M. G. Alexander, "Bond strength development between concretes of different ages," *Mag. Concr. Res.*, 60(1), 2008, pp.65–74.
58. B. Omar and T. H. Boumediene, "Influence of the roughness and moisture of the substrate surface on the bond between old and new concrete," *Contemp. Eng. Sci.*, 3(1), 2016, pp.139–147.
59. D. K. Harris, M. A. Carbonell Muñoz, A. Gheitasi, T. M. Ahlborn, and S. V. Rush, "The challenges related to interface bond characterization of ultra-high-performance concrete with implications for bridge rehabilitation practices," *Adv. Civ. Eng. Mater.*, 4(2), 2015, pp.75–101.
60. A. M. Wood, "Structural repairs to the monuments of the Acropolis—the Parthenon," *Proc. Inst. Civ. Eng. Civ. Eng.*,97(4), 1993, p. 155-165.
61. Ma Hongqiang, Yi Cheng, and Wu Chao, "Review and outlook on durability of engineered cementitious composite (ECC)," *Constr. Build. Mater.*, 287(1), 2021, pp.1-12.
62. G. Yildirim, M. Şahmaran, M. K. M. Al-Emam, R. K. H. Hameed, Y. Al-Najjar, and M. Lachemi, "Effects of compressive strength, autogenous shrinkage, and testing methods on bond behavior of high-early- strength engineered cementitious composites," *ACI Mater. J.*, 112(3), 2015, pp.409–418.
63. A. Sadrmomtazi and R. K. Khoshkbijari, "Determination and prediction of bonding strength of polymer modified concrete as the repair overlay on the conventional concrete substrate," *KSCE J. Civ. Eng.*, . 23(3), 2019, pp.1141–1149.
64. P. D. dos Santos, "Assessment of the shear Strength between

cconcrete layers," 2009.
65. A. A. Semendary and D. Svecova, "Factors affecting bond between precast concrete and cast in place ultra high performance concrete (UHPC)," *Eng. Struct.*, 216(1), 2020, pp.1-12.
66. S. Jafarinejad, A. Rabiee, and M. Shekarchi, "Experimental investigation on the bond strength between Ultra high strength Fiber Reinforced Cementitious Mortar & conventional concrete," *Constr. Build. Mater.*, 229(1), 2019 pp.1-9.
67. A. J. Al-Basha, W. K. Toledo, C. M. Newtson, and B. D. Weldon, "Ultra-High Performance Concrete Overlays for Concrete Bridge Decks," in *IOP Conference Series: Materials Science and Engineering*, 471(3), 2019, pp.1-10.
68. G. A. Rao and B. K. R. Prasad, "Influence of the roughness of aggregate surface on the interface bond strength," *Cem. Concr. Res.*, 32(1), 2002, pp.253–257.
69. L. Courard, T. Piotrowski, and A. Garbacz, "Cement & concrete composites near-to-surface properties affecting bond strength in concrete repair," *Cem. Concr. Compos.*, 46(1), 2014, pp.73–80.
70. M. K. Antoon and J. L. Koenig, "Irreversible effects of moisture on the epoxy matrix in glass-reinforced composites," *J. Polym. Sci. Part A-2, Polym. Phys.*, 19(2), 1981, pp.197–212.
71. T. Marchment, J. Sanjayan, and M. Xia, "Method of enhancing interlayer bond strength in construction scale 3D printing with mortar by effective bond area amplification," *Mater. Des.*, 169(1), 2019, pp.1-11.
72. K. Grigoriadis, P. S. Mangat, and S. Abubakri, "Bond between microwave cured repair and concrete substrate," *Mater. Struct.*, . 50(2), 2017, pp.1-15.
73. H. C. Shin and Z. Wan, "Interfacial shear bond strength between old and new concrete," *Fract. Mech. Concr. Concr. Struct. - Assessment, Durability, Monit. Retrofit. Concr. Struct.*, 2010, pp.1195–1200.
74. S. Kristiawan, B. Santosa, E. Purwanto, and R. A. Caesar, "Slant shear strength of fibre reinforced polyvinyl acetate (PVA) modified mortar," in *MATEC Web of Conferences*,.2018, pp.1-9.
75. Z. B. Haber, J. F. Munoz, I. De la Varga, and B. A. Graybeal, "Bond characterization of UHPC overlays for concrete bridge decks: Laboratory and field testing," *Constr. Build. Mater.*, 190(1), 2018, pp.1056–1068.
76. M. Mousa, "Factors affecting bond between repairing concrete and concrete substrate," *Int. J. Eng. Innov. Technol.*, 4(11),2015, pp.2277–3754.
77. M. A. Yazdi, E. Dejager, M. Debraekeleer, E. Gruyaert, K. Van Tittelboom, and N. De Belie, "Bond strength between concrete and repair mortar and its relation with concrete removal techniques and substrate composition," *Constr. Build. Mater.*, 230(1), 2020, pp.1-12.
78. J Sillfwerbrand, "Shear bond strength in repaired concrete structures," 2003.
79. J. Liu, Z. Chen, D. Guan, Z. Lin, and Z. Guo, "Experimental study on interfacial shear behaviour between ultra-high performance concrete and normal strength concrete in precast composite members," *Constr. Build. Mater.*, 261(1), 2020 pp.1-12.
80. S. H. Abo Sabah, N. L. Zainal, N. Muhamad Bunnori, M. A. Megat Johari, and M. H. Hassan, "Interfacial behavior between normal substrate and green ultra-high-performance fiber-reinforced concrete under elevated temperatures," *Struct. Concr.*, 20(6), 2019, pp.1896–1908.
81. P. Winkler, "Selecting and specifying concrete surface preparation for sealers, coatings, and polymer overlays," *Concr. Repair Bull.*, 2013, pp.1361–1402.
82. J. Zhang and W. L. Lu, "Study on bonding performance of interlayer materials between old cement slab and asphalt overlay," in *Advanced Materials Research*,, 213(1), 2011, pp.633–637.
83. M. Chilwesa, F. Minelli, A. Reggia, and G. Plizzari, "Evaluating the shear bond strength between old and new concrete through a new test method," *Mag. Concr. Res.*, 69(9), 2017, pp.425–435.
84. T. Kamada and V. C. Li, "The effects of surface preparation on the fracture behavior of ECC / concrete repair system," *Cem. Concr. Compos.*, 22, 2000.
85. H. Heinrich, "Evaluation and preparation of surfaces for flooring systems," 2019.
86. F. Miguel Arrieta Pestana Miranda Ceia, J. Manuel Matos Noronha da Câmara Supervisor, E. Nuno Brito Santos Júlio Co-Supervisor, and J. Manuel Caliço Lopes de Brito, "Shear strength in the interface between normal concrete and recycled aggregate concrete," 2013.
87. M. R. Doria, A. T. C. Sales, and N. F. D. A. Andrade, "Bond strength between stell-concrete and between concretes with different ages in structural rehabilitation," *Rev. IBRACON Estruturas e Mater.*, 8(5), 2015, pp.604–624
88. B. A. Magbool, Hassan M. Tayeh, "Influence of substrate roughness and bonding agents on the bond strength between old and new concrete," 2021.
89. E. K. Tschegg and S. E. Stanzl, "Adhesive power measurements of bonds between old and new concrete," 1991.
90. L. Courard, "Parametric study for the creation of the interface between concrete and repair products," *Mater. Struct.*, 33(1), 2000, pp.65–72.
91. D. K. Harris, J. Sarkar, and T. T. M. Ahlborn, "Characterization of interface bond of ultra-high-performance concrete bridge deck overlays," *Transp. Res. Rec.*, 2240(1), 2011, pp.40–49.
92. Q. Luo, W. Wang, B. Wang, S. Xu, and Z. Sun, "Numerical study on interface optimization of new-to-old concrete with the slant grooves," *Structures*, 34(1), 2021, pp.381–399/
93. P. Ganesh and A. Ramachandra Murthy, "Simulation of surface preparations to predict the bond behaviour between normal strength concrete and ultra-high performance concrete," *Constr. Build. Mater.*, 250(1), 2020, pp.1-12.
94. B. Zareiyan and B. Khoshnevis, "Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete," *Autom. Constr.*, 83(1), 2016, pp.212–221.
95. R. Z. Al-rousan and M. F. Al-tahat, "Consequence of surface preparation techniques on the bond behavior between concrete and CFRP composites," *Constr. Build. Mater.*, 212(1), 2019, pp.362–374.
96. N. Su, L. Lou, A. Amirkhanian, S. N. Amirkhanian, and F. Xiao, "Assessment of effective patching material for concrete bridge deck -A review," *Constr. Build. Mater.*, . 293, p. 123520, 2021, doi: 10.1016/j.conbuildmat.2021.123520.
97. P. M. D. Santos, E. N. B. S. Júlio, and V. D. Silva, "Correlation between concrete-to-concrete bond strength and the roughness of the substrate surface," *Constr. Build. Mater.*, 21(8), 2007, pp.1688–1695.
98. G. Peng, D. Niu, X. Hu, B. Pan, and S. Zhong, "Experimental study of the interfacial bond strength between cementitious grout and normal concrete substrate," *Constr. Build. Mater.*,273(1), 2021, pp.1-12.
99. T. Guo, Y. Xie, and X. Weng, "Evaluation of the bond strength of a novel concrete for rapid patch repair of pavements," *Constr. Build. Mater.*, 186(1), 2018, pp.790–800.
100.Z. Tang, F. Huang, and H. Peng, "Effect of 3D roughness characteristics on bonding behaviors between concrete substrate and asphalt overlay," *Constr. Build. Mater.*, 70(1), 2021, pp1-12.
101.J. Van Der Putten, G. De Schutter, and K. Van Tittelboom, "Surface modification as a technique to improve inter-layer bonding strength in 3D printed cementitious materials," *RILEM Tech. Lett.*, 4(1), 2019, pp.33–38.
102.E. S. Júlio, F. Branco, and V. D. Silva, "Structural rehabilitation of columns with reinforced concrete jacketing," *Prog. Struct. Eng. Mater.*,5(1), 2003, pp.29–37.
103.F. Pultorak, Andrew S.; Rutz, "The effects of common surface pre-treatments on the shear strength of bonded concrete overlays," 2016.
104.J. Silfwerbrand, "Shear bond strength in repaired concrete structures," *Mater. Struct.*,36(6), 2003 pp.419–424.
105.M. Norbert, A. Nanni, J. J. Myers, and G. Galecki, "Laser profilometry for concrete substrate characterization prior to FRP laminate application durability of GFRP rebars in seawater environments view project life cycle cost and life cycle assessment analyses of FRP structures view project," 2001.
106.G. Torelli and J. M. Lees, "Interface bond strength of lightweight low-cement functionally layered concrete elements," *Constr. Build. Mater.*, 249(1), 2020, pp.1-12.
107.Y. He, X. Zhang, R. D. Hooton, and X. Zhang, "Effects of interface roughness and interface adhesion on new-to-old concrete bonding," *Constr. Build. Mater.*, 151(1), 2017, pp.582–590.
108.J. Fan, L. Wu, and B. Zhang, "Influence of old concrete age, interface roughness and freeze-thawing attack on new-to-old concrete structure," *Materials (Basel).*,14(5), 2021, pp.1–15.
109.A. Al-ostaz, M. Irshidat, B. Tenkhoff, and P. S. Ponnapalli, "Deterioration of bond integrity between repair material and concrete due to thermal and mechanical incompatibilities," *J. Mater. Civ. Eng.*, 22(1), 2010, pp.136–144.
110.E. N. B. S. Júlio, F. A. B. Branco, and V. D. Silva, "Concrete-to-

concrete bond strength: Influence of an epoxy-based bonding agent on a roughened substrate surface," *Mag. Concr. Res.*, 57(8), 2005, pp.463–468.
111.E. N. B. S. Júlio, F. A. B. Branco, V. D. Silva, and J. F. Lourenço, "Influence of added concrete compressive strength on adhesion to an existing concrete substrate," *Build. Environ.*,41(12), 2006, pp.1934–1939.
112.J. C. T. S. Climaco and P. E. Regan, "Evaluation of bond strength between old and new concrete in structural repairs," *Magazine of Concrete Research*, 2001 pp.377–390.
113.A. N. Cavalcanti, A. F. De Lima, A. R. Peris, F. H. O. Mitsui, and G. M. Marchi, "Effect of surface treatments and bonding agents on the bond strength of repaired composites," *J. Esthet. Restor. Dent.*, 19(2), 2007, pp.90–98.
114.A. Garbacz, M. Górka, and L. Courard, "Effect of concrete surface treatment on adhesion in repair systems," *Mag. Concr. Res.*, 57(1), 2005, pp.49–60.
115.M. Valipour and K. H. Khayat, "Debonding test method to evaluate bond strength between UHPC and concrete substrate," *Mater. Struct. Constr.*, 53(1), 2020, pp.1-10.
116.M. Kuroda, T. Watanabe, and N. Terashi, "Increase of bond strength at interfacial transition zone by the use of fly ash," *Cem. Concr. Res.*, 30(2), 2000, pp.253–258.
117.J. Shao *et al.*, "Effect of waste rubber particles on the mechanical performance and deformation properties of epoxy concrete for repair," *Constr. Build. Mater.*, 241(1), 2020, pp.1-12.
118.R. Radhakrishnan, S. V Prakash, C. K. Prasad, and V. Thampan, "Performance of styrene butadiene rubber as a concrete repair material in tropical climate," *Int. J. Adv. Res. Technol.*, 1(1), 2012, pp.1-12.
119.Y. Zhang, P. Zhu, X. Wang, and J. Wu, "Shear properties of the interface between ultra-high performance concrete and normal strength concrete," *Constr. Build. Mater.*, 248(1), 2020, pp.1-14.
120.M. Rith, Y. K. Kim, S. W. Lee, J. Y. Park, and S. H. Han, "Analysis of in situ bond strength of bonded concrete overlay," *Constr. Build. Mater.*, 111(1), 2016, pp.111–118.
121.A. Valikhani, A. J. Jahromi, I. M. Mantawy, and A. Azizinamini, "Effect of mechanical connectors on interface shear strength between concrete substrates and UHPC: Experimental and numerical studies and proposed design equation," *Constr. Build. Mater.*, 267(1), 2021, pp.1-12.
122.S. Feng, H. Xiao, M. Ma, and S. Zhang, "Experimental study on bonding behaviour of interface between UHPC and concrete substrate," *Constr. Build. Mater.*, 311(1), 2021,pp.1-14.
123.N. K. Emberson and G. C. Mays, "Significance of property mismatch in the patch repair of structural concrete Part 1: Properties of repair systems," *Mag. Concr. Res.*, 42(152), 1990, pp.147–160.
124.W. Ten Kuo, M. Y. Liu, and C. U. Juang, "Bonding behavior of repair material using fly-ash/ground granulated blast furnace slag-based geopolymer," *Materials (Basel).*,12(10), 2019, pp.1-9.
125.G. Xiong, J. Liu, G. Li, and H. Xie, "A way for improving interfacial transition zone between concrete substrate and repair materials," *Cem. Concr. Res.*, 32(12), 2002, pp.1877–1881.
126.J. Fan and B. Zhang, "Repair of ordinary Portland cement concrete using alkali activated slag/fly ash: Freeze-thaw resistance and pore size eution of adhesive interface," *Constr. Build. Mater.*, 300(1), 2021, pp.1-12.
127.K. W. Shah and G. F. Huseien, "Bond strength performance of ceramic, fly ash and GBFS ternary wastes combined alkali-activated mortars exposed to aggressive environments," *Constr. Build. Mater.*, 251 (1), 2020, pp.1-12.
128.A. Islam, U. J. Alengaram, M. Z. Jumaat, and I. I. Bashar, "The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar," *Mater. Des.*, 56(1), 2014, pp.833–841.
129.S. M. Laskar and S. Talukdar, "Preparation and tests for workability, compressive and bond strength of ultra-fine slag based geopolymer as concrete repairing agent," *Constr. Build. Mater.*, 154(1), 2017, pp.176–190.
130.J. Fan, H. Zhu, J. Shi, Z. Li, and S. Yang, "Influence of slag content on the bond strength , chloride penetration resistance , and interface phase eution of concrete repaired with alkali activated slag / fly ash," *Constr. Build. Mater.*, 263(1), 2020, pp.1-8.
131.S. B. Singh and P. Munjal, "Engineered cementitious composite and its applications," *Mater. Today Proc.*, 32(1), 2020, pp.797–802.
132.M. D. Lepech and V. C. Li, "Sustainable pavement overlays using Engineered Cementitious Composites," *Int. J. Pavement Res. Technol.*, 3(5), 2010, pp.241–250.
133.E. Vasconcelos, S. Fernandes, B. De Aguiar, and F. Pacheco-Torgal, "Concrete Retrofitting Using CFRP and Geopolymer Mortars," 2011.

Abbreviation

α	Interface angle with vertical (in degree)	LRG	Low Roughness
τ	Shear strength(MPa)	SCRM	Supplementary Cementitious Repair Materials
h	Height (mm)	HRGDH	High Roughness Texture with Drilled Holes
φ	Diameter (mm)	L-SST	L Shaped Slant Shear Test
B_h	Base Height (mm)	MCM	Modified Cementitious Mortars
t	Thickness (mm)	MKPC	Magnesium Potassium Phosphate Ceramics Mortar
R	Rough-Aggregate Exposure	MPC	Magnesium Phosphate Cement
HS	Hand Scrubbed	M-SST	Modified Slant Shear Test
W	Wavy Surface	NC	Normal Concrete
W/B	Water Binder Ratio	OTZ	Overlay Transition Zone
K100	K100 Polymer Adhesive	PC	Portland Cement
AC	Asphalt Concrete	POT	Pull-Off Test
ACI	American Concrete Institute	PVA	polyvinyl acetate
AMCM	Adhesive Modified Cementitious Mortar	SHB	Shot-Blasted
ASD	Air Surface Dry	RAC	Recycled Aggregates Concrete
ASW	Air Surface Wet	RPC	Reactive Powder Concrete
CC	Conventional Concrete	RSA	Rapid-Setting Adhesive
CS	Compressive Strength	SAC	Sulpho Aluminate Cement
CSP	Concrete Surface Profiles	SB	Sand Blasting
DH	Drilled Hole	SBR	Styrene-Butadiene Resin
DST	Double Sleeve Tests	SCC	Self-Compacting Concrete
DTT	Direct Tensile Test	SCHPC	Self-Compacting High-Performance Concrete

ITZ	Interfacial Transition Zone	SCM	Self-Consolidated Mortar
ICRI	International Concrete Repair Institute	SF	Silica Fume
EBA	Epoxy-Based Adhesives	UHPC	Ultra-High-Performance Concrete
ECC	Engineered Cementitious Composite	SFRC	Steel Fiber Reinforced Concrete
FR-SCRMs	Fiber Reinforced Self-Consolidating Repair Mortars	SSD	Saturated Surface Dry
GS	Grooved Surface	SSBS	Slant Shear Bond Strength
GUSMRC	Green Universiti Sains Malaysia Reinforced Concrete	SC	Surface Chipping
HCS	Hammered Concrete Surface	SST	Slant Shear Test
HDC	Hammer Drilling with Chipping	STT	Splitting Tensile Test
HPFRC	High-Performance Fiber Reinforced Concrete	VD	Valley Depth (mm)
HPFRM	High-Performance Fiber-Reinforced Mortar	UHPFC	Ultra-High-Performance Concrete
HRG	High Roughness Surfaces	WB	Wire Brushed