Advances in Concrete Construction, *Vol. 13, No. 3 (2022) 265-279*
https://doi.org/10.12989/acc.2022.13.3.265

Bond behaviour at concrete-concrete interface with quantitative roughness tooth

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(*Received February 20, 2022, Revised March 18, 2022, Accepted March 30, 2022*)

Abstract. The roughness of substrate concrete interfaces before new concrete placement has a major effect on the interface bond behaviour. However, there are challenges associated with the consistency of the final roughness interface prepared using conventional roughness preparation methods which influences the interface bond performance. In this study, five quantitative interface roughness textures with different roughness tooth angles, depths, and tooth distribution were created to ensure consistency of interface roughness and to evaluate the bond behaviour at a precast and new concrete interface using the splitting tensile test, slant shear test, and double-shear test. In addition, smooth interface specimens and two separate the pitting interface roughness were also utilized. Obtained results indicate that the quantitative roughness has a very limited effect on the interface tensile bond strength if no extra micro-roughness or bonding agent is added at the interface. The roughness method however causes enhanced shear bond strength at the interface. Increased tooth depth improved both the tensile and shear bond strength of the interfaces, while the tooth distribution mainly influenced the shear bond strength. Major failure modes of the test specimens include interface failure, splitting cracks, and sliding failure, and are influenced by the tooth depth and tooth distribution. Furthermore, the interface properties were obtained and presented while a comparison between the different testing methods, in terms of bond strength, was performed.

Keywords: bond strength; cohesion; double-shear test; friction coefficient; precast and new concrete; quantitative roughness; slant shear test; splitting tensile test

1. Introduction

In a multi-phased civil engineering concrete construction, concrete-concrete connection interfaces exist between the parts cast at separate times. Be it a cast-in-place construction or a precast project, concrete-concrete interfaces exist in all medium or large-scale construction projects. The performance of these interfaces under loading is of primary concern to both structural and research engineers, as excellent interface bond behaviour is needed for adequate structural performance of the composite concrete member. As the performance of these interfaces are essential to the overall structural integrity, extensive research focus has been placed on the interface, with conclusions indicating that the interface is the weak link in the composite concrete structure (Hu *et al.* 2020, Zanotti *et al.* 2014, Magbool and Tayeh 2021). Since the interfaces cannot be completely avoided, several research attempts have been made to improve the interface behaviour, especially its bond strength in tension and shear.

To improve bonding behaviour of concrete connection interfaces, substrate concrete interface treatment using conventional methods such as sandblasting, shot-blasting, wire-brushing, chiselling, hand-scrubbing, chipping, and grooving are suggested (Julio *et al.* 2004). These treatment methods are however employed on already hardened concrete interfaces and therefore have varying effects on different substrate interfaces. During the treatment of these interfaces, factors such as the technician's skills, applied pressure on the surface, operation time, and age of the concrete materials significantly affect the final prepared interface. Completely different surface roughness may result from same treatment method, and even a rougher surface may arise from a lower level surface treatment method than that from a higher level treatment technique (Santos and Júlio 2013). In addition, high impact energy roughness methods which produce rougher interfaces often create interface zones marred with high void ratios, stress concentrations and micro cracking (He *et al.* 2017). In order to eliminate the uncertainty and lack of consistency of the final produced interfaces roughness and to ensure ease of reproducibility on multiple interfaces, some quantitative roughness preparation methods have been proposed and the influence of the quantitative roughness on the interface behaviour evaluated (Diab *et al.* 2017, Hu *et al.* 2020, Sharma *et al.* 2021, Luo *et al.* 2021). Diab *et al.* (2017) performed slant shear tests on a new self-compacting concrete and old concrete utilizing grooves of depths and widths of 3 mm and 6 mm; and 6 mm and 3 mm, respectively. Other conventional treatment methods were used along with the grooved roughness. Bond strength

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http://www.techno-press.org/?journal=acc&subpage=7

ISSN: 2287-5301 (Print), 2287-531X (Online)

increase of 26% was however obtained when the 6mm groove height and 3 mm groove width was used compared to other treatment methods. Hu *et al.* (2020) also conducted slant shear tests on quantitative rectangular slant grooves when examining the effects of static and dynamic loading on a new and old concrete interface. The slant grooved surface roughness had very limited effect on the interface shear behaviour, as reported by the authors. According to them, this result could be attributed to the matching dimensions of the designed roughness width and spacing. Luo *et al.* (2021) in their study on the optimization of old-new concrete interface expanded on Hu *et al.* (2020)'s research. In the study, the authors utilized the slant rectangular grooves designed by the primary researchers to alter the failure pattern, enhance bonding ability and improve the new-to-old concrete interface mechanical interlock. The study results indicate that a lone rectangular groove of depth 9 mm and width 55 mm produced the maximum interface shear strength between their new and old concrete. The researchers however pointed that excessive width of the roughness tooth weakens the concrete interface.

The effects of the new concrete mechanical properties on the composite concrete interface bond strength are important parameters for proper the bond performance. Silfwerbrand *et al.* (2011) highlighted that the compressive strength of the new concrete material does not significantly influence the interface bond strength, and only the new material tensile strength is important as it affects crack development at the interface. In contrast, Diab *et al.* (2017), while examining the influence of new concrete strength on slant shear bond strength observed a significant bond strength increase when the new concrete strength increased from 25 MPa to 35 MPa. Rahal *et al.* (2016) conducted experimental investigation on push-off specimens to evaluate the shear bond strength of normal and high strength self-compacting concrete. The authors observed that increasing the self-compacting concrete strength led to an increase in the specimen's maximum shear strength. Also, from Julio *et al.* (2006)'s study on interface adhesion between old and new concrete, increasing the new concrete strength resulted in an increase in the interface bond shear strength.

To comprehensively evaluate the bond performance at concrete interfaces, it is vital to determine concrete bonding under different stress states. Generally, tensile stress, shear stress and combined shear and compression stress state constitute the main stress conditions (Espeche and León 2011). Tensile stresses cause failure of the loading plane and split the specimen into two halves. The experimental tests under tensile stresses include direct tensile test, pull-off test, flexural test, and splitting test (Momayez *et al.* 2005). For shear stress states, test methods to evaluate interfaces under pure shear stresses include single shear test, double-shear test (push-out), direct shear test, bi-surface shear test, core drilling test, and bond-slip tests. Slant shear test is the main recognised test for concrete bonding interface subjected to combined shear and compression stresses and has been adopted by a several engineering design codes as a test method for evaluating the bond between concrete substrates and resinous repair materials.

As briefly presented previously, earlier studies indicate that adequate roughness of the substrate concrete interface can improve the bond behaviour at concrete-concrete interfaces, particularly the bond strength. The repeatability and consistency of the desired interface roughness (using conventional treatment methods) on multiple interfaces is however a challenge in practical Engineering (Aaleti and Sritharan 2019, Sharma *et al.* 2021). Efforts to address this problem birthed research into the use of quantitative roughness treatment methods. Quantitative roughness treatment also possesses extra advantage of greater control of the final surface roughness texture for improved interface bond hehaviour. However, there are very limited use of this quantitative roughness in research especially for normal strength concrete interfaces. In addition, the design of quantitative roughness to ensure improved interface bond behaviour needs further study. Therefore, a comprehensive experimental program involving the splitting tensile test, the slant shear test and the double-shear test was designed, implemented and presented in this paper. The effects of roughness tooth depth and roughness tooth distribution on the interface bond strength received special attention. The interface properties such as friction and cohesion coefficient were obtained from the slant shear test results. Finally, the bond strength of the interfaces obtained using the different testing methods were compared and conclusions presented.

2. Experimental program

2.1 Specimen design

2.1.1 Splitting test specimen design

Based on general acceptability on its ability to determine the tensile bond strength between a substrate concrete and an added concrete layer, the splitting tension test was employed for use in this study. The split tensile test is an indirect tensile test method often employed to obtain the bond strength at concrete to concrete connection interfaces. The substrate and the repair specimen parts were each made of semi-cube dimensions of 150 mm×150 mm×75 mm and cast at different times (Fig. 1(a)). The interface roughness texture on the substrate concrete was made using pre-designed interface roughness textures, positioned at the midpoint of the concrete cube formwork before casting. A test matrix of eight (8) varying roughness textures was used to evaluate the effect of different interface roughness on the tensile bond strength of the old and new concrete interface. The interface bond strength obtained using this test method is calculated using Eq. (1)

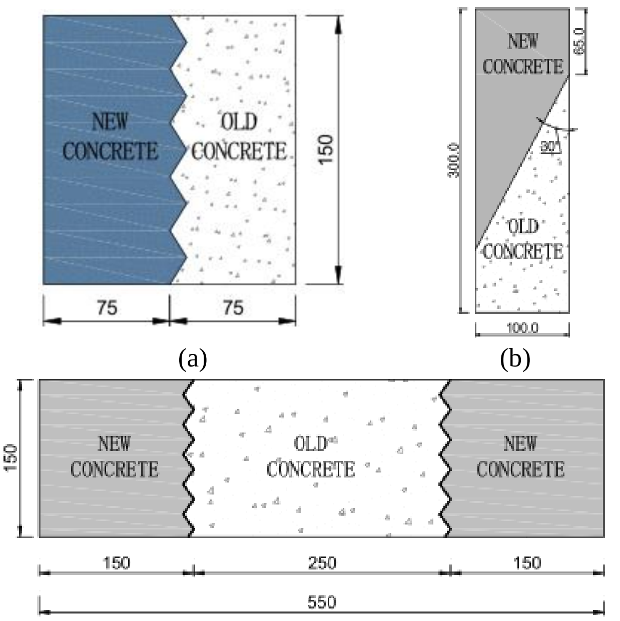
$$f_t = \frac{2P}{\pi A} \tag{1}$$

where

f_t is the splitting tensile strength (MPa)

P is the failure load (N)

A is the area of the interface (mm^2)



(c)

Fig. 1 Specimen details for the (a) splitting tensile test (b) Slant shear test (c) Double-shear test

2.1.2 Slant shear specimen design

The slant shear test is a popular and unique test method for the evaluation of the shear bond strength of an old and new concrete interface because of its ability to determine the bond strength of an interface subjected to combined compressive and shear stresses. This method has also been selected because of its sensitivity to interface roughness (Julio *et al.* 2004). In this method, the compressive stresses causes higher bond strength due to the increase in interface friction (Valikhani *et al.* 2020). The slant shear test is usually made with prismatic specimens of either cylindrical or square base. In this study, the slant test specimens were made of prismatic members with square base, with each composite member made of cross sectional area of 100 mm×100 mm and 320 mm long (Fig. 1(b)). The mid-height of the composite specimen consists of the pre-designed interface roughness textures, placed at an angle of 60° to the horizontal axis. The normal compressive stresses and shear stress acting on the interface of the slant shear specimen are calculated using Eqs. (2) and (3), respectively

$$\sigma_n = \frac{P}{A}\sin^2\alpha \quad (2)$$

$$\tau_n = 0.5\frac{P}{A}\sin(2\alpha) \quad (3)$$

where

P is the maximum applied compressive load on the specimen (N)

A is the area of the slant bonding interface

τ_n and σ_n are the interfacial shear and normal bond stresses, respectively

α is the interface angle.

Using the Mohr-Coulomb theory, a failure envelope is applied to obtain the interface bond cohesion parameters

$$\tau_n = c + \mu\sigma_n \quad (4)$$

where

c is the cohesion strength (or the pure shear strength)

μ is the friction coefficient

2.1.3 Double-shear test specimen design

The double-shear test specimen is easily producible and can be achieved with less ambiguity of construction process. In the testing method, the small bending moments on the interfaces at both ends of the old concrete (due to horizontal displacement during loading) cancel each other out, thereby improving the overall stability of the testing method. The composite specimen consists of two parts: the old and new concrete, arranged into a New-Old-New concrete set up. The composite specimen has an overall dimension of 150×150×550 mm, with the old concrete part with dimension 150×150×250 mm, and the new concrete parts with dimensions of 150×150×150 mm, representing height×width×length, respectively (Fig. 1(c)). The pre-designed interface roughness texture formworks were positioned at the old and new concrete interface boundary, and two additional roughness textures made using chipping method was also made at the interface. Further details on the interface roughness preparation is presented in the roughness preparation section.

The interface bond shear strength obtained from the double-shear test is evaluated using

$$\tau = \frac{P}{2A} \quad (5)$$

where

τ is the interface bond shear strength (MPa)

P is the shear load (N)

A is the area of the interface (mm^2)

2.2 Test specimen preparation

2.2.1 Concrete specimen preparation

For the splitting test specimens, the old concrete part was cast using the prepared plastic concrete cube with appropriate interface roughness template. The old concrete halves of the composite splitting test specimens were cast, demolded and air cured in the laboratory for 28 days. After, the cured specimens were cleaned and returned into the formwork for casting of the new concrete layer. In the casting project, water based releasing agent was used to ensure that the bond interface area was not contaminated with any oily substance. A standard vibrator was also used during casting to ensure concrete was well compacted and quality roughness interface was obtained. A typical specimen fabrication process for the splitting test specimen is presented in Fig. 2(a).

For the slant shear test specimens, a thin wooden plate was placed at the middle of each mold with designed inclination angle of 30°. This was done to ensure each mold can produce two concrete specimens with the designed slant shear test angle. The appropriate 3D printed interface template was positioned on the slant wooden plate and properly fixed before the old concrete half was cast and

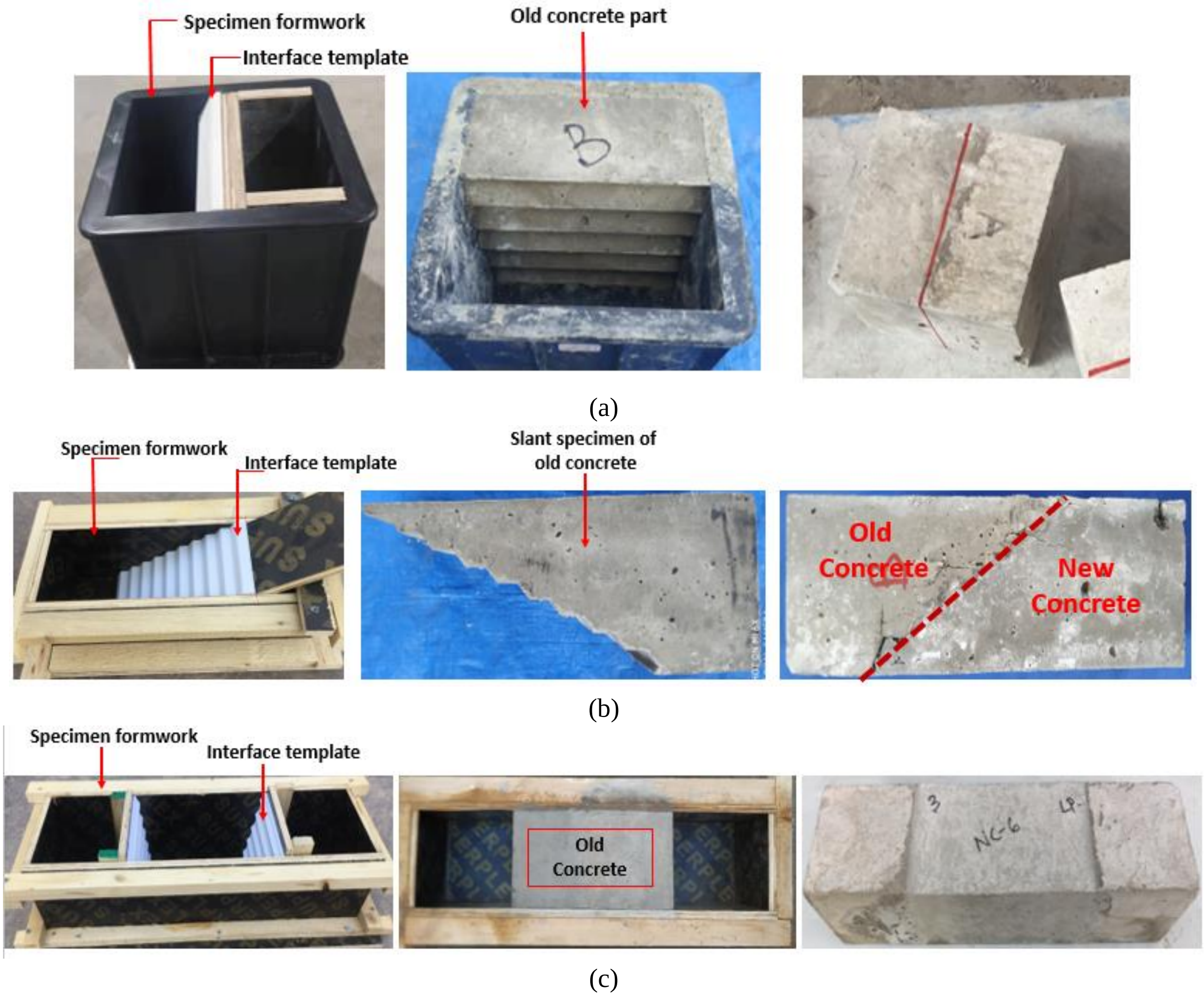


Fig. 2 Fabrication of test specimens (a) Splitting tensile specimen (b) Slant shear specimen (c) Double-shear specimen

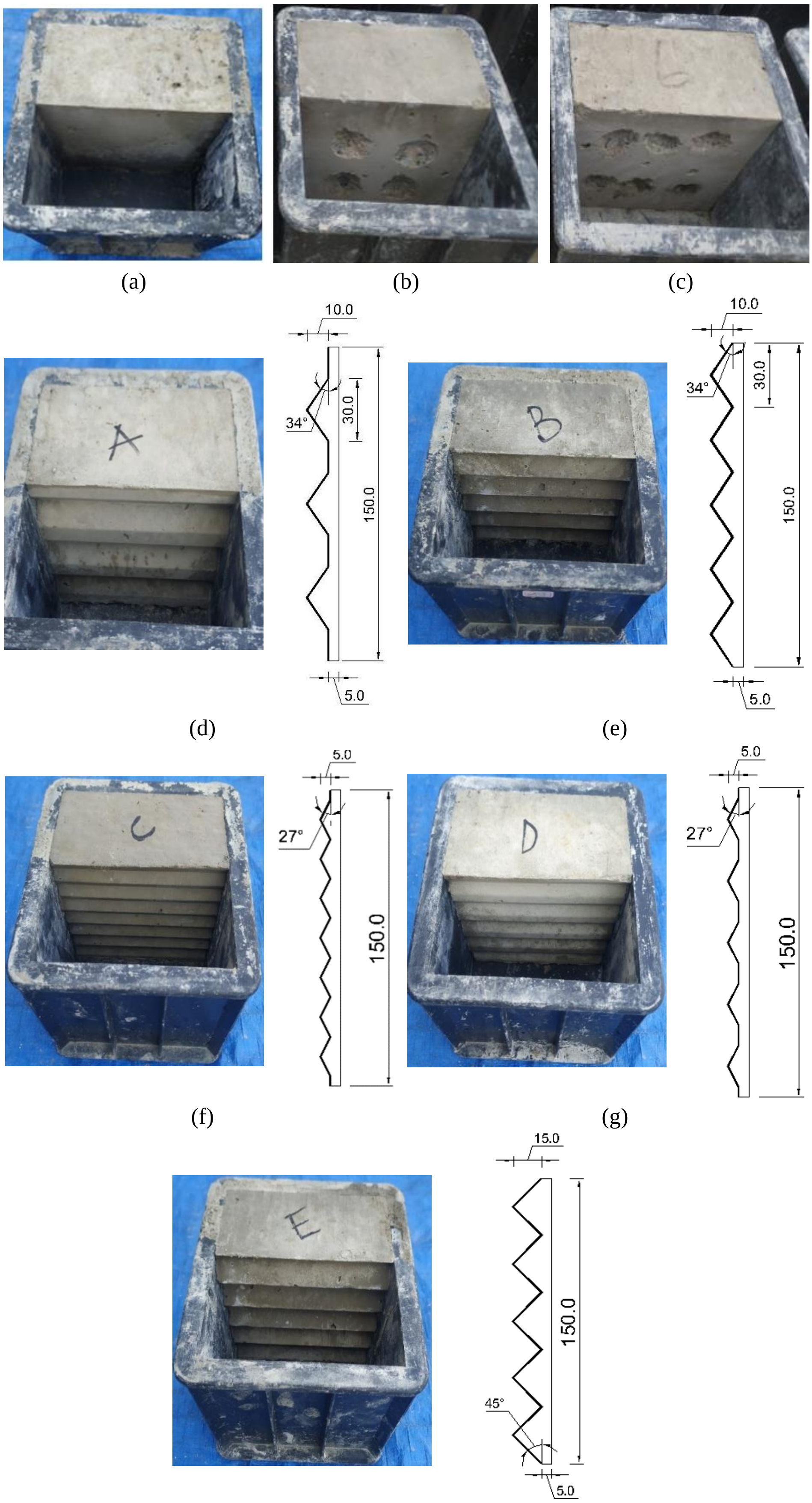
cured in the laboratory. After, the air cured and cleaned specimen was re-positioned in the composite slant shear specimen wooden formwork after which the new concrete was added to the slant side and filled up to the end of the formwork and make the composite slant shear specimen. The complete casting process is described in Fig. 2(b). For each experiment group, three specimens were made and the appropriate interface template was poisoned at the midpoint of the composite specimen during casting.

For the double-shear test concrete specimens, a wooden frame was made for the specimen casting, where the sections of the old and new concrete parts were properly demarcated. The old concrete part was first cast in the prepared wooden frame (with appropriate interface texture template) and stored under the same temperature and relative humidity conditions in the laboratory yard. Demolded after 36 h, the specimens were wetted daily for 28 days and placed under a plastic polyethylene covering in the laboratory. After the 28 days of wetted curing, the toothed interfaces of the old concrete specimens were cleaned with a steel brush to remove any dust or dirt particles on the interface and finally wetted before the new concrete was added. The complete new-old-new composite concrete was further daily cured for 28 days. The complete specimen preparation process is shown in Fig. 2(c).

In total, sixty (60) composite specimens were cast, comprising of twenty-four (24) splitting test specimens, fifteen (15) slant shear test specimens, and twenty-one (21) double-shear test specimens. From the specimens, three (3) repeated specimens were used to study same parameter, and classified as a test group.

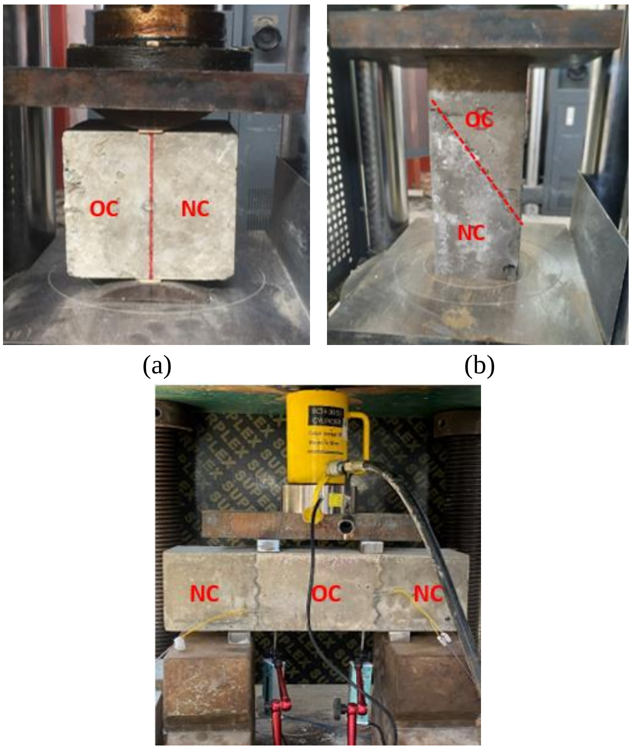
2.2.2 Interface roughness preparation

Several interface roughness preparation methods for concrete-concrete interfaces are available from existing research, such as sandblasting, water jetting, surface chipping, steel brushing, hydro-demolition and surface grooving. However, these methods produce inconsistencies in roughness preparation and quantification when same method is applied on different interfaces due to inability to perfectly reproduce the same interface treatment on different interfaces. Furthermore, these methods produce roughness interfaces subjected to error of judgement for its characterization. To prevent that in this research and to ensure consistency of interface roughness for the same category of test samples, quantitative roughness technique was used. Selected conventional interface treatment methods were also employed. In general, the roughness surfaces considered include smooth interfaces (left as cast and untreated), two separate surface chipping (using



(h)

Fig. 3 Split tensile test specimens with the different interface roughness of the old concrete (a) Smooth (b) Pit-N4 (c) Pit-N6 (d) A-R28%P (e) B-R78%P (f) C-R68%P (g) D-R35%P (h) E-R78%P



(a) (b)

(c)

Fig. 4 Test set-up for the (a) Splitting tensile test (b) Slant shear test (c) Double-shear test (OC: Old concrete. NC: New Concrete)

pneumatic hammer) patterns and five different pre-designed quantitative interface roughness, as shown in Fig. 8. The pit interfaces were restricted to only two patterns as creating higher number of pits at the interface lead to undesired visible damage to the old concrete part. The different pre-designed template patterns were selected to replicate typical pit interfaces made using a pneumatic hammer, as observed during practical interface treatment. The degree of the interface roughness in each case was controlled by the tooth angle, tooth depth and the percentage tooth distribution. A tooth angle of 35° to the horizontal was used as it provides the maximum shear behaviour when designing a triangular roughness interface at the interface (Al-fasih *et al.* 2021). The tooth depths were controlled by desired depth of pit interface penetration varying between 5 mm and 15 mm of the roughness tooth. The roughness surface templates were named according to the tooth angle, tooth depth and tooth distribution sequence. Schematic details and pictures of the different surface textures used for the concrete interface roughness in the tests are shown in Fig. 3.

The specimen naming format assumes a simple method, with the pit interfaces named as Pit-N (*n*), where *n* refers to the number of the pit. For the quantitative roughness, the format A-R28%P is adopted. Typically, *A* indicates the first roughness group and all other roughness groups follow the general alphabetical order. *R* refers to roughness, while the percentage value is the percentage of the interface occupied by the roughness pit, *P*.

2.3 Studied parameters

Table 1 Mixture proportions of concrete materials (kg/m^3)

Series	Grade	Water	Cement	Fine aggregates	Coarse aggregates
Old concrete	C30	185	380	648	1198
New concrete	C35	185	430	615	1205

For the splitting tests, all the interface texture categories were studied for their effect on the tensile bond strength at the old-new concrete interface. For the slant shear specimens, only the smooth and interface textures A, B, C and D were studied because the pit interfaces failed prematurely during the roughness tooth creation. For the double-shear test specimens, all quantitative interface textures were studied including the pitted interfaces except the smooth interface specimens, as the smooth specimens experienced premature failure during the testing process. This is attributed to the presence of some initial cracks along the smooth interface observed before testing.

2.4 Materials and mix ratios

The old and new concrete were made of Normal strength concrete with mix proportions as presented in Table 1. The coarse aggregates used were crushed stones with a maximum particle size of 25 mm, washed and sun-dried to remove any impurities. Fine aggregates of particle size between 2 mm and 4 mm were obtained from natural river, sieved and sun dried for use in the concrete making. The cement used was an ordinary Portland cement of 42.5 grades (P.II 42.5) with Blaine fineness of 375 m^2/kg. With the appropriate volume of the tap water (based on the mix ratio), the concrete mixture was prepared in an electric concrete mixer. Six standard cubic specimens of size 150 mm were used to confirm the respective concrete compressive strengths after 28 days of curing. The designed concrete strengths for the old and new concrete were 30 MPa and 35 MPa, respectively.

2.5 Test set-up and loading

The experimental set-up for the splitting tensile test, slant shear tests and the double-shear test are presented in Fig. 4. For the splitting tensile test (Fig. 4(a)), a compressive loading was applied on the composite specimen through the system shown in the figure, and at a loading rate of 0.05 MPa/s. The peak load (*P*) and failure mode from the test were recorded. Using Eq. (1), the bond splitting tensile strength was obtained. The slant shear test specimens were also subjected to a compressive loading, as shown in Fig. 4(b). The compressive loading was supplied from a universal testing machine, at a regulated loading rate of 0.5 kN/s. This loading pattern subjected the inclined interface to combined normal and shear stresses. The peak load and specimen failure mode were recorded. For the double-shear test, test formation similar to a four-point loading system was utilised as shown in Fig. 4(c). The composite specimen was loaded at a rate of 0.5 kN/sec, and readings measured by the attached load cell. The specimens were tested under load-control, and the experimental data was recorded every second.

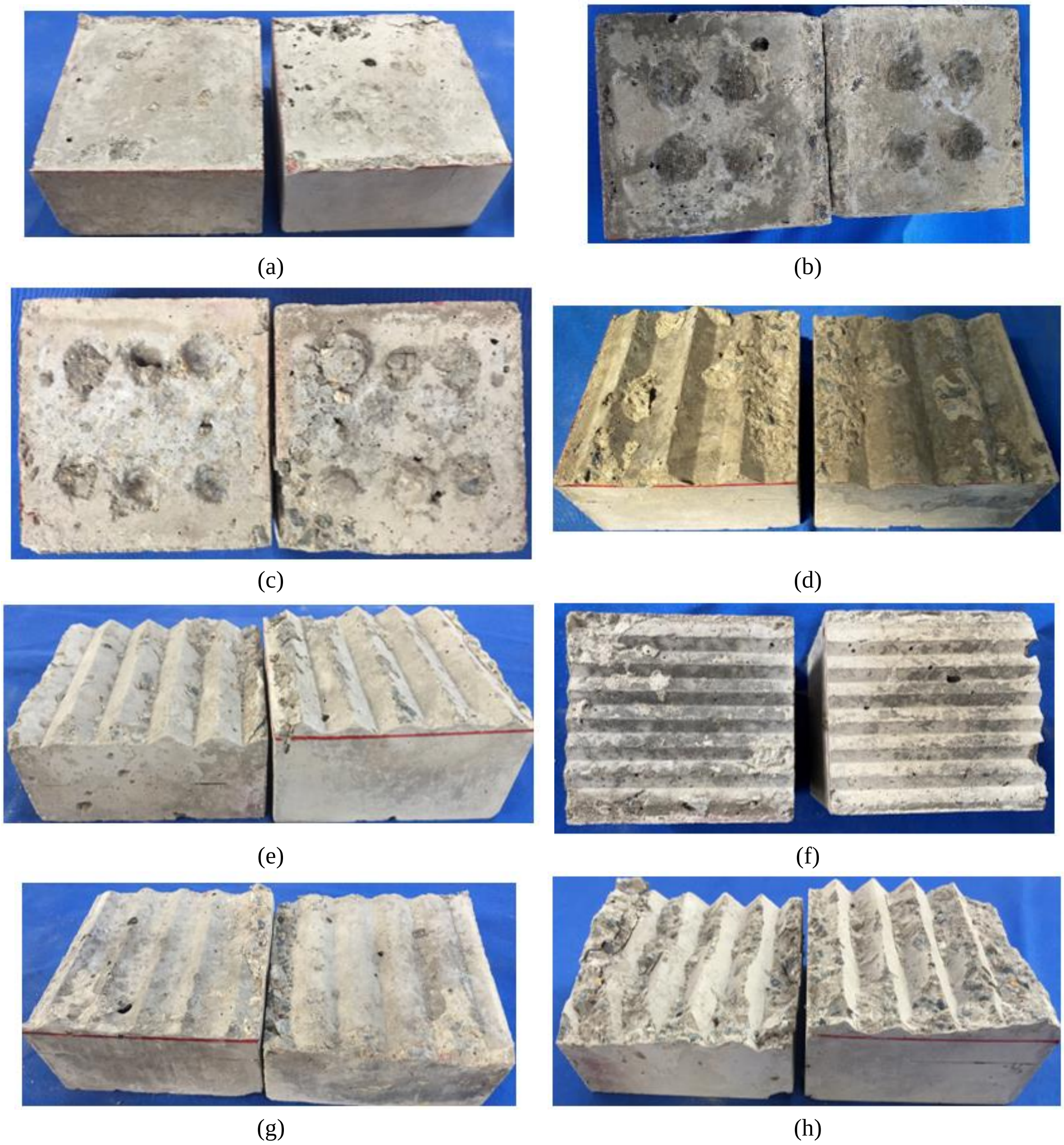


Fig. 5 Representative failure modes of the different interface textures under splitting test (a) Smooth (b) Pit-N4 (c) Pit-N6 (d) A-R28%P (e) B-R78%P (f) C-R68%P (g) D-R35%P (h) E-R78%P

3. Results and discussion

3.1 Splitting test

3.1.1 Failure behaviour

The primary failure pattern for the splitting tensile specimens is interface failure. This refers to failure pattern where the composite specimen failed at the interface between the old and new concrete parts, with almost no failure of the bulk concrete part. However, few specimens showed combination of interface failure and partial failure in the old concrete. For specimens where this combined failure behaviour was observed, the old concrete parts stuck to the ridges of the roughness tooth in the new concrete part. Typical specimen failure behaviours for the different categories of specimens tested in the experiment are presented in Fig. 5. The overall failure behaviour indicates that the bond at the old and new concrete interface is very small.

3.1.2 Tensile splitting strength

The splitting tensile bond strength estimated from the experimental results using Eq. (1) is presented in Table 2, alongside the obtained coefficient of variation (COV) for each roughness texture considered. For the smooth interface specimens, an average splitting tensile strength of 1.48 MPa was obtained at the interface, with a COV of 2.46%. The low COV value for the smooth interface specimens confirms the consistency of the test results on the specimens.

Table 2 Summary of splitting test results

Specimen	Tensile strength			Failure mode
	N	f_t	COV (%)	
Flat	3	1.48	2.46	Interface failure
Pit-N4	5	1.33	16.2	Interface failure and little old concrete failure
Pit-N6	5	1.27	16.8	Interface failure and little old concrete failure
A-R28%P	3	1.51	5.1	Interface failure and partial old concrete failure
B-R78%P	3	1.15	4.0	Interface failure and partial old concrete failure
C-R68%P	3	1.38	0.61	Interface failure
D-R35%P	3	1.05	7.85	Interface failure
E-R78%P	3	1.52	7.88	Interface failure and partial old concrete failure

For the interfaces with pit roughness, average tensile bond strength values of 1.33 MPa and 1.27 MPa were obtained or the 4-pit and 6-pit interfaces, respectively. Noticeably, these results are lesser than the smooth interface specimens' results and suggests that pit interface roughness only causes damage to the old and new concrete interface and is not suitable for making interface roughness expected to enhance interface bond strength. In addition, the result of the 4-pit interface is considerably higher than that for the 6-pit interface, which further emphasize that the more the pit, the more the damage to the interface and the bond strength of the interface is further reduced. Large COV was however obtained for the pit interfaces and this is due to the small stress values obtained during the initial trails of the test. In alignment with the ASTM Protocol (Hussein *et al.* 2016), the small stress values were omitted from calculating the average tensile bond strength of the old and new concrete interface, and only consistent test values were considered.

For the quantitatively roughened interface, the interfaces' average tensile bond strength values varied between 1.05 MPa and 1.52 MPa, with coefficient of variation between 0.6 and 7.88%. Generally, this result suggests that the quantitative roughness of the interface without interface bonding agent, has no significant effect on the interface tensile bonding strength. From the results, the highest tensile bond strength was obtained for specimen E-R78%P, with the largest roughness tooth depth. This suggest that despite the lack of significant improvement in the interface tensile bond strength, increasing the tooth depth can enhance the bond strength. The least tensile bond strength was however obtained for specimen D-R35%P. Typically, this specimen contains interface with lower tooth roughness depth and a full interface roughness. It can be assumed from this result that low roughness tooth depth and lack of interface bonding agent renders the quantitative roughness incapable of enhancing interface tensile bond strength, and should not be encouraged in old and new concrete bond enhancement considerations. Further, specimen A-R28%P produced a higher average tensile bond strength of the interface compared to specimen B-R78%P, which only differed by the tooth distribution, while other roughness interface quantitative parameters remained same. This observation suggests that the tensile bond strength of the interface reduces with increase in the number of the roughness tooth. However, same conclusion cannot be said for the comparison between specimens C-R68%P and D-R35%P whose interface roughness texture also only differ by the tooth distribution. Specimen C-R68%P (with full interface roughness) produced an average tensile strength of 1.38 MPa which is higher than the tensile bond strength value of 1.05 MPa obtained from specimen D-R35%P (with scattered interface roughness tooth). This result can be attributed to the effect of the roughness depth in improving the interface tensile bond strength of the fully rough interface. Therefore, further works can be focused on the splitting test specimens with larger roughness tooth distribution variation.

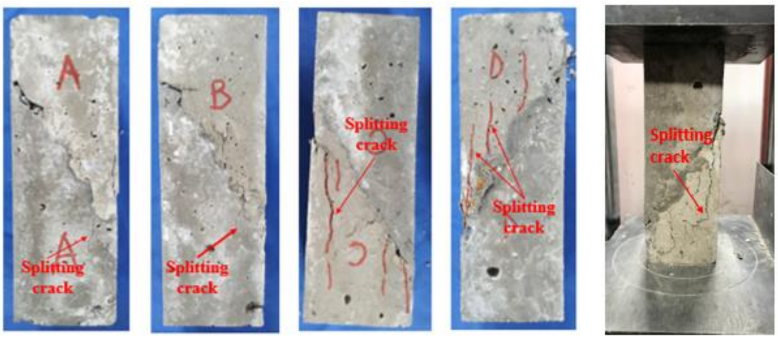
In general, the use of the quantitatively controlled interface did not appear to significantly influence the interface tensile bond strength. This is because the quantitative roughness was prepared with smooth interface formworks and no extra treatment was done on the formed toothed interface to further improve the roughness. It is therefore advised that in cases where quantitative roughness tooth is to be used for interface roughness formation, either extra roughness on the formed teeth should be made or the use of interface bonding agents should be considered alongside the toothed interface, for improved interface tensile bond strength.

3.2 Slant shear test

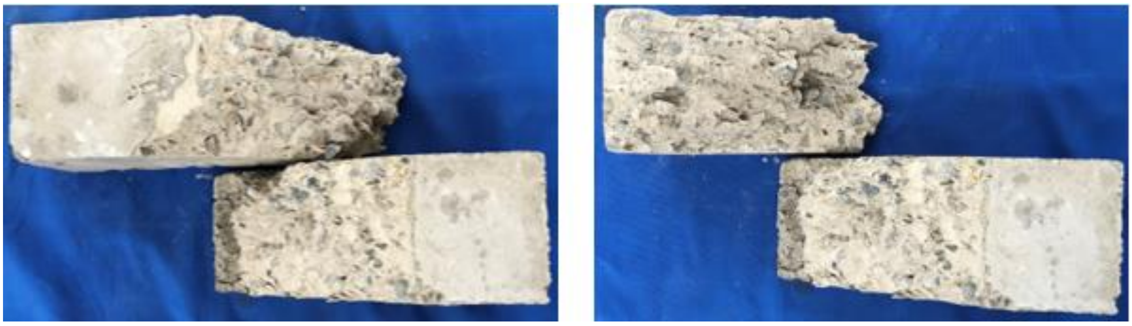
3.2.1 Failure behaviour

The failure behaviour of the slant shear test specimens was dominated by a combination of splitting cracks in the old concrete and little sliding failure along the old-new concrete interface. The dominance of the splitting cracks and sliding failure varied with the roughness tooth depth, as observed from the failure mode during the experiment. Splitting cracks at the interface refers to cracks that initiated at the ends of the old-new concrete interface and propagated into the old concrete (Aaleti and Sritharan 2019). The formation of these cracks indicates that the shear resistance at the interface between the old and new concrete is greater than the stress required to cause the splitting failure in the old concrete. This however suggests an improved interface bond performance due to the interface roughness (Feng *et al.* 2020). Sliding failure, on the other hand, refers to slip along the interface between the old and new concrete without any significant damage to the old concrete. This failure indicates a weak interface bond performance, and that the interfacial bond strength is weaker than the old concrete strength.

Generally, specimens with lower interface roughness depth experienced more interface sliding after initial formation of the splitting cracks in the old concrete. This suggests that the depth of penetration of the roughness tooth significantly affect the test failure behaviour of quantitatively roughened specimens. However, specimens with greater interface roughness tooth showed a significant presence of the splitting cracks, indicating that the failure occurred in the old concrete, rather than at the old-new concrete interface. In these kinds of specimens, some old



(a)



(b)

Fig. 6 Failure modes of slant shear specimen (a) Splitting cracks in the old concrete (b) Concrete failure

Table 3 Summary of slant-shear test results

Specimen	*N*	Average Interface bond strength			Failure mode
		τ	σ	COV (%)	
Flat	3	1.99	1.05	15.4	Sliding failure
A-R28%P	3	2.89	1.67	1.13	Splitting crack and sliding failure
B-R78%P	3	2.71	1.57	9.63	Splitting crack and sliding failure
C-R68%P	3	2.67	1.54	9.28	Splitting crack and sliding failure
D-R35%P	3	2.77	1.60	8.34	Splitting crack and sliding failure

concrete parts were remained between the ridges in the new concrete parts formed by the designed roughness tooth. This indicates that the overall interface behaviour is governed by the old concrete strength, and the interface shear strength can be predicted from the old concrete strength. For the different percentages of the roughness tooth textures utilized in this study, no much differences can be observed other than the broad classification of the interface failure as either splitting failure or the sliding failure. However, all the specimens examined showed a combination of the two failure patterns. A complete failure behaviour of all the tested specimens is shown in Fig 6.

3.2.2 Slant shear strength

Using the peak load obtained from the experiment, the interface normal bond stress and the interface shear bond stress calculated using Eqs. (2) and (3), respectively; and the coefficient of variation of the slant bond strength are presented in Table 3. Generally, the interface shear strength varied with increase in the interface roughness. As expected, the average interface slant shear strength obtained for the smooth interface specimens was significantly lower than those obtained for the quantitatively roughened interface specimens. For the smooth interface specimens, an average shear strength of 1.99 MPa was obtained with a coefficient of variation (COV) of 15.4%. The large COV is due to small stress obtained during the initial test trial. In calculating the average interface slant shear strength, the small stress value has been omitted.

For the varied percentage composition of roughness tooth, measured interface slant shear bond strength varied between 2.67 MPa and 2.89 MPa. This represents a 45.2% increase from the smooth specimens and show the influence of the quantitative roughness tooth on the interface shear strength. The interface slant shear strength is highest for specimen A-R28%P, and is 2.89 MPa, while the least interface shear strength was obtained for specimen C-R68%P and is 2.67 MPa. Noticeably the highest shear strength was obtained for the interface with higher tooth depth, compared to the specimen C-R68%P which had higher percentage roughness tooth distribution. This suggests that increased roughness tooth depth contributes more to the interface shear strength than the interface tooth distribution. Therefore, it can be concluded from the slant shear test result that improved interface roughness depth facilitates increased interface shear strength.

3.2.3 Interface cohesion and friction parameter

Beyond showing the failure behaviour and providing the shear strength of the interface, the slant shear testing method provides information about the interfacial properties (Hu *et al.* 2020, Zhang *et al.* 2020). The relationship between the interface shear bond strength and the interface normal bond strength obtained from the experimental data

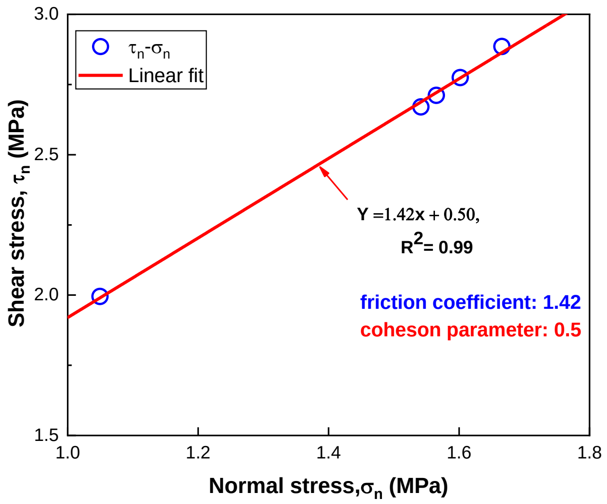


Fig. 7 Interfacial shear stress-normal stress interaction points at failure and linear fitting

is given in Fig. 7. From the figure, a linear relationship exists between the interfacial shear stress and the normal compressive stress. Based on the Mohr-Coulomb criterion, the equation of the trend line provides information about the interface friction and cohesion. From the equation, the friction coefficient of the interface is obtained, a value of 1.42, with a cohesion parameter of 0.50. This result indicates that the adhesion property at the old-new concrete used in this study is very little and much higher new concrete material should be utilized if improved interface adhesion is desired.

Typically, the cohesion and friction parameters of Normal Strength Concrete connection is given by Engineering design codes, such as the Eurocode 2, considering various substrate roughness. The roughness of the interfaces is categorized as very smooth, smooth, rough and indented, with cohesion and friction coefficients of 0.025 and 0.5, 0.2 and 0.6, 0.4 and 0.7; and 0.5 and 0.9, respectively (Santos and Júlio 2013). In comparison with the code provisions, the cohesion coefficient obtained in this study aligns with the indented roughness category in the code. Typically, the quantitative roughness tooth is similar to indented roughness category of the code, but with different tooth geometrical parameters and tooth distribution. The friction coefficient of the old and new concrete in this study is however greater than that provided by the code for the indented category. This can be attributed to the greater control of the roughness tooth geometry and establishes the difference between this research and already existing results in the code. In addition, the roughness tooth geometry and distribution in this study ensures greater friction transfer at the interface and therefore provide improved interface bond strength and shear capacity.

3.3 Double-shear test

3.3.1 Failure behaviour

The double-shear test specimens showed interface shear failure for all the specimens tested. The failure of the interfaces was similar to that observed for the splitting tensile test. Cracks initiated at the lower interface area at small amount of the applied vertical loading. With slightly increased loading, the shear cracks propagated rapidly along the interface and caused the complete failure of the interfaces, as well as a total separation between the old and new concrete parts.

For the pit interfaces, rapid failure behaviour was observed and the pit holes experienced a separation between the old and new concrete parts with no significant damage to the new concrete dents made in the pit of the old concrete. This shows that the smooth part of the pit interfaces controlled the interface failure behaviour and indicates a weak adhesion at the pitted interface. For interfaces with quantitatively defined roughness tooth, separation along the tooth interface was also noticed while specimens with greater tooth depth showed some old concrete damage alongside the interface failure. This indicates a slightly improved adhesion for the quantitatively roughened interfaces with deeper roughness tooth.

Table 4 Summary of double-shear test

Specimen	Shear strength		
	N	*τ*	COV (%)
Flat	-	-	-
Pit-N4	3	0.98	2.54
Pit-N6	3	1.55	0.94
A-R28%P	2	2.34	1.04
B-R78%P	3	2.06	4.11
C-R68%P	3	2.11	10.71
D-R35%P	3	2.89	5.27
E-R78%P	3	3.11	4.24

3.3.2 Interface shear strength

For the double-shear tests, load-slip curves for all three repeated specimens were obtained and the interface shear strength evaluated using Eq. (4). The experimental curves are presented in Fig. 8, and the interface shear strength alongside the result's coefficient of variations are detailed in Table 4. In general, the behaviour of the load-slip curves for all the roughness categories is approximately linear until sudden failure of the interface. The interface shear strength however slightly varies with the roughness of the interface. For the smooth interface specimens, no useful data was obtained for the interface shear strength, as the specimens either failed before testing or had pre-crack at the interface which significantly influenced the interface shear strength. For the pit interfaces, average interface shear strength values of 0.98 MPa and 1.55 MPa were obtained for specimens Pit-N4 and Pit-N6, respectively, with a coefficient of variation of 2.54% and 0.94%. This low coefficient of variation indicates the consistency of the test results. Noticeably, the shear strength of the Pit-N6 specimen is greater than the specimen Pit-N4, which suggests an improved shear behaviour with increase in the interface pit roughness. This is however contrary to the interface tensile bond behaviour observed during the splitting testing, where the tensile bond test of the Pit-N4 was observed to be greater than the Pit-N6 specimen.

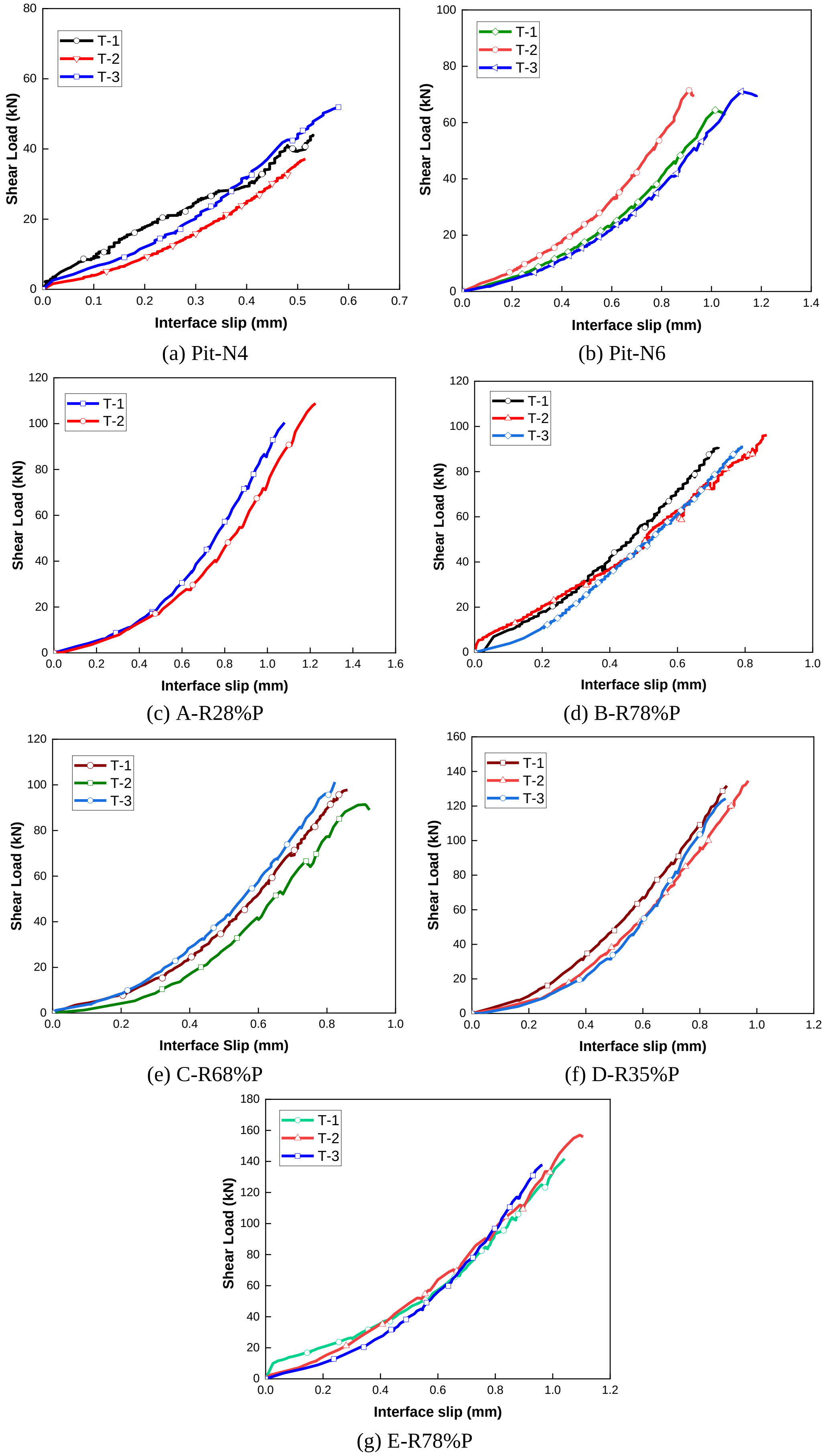


Fig. 8 Load-slip curves of double-shear tests

Table 5 Comparative analysis of different bond strength test results

Specimen	Bond strength		
	Splitting test	Slant shear	Double-shear test
Flat	1.48	1.99	-
Pit-N4	1.33	-	0.98
Pit-N6	1.27	-	1.55
A-R28%P	1.51	2.89	2.34
B-R78%P	1.15	2.71	2.06
C-R68%P	1.38	2.67	2.11
D-R35%P	1.05	2.77	2.89
E-R78%P	1.52	-	3.11

For the percentage roughened interface, the interface shear strength values varied between 2.34 MPa and 3.11 MPa. With a coefficient of variation (COV) between 1.04% and 10.71%, the obtained results can still be considered as consistent. From the results of the specimen E-R35%P, with the deepest tooth texture gave the highest interface shear strength and again validates the claim that increased tooth depth improves the interface shear capacity. The least interface shear capacity was however obtained for specimen B-R78%P. Typically, the specimen's interface has uniform roughness teeth with same tooth angles and tooth depths. For specimens A-R28%P and B-R78%P which have same tooth angles and tooth depth but with different tooth distribution, results indicate that numbered roughness tooth produce better results than a fully rough interface for the quantitatively roughened interface. Similarly, comparing specimen C-R68%P and D-R35%P, the result showed that specimen D-R35%P, which had numbered distribution of the roughness tooth produced higher result than the fully roughened specimen C-R68%P. This observation indicates that proper distribution of the roughness tooth at the interface is vital for improved interface shear capacity. From the results, lesser number of interface roughness tooth produce better interface shear capacity than higher number of interface roughness tooth and is in agreement with the conclusion of Alcalde *et al.* (2013).

3.4 Comparative analysis of testing methods

The interface bond strength between the old and new concrete is influenced by the testing method employed, and the strength values can vary by up to eight (Momayez *et al.* 2005). A comprehensive comparative analysis of the test results obtained from the splitting tensile test, slant shear test, and the double-shear tests in this study was conducted and values presented in Table 5. For the tensile tests, the tensile bond strength was considered, while the interface shear strength was considered for the double-shear test. For the slant shear test, the pure interface shear strength obtained from the total interface bond strength was considered. From the results, it can be seen that the slant shear tests resulted in the highest bond strengths for all the specimens. This is due of the influence of friction forces at the interface and the high mechanical interlock facilitated by the compressive stresses at the interface (Momayez *et al.* 2005, Zhang *et al.* 2020).

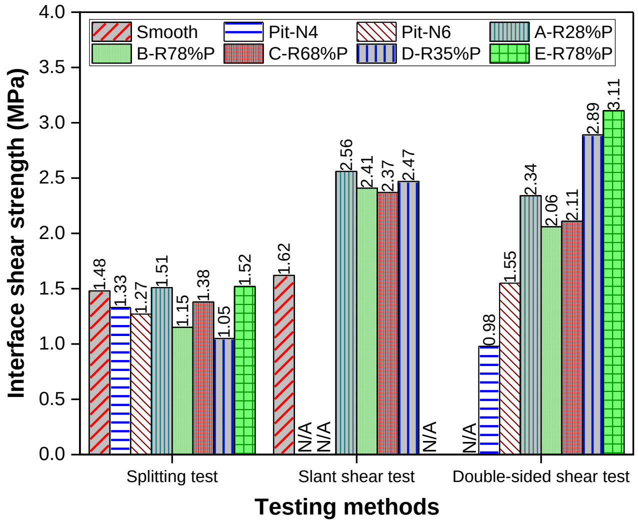


Fig. 9 Effects of interface roughness on the interfacial bond strength

The splitting tensile test results produced the least values for the interface bond strength for most of the tested specimens, much lower than the values of the double-shear test and the slant shear test. This is expected as the testing method evaluates the interface bond strength under tensile stress alone. However, the interface pure shear strengths obtained from the slant shear test is very close to the interface shear strength values obtained from the double-shear test method. This observation validates the bond strength of the interface under shear stresses. The results from this research indicates that the slant shear test can be used to obtain the interface pure shear strength when appropriate deduction of the effect of the normal stresses on the interface has been considered.

Furthermore, the coefficient of variation (COV) of the test results obtained for all the old-new concrete interface testing methods employed in this research varied between 0.94% and 16.9%, with an average of 8.92%. The COV data from the tables however shows most of the test results occurred with less than 8.0% variation with only few specimens above 10.0% variation. The COV of the bond strengths at the old and new concrete interface is similar to the COV obtained by other researchers on bond performance such as Momayez *et al.* (2005), Zhang *et al.* (2020), Muñoz *et al.* (2014), Hussein *et al.* (2016), and Tayeh *et al.* (2012). In general, the COV obtained in this study indicates the consistency and reliability of the test results.

3.5 Effect of roughness tooth depth, and tooth distribution

The surface roughness of the substrate concrete plays important role on the interface bond behaviour (Santos *et al.* 2007, Julio *et al.* 2004, He *et al.* 2017). The interface bond strength obtained from the three testing methods considering the different interface treatment categories is graphically presented in Fig. 9. From the figure, the

Table 6 Bond-slip model parameters

Specimen ID	A	b	$\tau_{\max}$	$s_{\tau.\max}$
Pit-N4	1.75	1.02	1.15	0.58
Pit-N6	1.34	1.56	1.59	0.91
A-R28%P	1.78	1.91	2.42	1.23
B-R78%P	2.56	1.23	2.14	0.86
C-R68%P	2.86	1.76	2.50	0.82
D-R35%P	3.34	1.82	2.99	0.97
E-R78%P	2.99	1.60	3.49	1.09

sensitivity of the interface bond strength from the different testing methods to the roughness of the interface is clear, especially interfaces with greater depth of the roughness tooth and those with controlled tooth distribution. Typically, from the splitting test and the double-shear tests, interface *E* (specimen E-R78%P) with the greatest tooth depth provided the highest interface bond strength. This occurrence can be attributed to the increased mechanical interlocking with greater tooth depth and is supported by the ACI design code and Momayez *et al.* (2005). Furthermore, the results show that the desired increase in interface bond strength with the quantitatively created roughness cannot be achieved with small roughness tooth depth, as the interface behaviour is similar to that of smooth interfaces especially when no extra interface treatment is employed nor a bonding agent utilized alongside the quantitative roughness method. The effect of the roughness tooth distribution on the tensile and shear bond strengths of the interfaces vary, as obtained from the test results. For the tensile tests, the numbered/controlled roughness tooth distribution with greater tooth depth showed improved bond behaviour compared to the full roughness with similar depth. However, smaller tooth depth with controlled tooth distribution indicated lesser bond behaviour compared to the full roughness interface. This negative effect can be attributed to the depth of the interface and the weak interface adhesion, as failure occurred quite rapidly. However, the slant shear test and the double-shear test results indicate that the controlled roughness tooth with greater or smaller tooth depth provides improved interface bond strength compared to the full interface roughness. It is generally agreed that the rougher the interface, the greater the interface bond strength. However, for quantitatively controlled toothed interfaces with no adhesive material at the interface, the bond strength of the controlled/numbered key is greater than the bond strength of the full roughness interface. This is synonymous to Zhou *et al.* (2005)'s conclusion that the shear capacity of keys in single keyed joint is always greater than that of multiple-keyed joints.

In conclusion, the quantitative roughness method can produce improved and consistent interface roughness and bond strength when designed and optimized using higher roughness tooth depth and numbered/controlled tooth distribution for the old concrete interface.

3.6 Bond-slip constitutive model for concrete to concrete interface

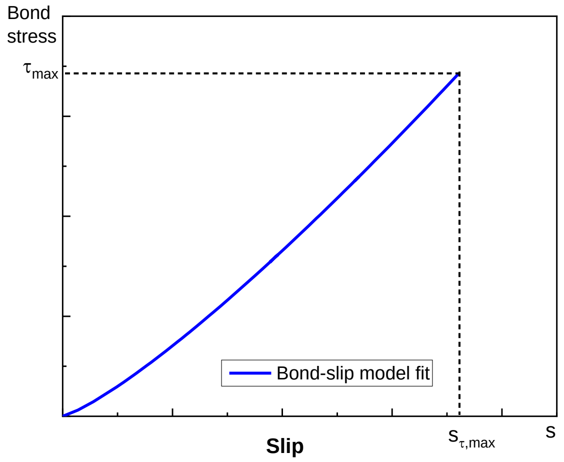


Fig. 10 Typical Bond-slip constitutive model

Generally, from the experimental results, a near-linear relationship occurs between the interface bond strength and the vertical slip till failure. A typical bond-slip model of the interfaces is presented in Fig. 10, and the characteristic bond-slip parameters for all the roughness surface is presented in Table 6. To accurately describe the bond-slip characteristics of the interface, the mathematical expression presented below was used

$$\tau=\tau_{\max}\left(\frac{s}{s_{\tau.\max}}\right), 0 \leq s \leq s_{\tau.\max} \quad (6)$$

The mean curve of the three repeated curves for each interface roughness was obtained using:

$$\tau=A(s)^{b} \quad (7)$$

where

A is a constant that varies based on the curve stiffness
b is the exponential coefficient
τ is the interface bond stress.
$\tau_{\max}$ is the maximum bond stress
s is the interface slip
$s_{\tau,\max}$ is the slip at maximum bond stress

4. Conclusions

The bond behaviour of concrete-concrete interface with quantitative roughness tooth was evaluated in this study. The effects of the roughness tooth texture, mainly the tooth depth, and tooth distribution on the interface bond strength was tested by the splitting tensile test, slant shear test and the double-shear test. The experimental results including the failure modes, interface tensile and shear bond strengths, load-deformation curves for the double-shear tests, interface friction and cohesion coefficients were presented and discussed. Based on the study findings, the followings conclusions are drawn

1. In the splitting tensile test, the quantitative roughness tooth has little or no influence on the interface tensile bond strength. However, increased roughness tooth depth slightly improved the interface bond strength, while the tooth distribution showed no major advantage

for the tensile test. These results indicate that plain quantitative roughness tooth without additional interface micro-roughness or bonding agent has very limited influence on the interface tensile strength.

2. For both the slant shear test and the double-shear test, the quantitative roughness tooth considerably improved the interface shear bond strength. The quantitative roughness increased the interface slant shear pure strength by an average of 45.2% when compared to the smooth interface. The roughness tooth depth further enhanced the interface shear bond strength as the roughness texture with the maximum depth produced the highest recorded interface shear strength among the quantitative roughened interfaces (2.89 MPa). The tooth distribution result indicate that the interface shear bond strength reduces with an increase in the number of roughness tooth at the interface.

3. Interface pit roughness reduces the bond strength and largely affects the interface bond behaviour. Pitting, using hammer, introduces damage into the interface zone and the more the pitting, the more the interface damage. This confirms reported conclusions of the negative effects of pitting roughness, especially for concrete materials with low mechanical strengths.

4. The obtained interface cohesion parameter agrees with the Eurocode 2 provision for that of a smooth interface. However, the interface friction was enhanced by the quantitative roughness tooth. Typically, and from the experimental results, cohesion and friction coefficients of 0.5 and 1.42, respective values were obtained.

5. Specimen failure behaviour shows that interface failure dominated the splitting test while a combination of splitting cracks in the old concrete parts and interface sliding failure dominated the slant shear test results. The double-shear test failure behaviour coincides with that of the splitting tests mostly.

6. while the interface shear strength varies with the testing method utilized, the pure shear strength obtained from the slant shear test method and the interface shear strength from the double-shear test showed good agreement.

Acknowledgement

The authors specially appreciate the financial support of the Natural Science Foundation of China (Grant No. 51978242).

References

Aaleti, S. and Sritharan, S. (2019), "Quantifying Bonding Characteristics between UHPC and normal-strength concrete for bridge deck application", *J. Bridge Eng.*, **24**(6), 04019041. https://doi.org/10.1061/(asce)be.1943-5592.0001404.

Al-fasih, M.Y., Mohamad, M.E., Ibrahim, I.S., Ahmad, Y., Ariffin, M.A.M., Sarbini, N.N., Mohamed, R. and Kueh, A.B. (2021), "Experimental and numerical evaluations of composite concrete-to-concrete interfacial shear strength under horizontal and normal stresses", *PloS One*, **16**(5), e0252050. https://doi.org/10.1371/journal.pone.0252050.

Alcalde, M., Cifuentes, H. and Medina, F. (2013), "Influence of the number of keys on the shear strength of post-tensioned dry joints", *Constr. Mater.*, **63**(210), 297-307. https://doi.org/10.3989/mc.2013.07611.

Diab, A.M., Abd Elmoaty, A.E.M. and Tag Eldin, M.R. (2017), "Slant shear bond strength between self compacting concrete and old concrete", *Constr. Build. Mater.*, **130**, 73-82. https://doi.org/10.1016/j.conbuildmat.2016.11.023.

Espeche, A.D. and León, J. (2011), "Estimation of bond strength envelopes for old-to-new concrete interfaces based on a cylinder splitting test", *Constr. Build. Mater.*, **25**(3), 1222-1235. https://doi.org/10.1016/j.conbuildmat.2010.09.032.

Feng, S., Xiao, H. and Li, H. (2020), "Comparative studies of the effect of ultrahigh-performance concrete and normal concrete as repair materials on interfacial bond properties and microstructure", *Eng. Struct.*, **222**, 111122. https://doi.org/10.1016/j.engstruct.2020.111122.

He, Y., Zhang, X., Hooton, R.D. and Zhang, X. (2017), "Effects of interface roughness and interface adhesion on new-to-old concrete bonding", *Constr. Build. Mater.*, **151**, 582-590. https://doi.org/10.1016/j.conbuildmat.2017.05.049.

Hu, B., Li, Y. and Liu, Y. (2020), "Dynamic slant shear bond behavior between new and old concrete", *Constr. Build. Mater.*, **238**, 117779(1-14). https://doi.org/10.1016/j.conbuildmat.2019.117779.

Hussein, H.H., Walsh, K.K., Sargand, S.M. and Steinberg, E.P. (2016), "Interfacial properties of Ultrahigh-Performance concrete and High-Strength concrete bridge connections", *J. Mater. Civil Eng.*, **28**(5), 1-10. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001456.

Julio, E.N.B.., Branco, F.A.B. and Silva, V.D. (2004), "Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface", *Constr. Build. Mater.*, **18**, 675-681. https://doi.org/10.1016/j.conbuildmat.2004.04.023.

Julio, E.N.B.S., Branco, F.A.B., Silva, V.D. and Lourenco, J.F. (2006), "Influence of added concrete compressive strength on adhesion to an existing concrete substrate", *Build. Envir.*, **41**, 1934-1939. https://doi.org/10.1016/j.buildenv.2005.06.023.

Luo, Q., Wang, W., Wang, B., Xu, S. and Sun, Z. (2021), "Numerical study on interface optimization of new-to-old concrete with the slant grooves", *Struct.*, **34**, 381-399. https://doi.org/10.1016/j.istruc.2021.07.094.

Magbool, H.M. and Tayeh, B.A. (2021), "Influence of the Roughness and Moisture of the Substrate Surface on the Bond between Old and New Concrete", *Adv. Concrete Constr.*, **12**(1), 33-45. https://doi.org/10.12989/acc.2021.12.1.033.

Momayez, A., Ehsani, M.R., Ramezanianpour, A.A. and Rajaie, H. (2005), "Comparison of methods for evaluating bond strength between concrete substrate and repair materials", *Cement Concrete Res.*, **35**, 748-757. https://doi.org/10.1016/j.cemconres.2004.05.027.

Muñoz, C., Harris, D.K., Ahlborn, T.M. and Froster, D.C. (2014), "Bond performance between Ultrahigh-Performance Concrete and Normal-Strength Concrete", *J. Mater. Civil Eng.*, **26**(8), 04014031. https://doi.org/10.1061/(asce)mt.1943-5533.0000890.

Rahal, K.N., Khaleefi, A.L. and Al-Sanee, A. (2016), "An experimental investigation of shear-transfer strength of normal and high strength self compacting concrete", *Eng. Struct.*, **109**, 16-25. https://doi.org/10.1016/j.engstruct.2015.11.015.

Santos, P.M.D., Ju, E.N.B.S. and Silva, D. (2007), "Correlation between concrete-to-concrete bond strength and the roughness of the substrate surface", *Constr. Build. Mater.*, **21**, 1688-1695. https://doi.org/10.1016/j.conbuildmat.2006.05.044.

Santos, P.M.D. and Júlio, E.N.B.S. (2013), "A state-of-the-art review on roughness quantification methods for concrete

surfaces", *Constr. Build. Mater*., **38**, 912-923. https://doi.org/10.1016/j.conbuildmat.2012.09.045.
Sharma, S., Ronanki, S.V., Aaleti, S. and Okumus, P. (2021), "Experimental investigation of surface preparation on normal and Ultrahigh-Performance concrete interface behavior", *J. Bridge Eng*., **26**(4), 04019041. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001697.
Silfwerbrand, J., Beushausen, H. and Courard, L. (2011), *Bonded Cement-Based Material Overlays for the Repair, the Lining or the Strengthening of Slabs or Pavements*.
Tayeh, B.A., Abu Bakar, B.H., Megat Johari, M.A. and Voo, Y.L. (2012), "Mechanical and permeability properties of the interface between normal concrete substrate and ultra high performance fiber concrete overlay", *Constr. Build. Mater*., **36**, 538-548. https://doi.org/10.1016/j.conbuildmat.2012.06.013.
Valikhani, A., Jahromi, A.J., Mantawy, I.M. and Azizinamini, A. (2020), "Experimental evaluation of concrete-to-UHPC bond strength with correlation to surface roughness for repair application", *Constr. Build. Mater*., **238**, 117753. https://doi.org/10.1016/j.conbuildmat.2019.117753.
Zanotti, C., Banthia, N. and Plizzari, G. (2014), "A study of some factors affecting bond in cementitious fiber reinforced repairs", *Cement Concrete Res*., **63**, 117-126. https://doi.org/10.1016/j.cemconres.2014.05.008.
Zhang, Y., Zhu, P., Liao, Z. and Wang, L. (2020), "Interfacial bond properties between normal strength concrete substrate and ultra-high performance concrete as a repair material", *Constr. Build. Mater*., **235**, 117431. https://doi.org/10.1016/j.conbuildmat.2019.117431.
Zhou, X., Mickleborough, N. and Li, Z. (2005), "Shear strength of joints in precast concrete segmental bridges", *ACI Struct. J*., **102**(1), 3-11.

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