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The influence of interfacial bond between substrate and overlay concrete by bi-surface shear test and split prism test

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Abstract

The interfacial bonding between damaged concrete structures and newly applied repair materials is one of the significant issues for the structure's functionality, safety, and durability. To prevent failure, a strong bond is required at the interface. This paper investigates the interfacial bond strength for different concrete mixes and the surface patterns used. In the present experimental study, three concrete mixtures, M20, M30, and M45 were used for substrate concrete casting, and based on the 28 days strength of substrate concrete, the concrete overlay mix of the same strength was used. Rectangular groove, V-type groove, U-type groove, S-type groove, Trapezoidal groove patterns, and As-cast with or without an Epoxy-based agent were used as different surface profiles on the substrate surface. Two types of direct shear tests, the Bi- Surface Shear test and the Splitting Prism test, were used to measure the bond strength after 28 and 56 days. The results concluded that at 28 and 56 days, the RG and EB had higher bond strength compared to the As-cast for both BSST and SPT.

Keywords: Bi-surface shear test, Bond strength, Interface layer, Overlay concrete, Split prism test, Substrate concrete

1. Introduction

During the service life, internal or external forces can damage the concrete structures. The demolition and construction of the new structure involve a huge amount of resources. So, the best method is repairment of the damaged structure. The bond between the substrate and overlay material is crucial in concrete repair. A good bond between two concrete surfaces enhances the structure's service life. The Bond strength of concrete mainly depends upon the surface roughness, loading condition, surface conditions, and other environmental factors such as temperature and other time-dependent factors. The type of overlay affects the bond strength, which influences load-bearing capacity and durability. The use of a strong interface connection can improve bond strength. Based on the type of stress, the tests used to measure the bond strength of substrate and overlay material can be classified into three main groups: pure shear, tension, and a combination of compression and shear [1-3]. However, most of the available bond tests showed lack of details due to the shear stresses, loading pattern, and other factors. For example, a compression-shear test is a method in which the specimen is compressed, not the interface. Interface layer bonding depends on various factors like workability [4,5] surface roughness [6-9], bonding agent [10], surface moisture condition [11,12], overlay materials strength [13-15], age of concrete [16,17] specimen size [5,18,19], micro-cracking [20] shrinkage of concrete [21,22] cohesion in the substrate concrete [23,24] aggregate interlock [24,25] and other time-dependent factors [1,26]

Early in this research, choosing the correct method is crucial because; various types of tests are available to determine the bond strength, like Bi-Surface Shear Test (BSST), Slant Shear Test (SST), Split Prism Test (SPT), etc. So, it is necessary to find the best and most simple method to determine the exact bond strength of the composite. SST is defined based on compression and shear stress loading, but; BSST is only due to pure shear stress. BSST was developed by Momayez et al. to evaluate the interferential bond strength of specimen 150(l) × 50(w) × 150(h) mm, low and high roughness [27]. This test resembles the Direct Shear Test (DST), but in BSST, the loading plane is single. According to the Beushausen et al. [28], BSST mainly depends on the substrate-overlay properties like surface texture, type of materials, etc. Lee et al. [29] examined the UHPC behavior as an overlay and found that the UHPC showed higher strength with this test. Valikhani et al. [16] used the 38 (t) × 51 (w) × 153 (l) sized specimen with and without a mechanical connector and found that the use of a connector lowered nearly half of the bond strength as compared to the rough surfaces.

The surface preparation mainly affects the bond strength, which increased up to 134% with a rough surface compared to a smooth surface [30]. A bond strength relationship between the SST and BSST was found by Al-Rubaye et al. [31] stated that the SST strength was nearly three times the BSST strength. BSST is a simple test to determine the bond strength as per the ASTM C 496:1996 [32]. BSST and SPT tests are similar to the split tensile test; the only difference is the specimen's geometry. Also, BSST gives that freeze-thaw effects on the bond strength [33]. Grigoriadis et al. [34] found out the durability behavior of bonding by SPT and stated that the fresh bonding is not influenced at 28 days of age with microwave curing. So, in the present study, various types of surface treatment were carried out to fulfill the demand for suitable bond surfaces. Also, a relationship between SPT and BSST with a suitable overlay grade was evaluated experimentally. BSST and SPT were adopted in this study due to the simplicity of specimen preparation and loading condition.

In case of combined shear and tension, reinforcement crossing the interface is required. In this case the shear strength of a concrete-to-concrete interaction depends on various factors, such as the adhesion of the particles, the friction between the concrete layers, and the shear force resisted by the reinforcement. The force transmission mechanism between the concrete and embedded steel reinforcing bars determines the composite performance of reinforced concrete. It depends on the test configuration, the size of the concrete specimen, the bond length, the placement of the rebar, and the loading rate. Randl et al. [35] conducted pullout tests on post-installed reinforcing bars to study the load transfer mechanisms under service loads. In this instance, both tensile and shear force plays the dominant role.

2. Materials and methods

In the present study, various types of surface patterns like Rectangular Groove (RG), V-type Groove (VG), U-type Groove (UG), S-type Groove (SG), Trapezoidal Groove (TG) patterns, and As-Cast (AC) with or without an Epoxy-Based agent (EB) were used as different surface profiles on the substrate surface. BSST and SPT were used to find their correlation among bond strength. The materials, methodology, specimen geometry, and outcome are below.

2.1 Materials

This experimental program used OPC43 grade cement with a specific surface area of 345 m^2/kg and a density of 3.15 g/cm^3. Crusher sand and coarse aggregate with a fineness modulus of 2.6 and 7.8 were used, respectively. Sika Plast 4202NS were used to achieve a 120-150 mm slump. Normal potable water was used in the mixing and curing process. The 211 DR. FIXIT Epoxy Bonding agent was also used as a surface treatment.

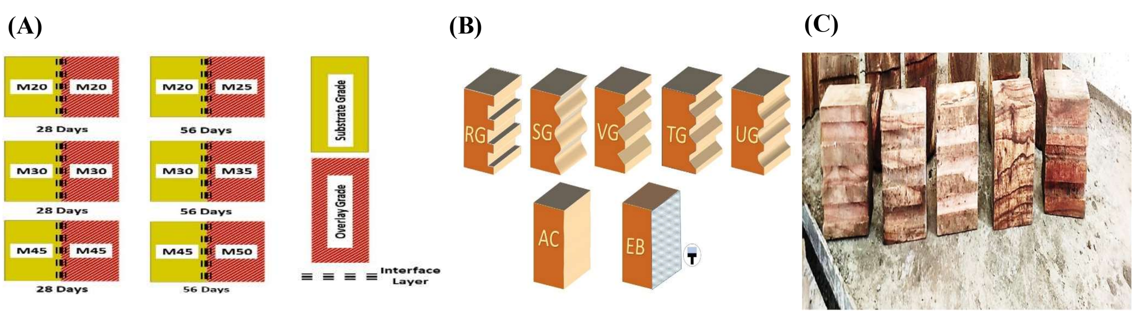

Figure 1 Specimen Setup, in which (A) Substrate and overlay combination, (B) Different types of surface profile, and (C) Fabricated samples for various surface profile.

2.2 Mix proportions

Three grades of standard concrete, M20, M30, and M45, were used for the substrate layer casting. The trial mixes were performed to obtain the maximum compressive strength of concrete. The compressive strength was measured with the help of a 150 × 150 × 150mm^3 cube. Based on higher strength and relative slump, suitable mixes were found (Table 1). All the mix grade was performed as per IS10262 and IS 456 codal provision. In the present experimental study, three concrete mixtures, M20, M30, and M45 were used for substrate concrete casting, and based on the 28 days strength of substrate concrete, the concrete overlay mix of the same strength was used. All the grade overlay combination with substrate has been shown in Figure 1(A).

Table 1 Mix Proportion of various concrete grade.

Grade	Cement	Sand	CA	W/C	SP(%)
M20	1	1.60	3.56	0.47	-
M25	1	1.49	3.04	0.45	-
M30	1	1.56	2.92	0.43	0.7
M35	1	1.58	2.47	0.42	0.7
M40	1	1.62	2.81	0.40	1
M45	1	1.58	2.34	0.40	1
M50	1	1.60	2.51	0.37	1

2.3 Preparation of the specimens

The wooden block was patterned into RG, VG, UG, TG, and SG to make various surface patterns**.** The details of surface patterns have been shown in Figure 1(B), and the fabricated wooden block in Figure 1(C). All the specimens were prepared at the wooden workshop of the institute. The valley depth of 4-8 mm and spacing of 20-50 mm was fixed for RG, SG, VG, TG, and UG patterns according to their shape. The width of the valley was changed due to the different surface patterns. Other than the groove patterns, the AC and EB surfaces were smooth. Whereas 'smooth' means the surface has no grooves or irregularities. However, it was considered that the surface roughness was similar for all the groove patterns. In AC, no surface preparation was carried out, but; for EB surface was prepared by application of the average 1mm thickness of the bonding agent.

Generally, surface preparation and cleaning of the concrete substrate is a decisive setup in concrete repair. An inadequately prepared surface will always be the weakest part of any repair, regardless of the quality of the repair material. Surface preparation involves the removal of damaged or deteriorated portions of the underlying concrete; whereas, surface cleaning typically refers to removing loose particles and impurities. Surface cleaning is also essential for concrete repairs since loose debris, grease, dirt, and other surface pollutants can decrease the bond strength [36]. So, in this research, surface cleaning is carried out before the overlay cast by removing dust and other foreign material by dry brushing. High workable repair material as overlay altered the bond strength, particularly for rough substrate surfaces. Subsequently, it can fill the substrate pores, creating a low porosity interfacial zone between the substrate and the overlay concrete.

Comparatively, poor workable repair materials may not fill gaps caused by rough surfaces and form pores in the interfacial region. However, proper care must be given because more workable repair materials may absorb more water, resulting in shrinkage of repair materials, stress concentration, and cracking at the interface zone.

In addition, if the polymer-based coating is applied on substrate-overlay concrete, its low w/b ratio can reduce the bond strength [37]. In overlay concrete, the addition of pozzolan to the cement slurry makes it more rigid and causes an increase in stresses at the interface, and decreases bond strength. Moreover, increased water usage decreases the efficiency of polymer-based adhesives [38].

Bond strength depends on overlay workability. Even stiff overlays can adhere well if pressure and placement application are appropriate. Also, the less workable repair material's mechanical strength directly affects bond strength. Shrinkage, elastic modulus, thermal coefficient, creep, permeability, fiber reinforcement, admixtures, and other material qualities that affect stress development in the repair and interface are also important.

2.4 Compressive strength

The compressive strength of the M20, M30, and M45 was measured at the age of 28,56 days. The cubes were cast as per IS10262 and IS456 and cured for a 28 days. After that, samples were stored for 56 days in the laboratory. The samples were protected by the direct wind, sun, and humidity. The compression test was carried out as per IS516:1959, and based on the 28 days strength of substrate concrete, the concrete overlay mix of the same strength was used. In the compression test, no surface treatment was included. Before pouring the concrete, all molds were lubricated to avoid the stickiness of the material with the cube surface. The samples were cured in the water tank and tested in a compression testing machine after 28 days of overlay casting. The full description of compressive strength has been shown in Figure 4.

2.5 Bi-shear surface test

The BSST was used to evaluate the substrate and overlay bond strength. The wooden block was cut into $150 \times 150 \times 50$ mm^3, and the surface patterns were designed. The prepared specimen was inserted into the cube $150 \times 50 \times 150$ mm^3. BSST was carried out to estimate the bond strength between substrate-overlay concrete at ages 28 and 56 d. In this test, one-third of substrate concrete and two-thirds of overlay concrete in a cube specimen was cast as per the test criteria and shown in Figure 2(A). The loading was done at the compression testing machine. For symmetric loading, a three-steel plate of size 150 in length, 50 mm in width, and 20 mm in thickness was fabricated and utilized, as shown in Figure 2(B). The Experimental setup of BSST is shown in Figure 2(C).

The BSST setup is comparable to the alos frenquently used so called ‘push-out’ setup. Similarly and as expected, the bond strength from the push-out test is lower than that from the SST. In SST, it is due to the application of compressive stresses at the interface and loading patterns, which are significantly affected by frictional and interlocking effects at the interface, unlike the push-out test. Also, due to unavoidable small eccentricities between the load point and support points, the interface in push-out tests is subjected to minimal bending moment effect and resulting tensile stresses. This effect might in addition contribute to somewhat lower bond values typically observed with this test setup [39], however, SST-setup has on the other side a clear beneficial effect on interface shear strength and contributing interlocking mechanisms.

(A) **(B)** **(C)**

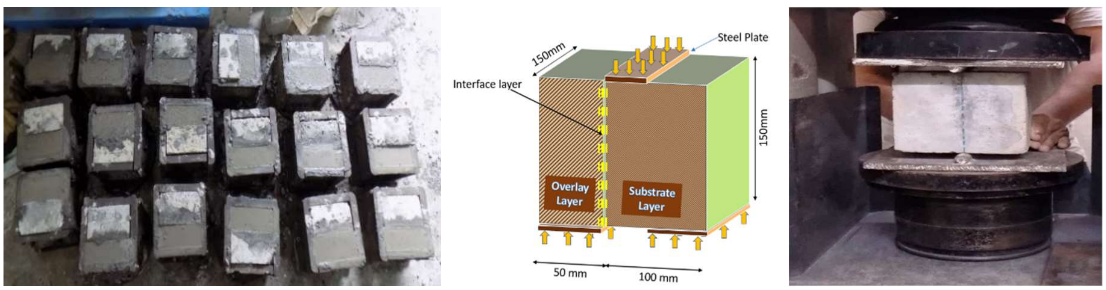

Figure 2 Experimental Setup, in which (A) Overlay casting of BSST and SPT, (B) BSST loading diagram, and (C) Experimental setup of BSST.

The plate was set up as per the testing procedure. The load was applied to the plate, which distributed the load evenly to the composite specimen. BSST strength was determined as per Equation 1.

$$\sigma_b = \frac{P_b}{A_b} \quad (1)$$

σ_b= BSST bond strength (MPa); P_b= ultimate load in (kN); A_b= Interface shear area (2 bd)(mm^2)

2.6 Splitting prism test

SPT samples were prepared by inserting half a wooden block in the 150 × 150 × 150 mm^3 molds. The 150(l) × 150(h) × 75(w) mm wooden blocks were patterned according to the RG, SG, VG, TG, and UG types surface profile to prepare the substrate specimen of SPT.

The SPT samples were cast into two steps. The cube molds were lubricated with oil, and the wooden fabricated block of different surface patterns was inserted into the cube mold. The substrate concrete was cast with the help of a concrete mixture and a vibrating table. The demolding process was finished after 24 h, and the substrate specimens were cured for 28 days under normal temperature and humidity conditions. The test samples were kept in the lab after 28 days in normal conditions for 28 days and 56 days overlay casting, away from the wind, sun, and rain, and no special curing process was used. In the second phase, the overlay concrete was designed based on the compressive strength of substrate concrete. After casting, the same overlay process was followed as per discussed previously. At the age of 28 days of overlay, the bond strength was determined. The SPT was carried out in a compression testing machine at 28 and 56 days according to the loading system shown in Figure 3(A). The experimental setup of SPT is shown in Figure 3(B). The SPT bond strength is determined by Equation 2.

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

T= SST strength (MPa); P= Applied load (kN); A= Bond Area (mm^2)

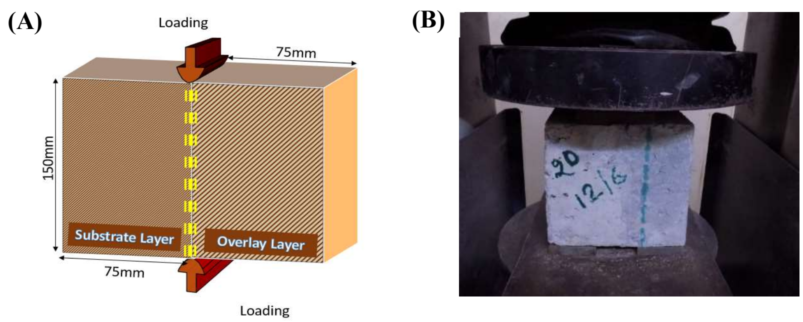

Figure 3 Experimental Setup of SPT, in which (A) Split prism test loading diagram, and (B) Experimental setup of SPT.

3. Results and discussion

3.1 Compressive strength

The compressive strength test was performed as per the IS 384:2000 guidelines. The overlay concrete mix grade was decided based on 28 and 56 days, and based on the 28 days strength of substrate concrete, the concrete overlay mix of the same strength was used. From Figure 4, it is clear that the substrate layer strength increased with the curing period. At 28 days, the M20 (28 days) strength was 27.63 MPa, so the mixed grade similar to that strength was defined as M20 (28 days). Similarly, M45 (56 days) strength was 57.25 MPa, so the mixed grade similar to that strength was defined as M50 (28 days).

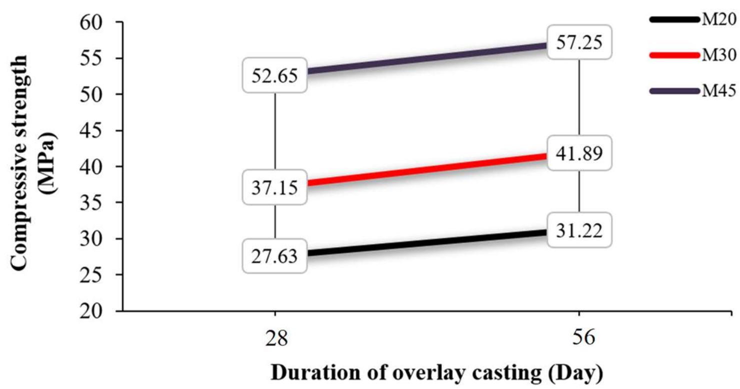

Figure 4 Compressive strength with required overlay mix grade of concrete.

3.2 BSST and SPT

In BSST and SPT types of bond strength tests, experimental data was collected to determine the stresses corresponding to the failure load. To examine the effects of the variable parameters on the performance of the bond between normal concrete (NC) over NC substrate depending on age, failure patterns were identified. As failure typically occurred in the interfacial zone, the failure resulting from stress was considered the bond strength. Alternatively, where the failure occurred in the concrete substrate, it was assumed that the bond strength was more significant than the strength of the substrate specimen. The interface shear strength determined through testing partially depends on the test setup. Several test methods relating to interface bonding are summarised in Refs. [3,39-41] such as pure tensile and shear bonding tests with or without compression stress. Normal and shear loads, stress states/distributions, load eccentricities, and load deviations between an acting load and supports make the test setup sensitive. Over that, there is no direct conversion formula between tensile and shear bond strength.

Figures 5(A), 5(B) and 6(A), 6(B) display the bond strength with of the seven types of surface treatments by BSST and SPT, respectively.

Figure 5(A) shows a variation of the bond strength by BSST, and it can be deduced that with a change in surface patterns from EB to RG, the bond strength increases by 123.33%, 124.24%, and 127.5% for M20, M30, and M45, respectively at 28 days. It was also found that the highest percent increment for the RG pattern is 86.11%, 85%, and 89.58% for M20, M30, and M45, respectively, compared to the AC pattern with all-surface treatment. The RG pattern shows the maximum bond strength for all types of mixes, whereas the EB type pattern shows the least effective bond strength corresponding to M20, M30, and M45, which can be attributed to the fact that the application of epoxy agent on the substrate creates a new layer that reduces friction between the two layers, which leads to a lack of proper bonds between them.

The bond strength was found to be 16.66%, 17.50%, and 18.75% for SG; 44.44%, 47.50%, and 47.91% for TG; 58.33%, 60%, and 62.5% for UG; and 77.77%, 80 %, and 81.25 % for VG pattern with M20, M30, and M45, respectively as compared to AC surface. The bond strength was found to be lowered by 16% for all grades when an epoxy agent was applied to the substrate surface. The bond strength was enhanced by approximately 10% and 20% when the substrate grade was changed from M20 to M30 and M30 to M45, respectively.

Figure 5(B) shows the variation of the bond strength by BSST, and it can be deduced that with a change in surface patterns from EB to RG, the bond strength increases by 123.33%, 124.24%, and 127.5% for M20, M30, and M45, respectively at 28 days. It was also found that the highest percent increment for the RG pattern is 85.36 %, 86.95%, and 87.5% for M20, M30, and M45, respectively, as compared to the AC pattern with all-surface treatment. The bond strength was found to be AC. 17.02%, 16.98%, and 15.38% for SG; 38.29%, 37.73%, and 35.38% for TG; 40.42%, 39.62%, and 40% for UG; and 57.44%, 58.49%, and 58.46% for VG pattern with M20, M30, and M45, respectively as compared to AC surface. The bond strength was lowered by 13% for all grades when an epoxy agent was applied to the substrate surface. The bond strength was enhanced by approximately 12% and 22% when the substrate grade was changed from M20 to M30 and M30 to M45, respectively.

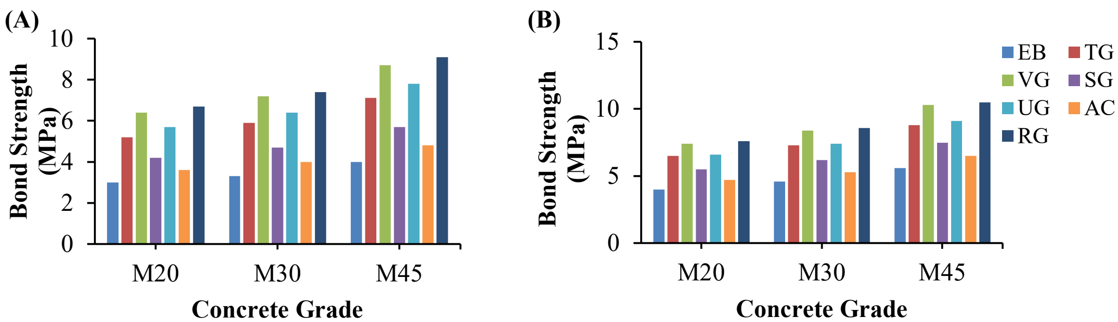

Figure 5 BSST results, in which (A) BSST bond strength at 28 days with different concrete grade, and (B) BSST bond strength at 56 days with different concrete grade.

Figures 5(A) and 5(B) show that; the increase in bond strength was higher after 56 days as compared to 28 days for all patterns because; the bond performed better at full heat of hydration with all grades. Specimen having surfaces with grooves increases the bond area and strengthens the fine material locking force creating the strongest bond. Out of all surface patterns, the EB surface pattern showed the most significant increase in bond strength because; the bond strength is influenced by the strength of the (interfacial transition zone) ITZ between substrate and overlay concrete. The strength of concrete increases as ITZ strength increases. The percentage increase in bond strength at 56 days compared to 28 days was lower for the AC, SG, TG, UG, VG, and RG patterns. Therefore, it was concluded that a significant influence in the bond strength at 56 days was less than at 28 days because; the groove pattern destroyed the top layer of the substrate and put stress on the edges of the grooves, which caused the reduction in BSST bond strength. Thus, the RG-type bond gives maximum strength among all possible shapes and is easier to construct. So, it is the most effective pattern that can be used to enhance bonds in concrete, and the use of RG, VG, and UG patterns showed better results than Al-Rubaye et al. [31].

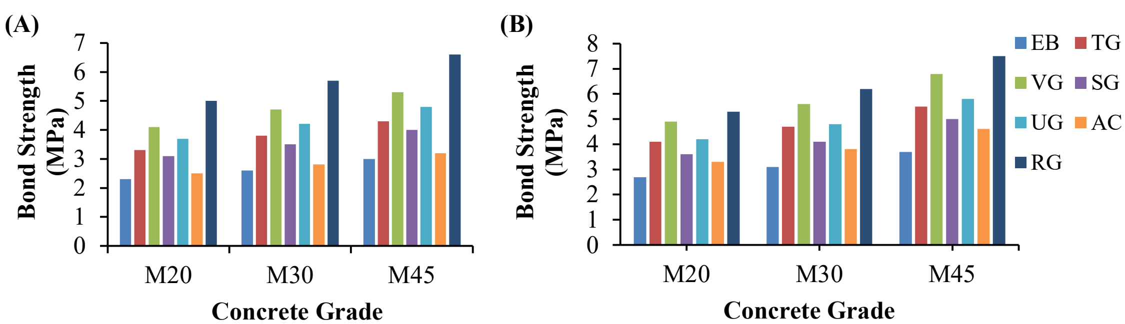

Figure 6 SPT results, in which (A) SPT bond strength at 28 days with different concrete grade, and (B) SPT bond strength at 56 days with different concrete grade.

Figure 6(A) shows the variation of the bond strength by SPT, and it can be deduced that with a change in surface patterns from EB to RG, the bond strength increases 117.39%, 119.23%, and 120% for M20, M30, and M45, respectively at 28 days. It was also found that the highest percent increment for the RG pattern is 100%, 103.57%, and 106.25% for M20, M30, and M45, respectively, compared to the AC pattern with all-surface treatment. The bond strength was found to be AC. 24%, 25%, and 25% for SG; 32%, 35.71%, and 34.37% for TG; 48%, 50%, and 50% for UG; and 64%, 67.85%, and 65.62% for VG pattern with M20, M30, and M45 respectively as compared to AC surface. The bond strength was found to be lowered by 8% for all grades when an epoxy agent was applied to the substrate surface. The bond strength was enhanced by approximately 13% and 15% when the substrate grade was changed from M20 to M30 and M30 to M45, respectively.

Figure 6(B) shows the variation of the bond strength by SPT, and it can be deduced that with a change in surface patterns from EB to RG, the bond strength increases by 96.29%, 100%, and 102.7% for M20, M30, and M45, respectively at 28 days. It was also found that the highest percent increment for the RG pattern is 60.60%, 63.15%, and 63.04% for M20, M30, and M45, respectively, as compared to the AC pattern with all-surface treatment. The bond strength was found to be AC. 9.09%, 7.89%, and 8.69% for SG; 24.24%, 23.68%, and 19.56% for TG; 27.27%, 26.31%, and 26.08% for UG; and 48.48%, 47.36%, and 47.82% for VG pattern with M20, M30, and M45, respectively as compared to AC surface. The bond strength was found to be lowered by 18% for all grades when an epoxy agent was applied to the substrate surface. The bond strength was enhanced by approximately 15% and 20% when the substrate grade was changed from M20 to M30 and M30 to M45, respectively.

The BSST and SPT bond strength directly influence the interface bond strength because the BSST strength is increased with the higher grade. Furthermore, as seen from the test results, the bond strength increased with the curing age of the substrate specimens**.** This increment in strength is due to the higher compressive strength leading to better bonding. The bond strength indicates that the overlay materials significantly affect the bond strength owing to their ability to fill the grooved on the substrate surface, which improves the mechanical interlocking in the substrate and the adequate contact area between the substrate and the overlay concrete.

In addition, compared to the AC and EB, the grooved specimens showed a definite increase in bond strength, and out of these two surface preparation specimens, the grooved specimens exhibited a higher bond strength for both tests. The RG and VG patterns showed higher bond strength because these specimens provided a better interlock between the overlay and substrate for BSST and SPT.

On the contrary, in BSST and SPT, the specimens with EB-treated surface treatment have the lowest bond strength because of slipping off the EB layer between the substrate and overlay concrete. Also, the effect of EB was reduced with available moisture content at the time of overlay casting. The addition of EB at the interface layer reduced the heat of hydration at the treated surface, reducing the bond strength. For more details, further study is required.

The mixed failure mode was recorded in the RG, UG, and TG patterns, showing better substrate bonding and overlay concrete in BSST and SPT. Similarly, for AC and EB, interface failure was observed.

From all observations of the bond strength, BSST shows approximately 1.5-2 times higher strength than SPT. Bond strength with all grooved patterns and surface preparation was suitable [42-45]. At the testing time, various types of failure occurred, like substrate failure, interface failure, and overlay failure, and a mix of them was recorded.

(A) **(B)**

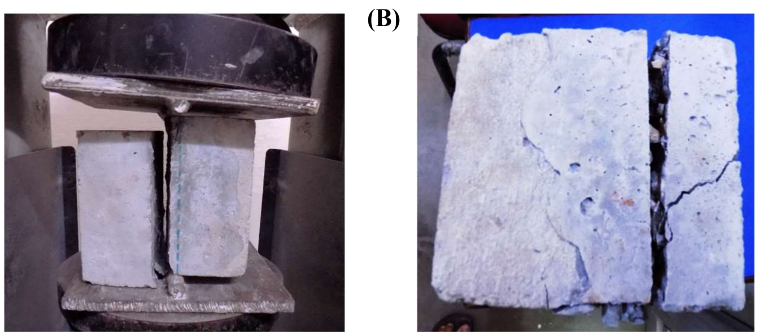

Figure 7 Failure behaviour, in which (A) SPT specimen failure, and (B) BSST specimen failure.

The different grooved patterns showed different failure modes. The failure mode of SPT and BSST has been shown in Figures 7(A) and 7(B), respectively. At 28 days of curing, most of the failure was overlay failure due to the lower age of overlay concrete. With increases in the age of curing of overlay concrete, mixed failure was observed, but pure interface failure was observed in the as-cast and EBA treatment. At 56 days, the substrate failure is the most observed failure due to the higher strength or overlay than the substrate concrete [46]. The RG and VG patterns showed higher bond strength because these specimens provided a better interlock between the overlay and substrate for BSST and SPT. At 56 days, the substrate failure is the most observed failure due to the higher strength or overlay than the substrate concrete. Adding an epoxy agent lowers the bond strength for all grades in both test setups. Among all the substrate-overlay specimens, grooved specimens showed the highest bond strengths at 28 and 56 days for both BSST and SPT.

4. Conclusion

This research investigates the effects of test setup and interface surface treatment for BSST and SPT on interface bond strength. The splitting tensile strength and bi-surface shear strength of the concrete-to-concrete interface were measured using concrete interfacial roughness with grooves and adhesives. The main outcomes of the study are given below. In addition, compared to the AC and EB, the grooved specimens showed a definite increase in bond strength, and out of these two surface preparation specimens, the grooved specimens exhibited a higher bond strength for both tests. From all observations of the bond strength, it is concluded that BSST shows approximately 1.5 to 2 times higher strength than SPT. The bond strength decreases in the following order: RG, VG, UG, TG, SG, AC, and EB.

The splitting tensile strength and bi-surface shear strength of the concrete-to-concrete interface were positively linear with the concrete interfacial fractal dimension. The binding strength of the concrete-to-concrete contact increased as the fractal dimension of the concrete interface increased; whereas, adhesive bond efficiency declined. When the concrete-to-concrete interface is weak, the failure mode is often characterized by a separation or detachment between the two surfaces, which is an unfavorable outcome. However, by increasing the interfacial roughness, the concrete-to-concrete interface becomes more strong, leading to a change in the failure mode. In this case, the concrete is more likely to resist separation. This is a favorable outcome because it indicates that the bonding between the two concrete surfaces is stronger, which ultimately strengthens the overall concrete structure.

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