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Comparison of methods for evaluating bond strength between concrete substrate and repair materials

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Abstract

This investigation was aimed at studying the effect of test methods on bond strength between concrete substrate and repair material. Four test methods with cementitious or modified-cementitious repair materials, and two surface roughnesses were studied. The methods used were pull-off, slant shear, splitting prism and a new direct shear named Bi-Surface shear test. While the coefficient of variation (COV) for each type of test was acceptable, the bond strengths from some tests were up to eight times larger than those obtained from others. It is imperative that the bond tests be selected such that they represent the state of stress the structure is subjected to in the field. The new test method was easy to carry out and had reasonable results and can be developed by further investigations.

Keywords: Bond strength; Surface layer; Tensile properties; Silica fume; Concrete

1. Introduction

In the field of repair and strengthening of concrete structures, the need often arises to place new concrete next to old, i.e., existing concrete. Examples of these applications include highway structures where concrete overlays are used and repair of corrosion-damaged concrete structures, where the deteriorated concrete must be replaced with new concrete. In these applications, the bond between the old and new concrete usually presents a weak link in the repaired structure. Several tests are available to measure the bond strength. However, little information is available on comparison of these various tests methods and the resulting bond strength values.

As demonstrated in this paper, the measured bond strength is greatly dependent on the test method. With the proliferation of chemical bonding agents, the design engineer is often faced with selecting the bond strength of a particular product based on the data reported by the manufacturer. Depending on the test method used, the reported bond strength may significantly overestimate the true strength of the product for the desired applications. Therefore, there is a need to compare different tests for measuring bond strength and to establish a relationship among the values obtained from each test.

The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface.

Friction and aggregate interlock on interface depend on parameters, such as aggregate size, aggregate shape, and surface preparation. In addition to the above factors, the measured bond strength is highly dependent on the test method used. Size and geometry of specimen and the state of stress on the contact surface are quite dependent on the chosen test method. It is noted that certain standard tests have been developed for specific applications and state of stress. For example, the slant shear is used to evaluate the bond strength of resinous materials, epoxy bonding agents, and latex bonding agents under a combined state of stress of compression and shear [1,2].

There are two problems that need to be addressed. First, what types of tests are appropriate for evaluating the bond

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strength for the state of stress that is commonly found in buildings, i.e., shear stress caused by loading and time-dependent factors. Second, what relationship exists between the results of different test methods? Repair materials can be divided into three main groups: cement based, modified cement based, and resin based. In recent years, with the popularity of resin-based materials, slant shear test became a widely accepted test. However, considering the cost and behavior of resin-based materials, the use of modified-cementitious materials has been on the increase in developing countries. In light of the weak bond strength of cement-based materials, modified cementitious materials offer a good compromise in terms of cost and behavior. As a result, there is renewed interest in developing tests to measure the bond of concrete substrates to modified cement-based or enriched cement-based repair materials. Considering the lack of consensus among practitioners, the objective of this study was to examine the various test methods for determining bond between concrete substrate and modified or enriched cement-based repair materials.

2. Existing methods

The existing tests to determine the bond between concrete substrate and repair material can be divided into several categories. The first category of tests measures the bond under tension stress. Pull-off [3] (Fig. 1a), direct tension [4], and splitting [5] (Fig. 1b) are the main tests under this category. In the splitting test, a prism with circular or square cross-section is placed under longitudinal compressive loading (Fig. 1b). Tension stresses cause failure in a plane passing through upper and lower axes of loading and split the specimen into two halves.

The second category of tests measures the bond under shear stresses, and are called direct shear methods. Several tests fall under this category, including L-shaped, mono-surface shear, etc. [6]. In most cases, the bond surface for a direct shear test is actually subjected to shear stress and a small bending stress. When a steel plate is used to transmit the shear force along the bond line, some stress concentration at the edge of the bonding plane is induced. Smaller stress concentration leads to smaller scatter in test results [4]. As a part of this investigation, a new direct shear method was developed which is hereafter referred to as Bi-Surface shear. Typical test specimen dimensions and loading are shown in Fig. 1c and further information on this test is provided elsewhere [7].

The third category measures the bond strength under a state of stress that combines shear and compression. All slant shear tests mentioned previously fall under this category. The slant shear test uses a square prism or a cylindrical sample made of two identical halves bonded at 30° and tested under axial compression, as seen in Fig. 1d. During loading, the interface surface is under compression and shear stresses. The slant shear test has become the most widely accepted test, and has been adopted by a number of international codes as a test for evaluating the bond of resinous repair materials to concrete substrates [8]. However, there is no general agreement among researchers as to the appropriateness of this test for nonresinous materials [4,8,9].

3. Literature review

In the direct tension test, the tensile force is transmitted to the concrete specimen either by glued metal or by special grips. A very careful alignment of the specimen in the axis of loading is essential [4]. Even a very small amount of misalignment may introduce eccentricities that will cause large scatter in test results. Performing a good tension test is difficult and time consuming. However, a recently proposed variation of the direct tension test, referred to as pull-off test, is easier to carry out and can produce good results [5].

Indirect tension tests include the flexural test and the splitting test. The flexural test offers low efficiency (the area of the bonded surface subjected to loading is small compared to the specimen volume). For such tests, only a very small part of the bonded plane is subjected to the maximum stresses [8]. Splitting test is more efficient in that regard.

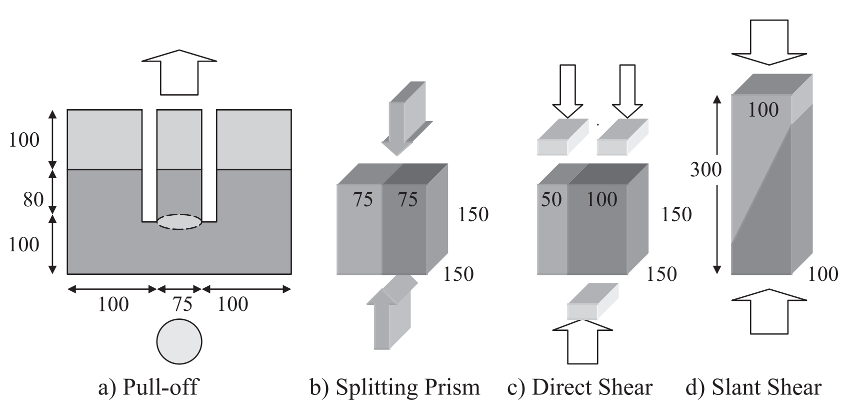

Fig. 1. Dimensions of tested specimens in millimeters (25.4 mm = 1 in.).

The splitting tensile strength of concrete is regarded as an indication of its tensile strength. The splitting tensile test of homogeneous cylindrical specimens was first proposed by Japanese researchers [10]. Further developments were carried out in Brazil [11], and the method was later adopted as a standard test ASTM C496 [12]. The test method is simple to perform and uses the same cylindrical specimen and test machine as a standard compression test.

Ramey and Strickland [13] used the ASTM C496 standard test method as a general guide and developed a splitting test for composite cylinders, constructed with one-half concrete and one-half repair material (Fig. 2). They measured the bond strength between the base concrete and the repair material as the splitting strength of the composite cylinder. Although the composite cylinder was made of two different concrete materials, they calculated the tensile strength of the composite cylinder using the same equation used for homogeneous cylinders. Their test results showed that the cylindrical splitting tensile gave consistent results. The average coefficient of variation (COV) for 26 test groups was 9.7%, and the COV of most groups was less than 13%.

In the slant shear test, the shear stress is combined with a compression stress in the axis perpendicular to the bonding plane. The slant shear test, which was proposed by University of Arizona researchers, is the most common method [14]. The test specimen is a composite cylinder, which has a diagonal bonded plane at an angle of 60° from the horizontal. The composite cylinder is loaded as in a standard compression test. Wall and Shrive [15] modified the Arizona slant shear test by using a prism with a length three times the cross-section dimension instead of a cylinder. Their research indicated that slight misalignment of the two halves of the prism specimen did not have a significant effect on the results. Abu-Tair et al. [8] reported that this method could be used for both resinous and cementitious repair materials. However, they proposed a flexural method to measure the effectiveness of repair materials in tension bond.

Fig. 2. Cylindrical splitting specimen at failure.

More recently, Delatte et al. presented methods for estimating the bond development between concrete overlay and its underlying substrate at early ages on the basis of concrete maturity. Tension bond strength and shear bond strength were reported to be a function of mixture proportioning and curing temperature [16]. Bond between concrete and overlays has also been studied by Petersen et al. [17].

In this article, besides splitting prism and shear slant tests, a newly developed direct shear method named Bi-Surface shear test is reported. This method is easy to carry out and no special form or apparatus is needed (Fig. 1c).

4. Research significance

With the rapid increase in the decay of infrastructure worldwide, there is a great deal of interest in bond between existing concrete substrate and repair materials. While bond tests have been developed for specific applications, there is no consensus among practitioners for evaluating the bond strength under a state of shear stress that is commonly encountered in buildings. This paper compares the bond strength measured by four different test methods and two different categories of repair materials. The test results should be of interest to design and construction engineers involved in evaluating the bond strength between existing and new materials.

5. Experimental study

The objectives of this report were to develop tests to measure the bond strength between repair materials and concrete substrate. The overall project evaluated several different types of bond tests, including pull-off, shear slant, circular and prism splitting, and Bi-Surface shear tests. Many specimens were constructed and tested and the study is still on going with testing additional bond specimens and half-scale beam specimens to develop an analytical model.

5.1. Test program

This paper includes 164 specimens tested in pull-off, splitting prism, and slant shear and presents a new direct shear test method based on bi-surface shearing. The size of all reported specimens are shown in Fig. 1. The pull-off specimens were cylindrical with a base radius of 75 mm (3 in.). The splitting prism specimens were $150 \times 150 \times 150$ mm ($6 \times 6 \times 6$ in.) cubes. In the Bi-Surface shear method, the repair material constitutes one third of the specimen. In other words, using 150 mm (6 in.) cube forms, prisms with a base size of 100×150 mm (4×6 in.) and a height of 150 mm (6 in.) are cast as old or substrate concrete (Figs. 1c and 3a); the repair materials are cast in prisms with a base of

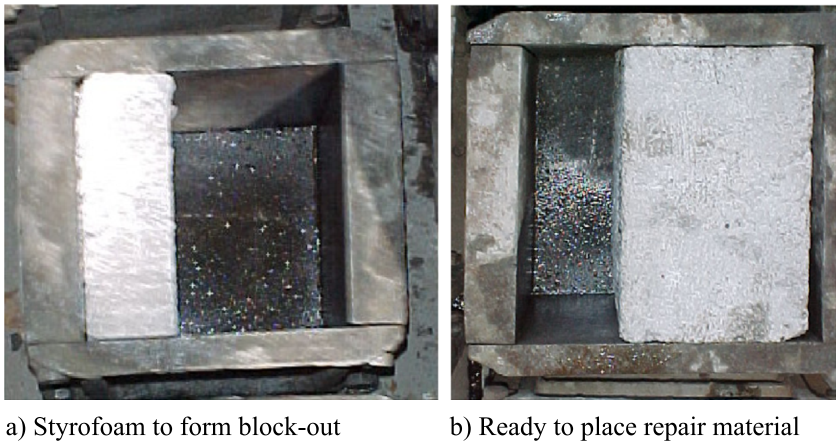

Fig. 3. Fabrication of cube samples for Bi-Surface shear test: (a) styrofoam to form block-out and (b) ready to place repair material.

150 × 50 mm (6 × 2 in.) and a height of 150 mm (6 in.) and are bonded to the concrete substrate (Fig. 3b). The loading on these specimens causes a shear failure. This failure is more common in practice compared to a shear-compression failure that is produced in slant shear tests.

5.2. Specimen preparation

The same mix design was used for the concrete in substrate portion of all specimens. The mix proportions were based on a 28-day compressive strength of $f'c = 35$ MPa (5076 psi), $w/c = 0.46$, a minimum Portland Cement Type II content of 400 kg/m^3 (674 lb/yard^3) and a maximum crushed aggregate size of 16 mm (0.63 in.). The concrete was manufactured in the laboratory by a 200-l (53-gal) mixer and was placed in lubricated steel forms. When necessary, Styrofoam was used to form the block-outs (Fig. 3a). Specimens were removed from the forms 24 h after casting and they were cleaned from any extra dust or particles.

Within the first 2 days of casting, repairing surfaces were roughened in one of two categories: low or high. The low-roughness category was obtained using a steel wire brush to remove slurry cement from external surface of both fine and coarse aggregates. The estimated amplitude of roughness was 3–4 mm (0.12–0.16 in.); using a similar approach, the high-roughness category was roughened to an amplitude of 7–8 mm (0.27–0.31 in.; Fig. 4). The concrete specimens were kept in water until the age of 28 days. The specimens were then left to dry for an additional 30 days before the repair material was placed. The contact surface of specimens was recleaned using a wire brush and high-pressure air a few hours before placing the repair materials.

As mentioned before, while there are standard tests for determining the bond strength of resinous repair materials, no standard methods exist to evaluate shear bond of cementitious or modified cementitious repair materials. Therefore, the primary focus of this study was on the latter.

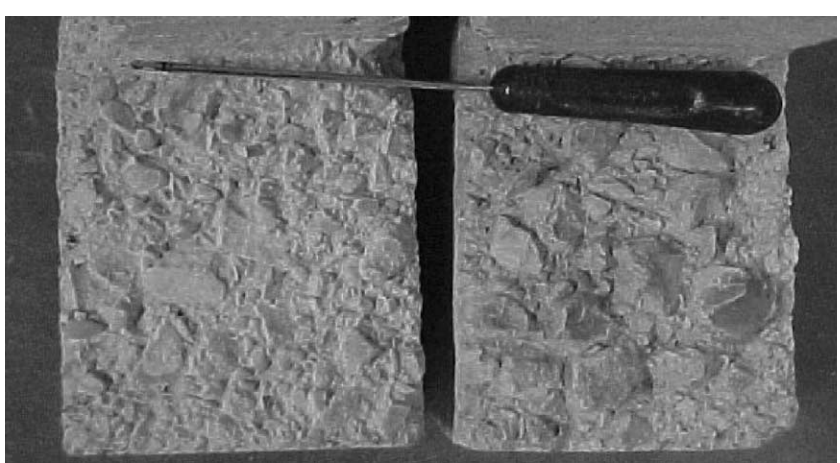

Fig. 4. Low (left) and high (right) roughness surface preparation.

Table 1
Test results of specimens at the age of 28 days

Specimen group	Repair material	f′c	Roughness	Pull-off (2 samples)		Splitting prism (4 samples)			Bi-surface shear (4 samples)			Slant shear (4 samples)		
				σ	N	σ	COV	N	σ	COV	N	σ	COV	N
RL	Reference	36	L	1.18	2	1.19	7.3	4	2.4	9.9	4	8.12	15.8	4
RH	(0% SF)		H	1.32	2	1.36	8.4	4	3.00	10.8	4	11.13	9.8	4
5L	5% SF	37	L	1.25	2	1.27	6.4	4	2.66	7.6	4	9.18	9.8	4
5H			H	1.38	2	1.44	7.2	4	3.29	10.4	4	11.9	8.4	4
7L	7% SF	41	L	1.37	2	1.38	10.4	4	2.98	6.5	4	10.32	9.4	3
7H			H	1.50	2	1.62	9.2	4	3.63	9.1	4	13.2	4.7	2
10L	10% SF	43	L	1.38	2	1.39	9.8	4	3.00	11.8	4	10.16	11.6	3
10H			H	1.53	2	1.64	11.2	4	3.66	13.3	4	13.02	7.3	2
KL	Modified	35	L	1.82	2	1.95	10.6	4	3.41	10.8	4	11.59	10.8	3
KL	by K100		H	1.95	2	2.14	10.9	4	3.82	7.2	4	13.56	6.1	2
SL	Modified	38	L	2.38	2	2.69	9.7	4	3.82	11.1	4	12.19	12.2	2
SH	by SBR		H	2.50	2	2.90	9.6	4	4.16	12.2	2	13.53	7.7	2
C	Continuous	36	–	3.18	–	3.97	–	–	4.50	–	–	14.11	–	–

σ = Mean bond strength (MPa), N = number of samples failed in bond, SF = silica fume, K100 = K100 polymer adhesive, SBR = styrene butadiene resin, COV = coefficient of variation (%).

Six mixes of repair materials were used and seven types of boundary interface were tested. One of the boundaries was a continuous bond composed of the substrate concrete material. Four of the repair materials and their corresponding interfaces were sand–cement mortars containing 0%, 5%, 7%, or 10% of silica fume. The remaining two repair materials and interfaces were modified cement based (Tables 1–3). One of the modified cementitious mortars was made by replacing 10% of cement content with a polymer concrete adhesive named K100 adhesive. The other modified cementitious mortar was made by replacing 20% of cement content with styrene butadiene resin (SBR; Table 3). Both of these admixtures were supplied by Master Builders.

For each group of cementitious repair materials, a different moisture condition on the interface boundary was used. For the cement-based materials, the samples were saturated with a dry surface; for the modified-cementitious materials, the surfaces were prepared following the manufacturers' recommendations. Repair material mixes were designed based on the following: a compressive strength of 35 MPa (5076 psi), maximum aggregate size 10 mm (0.4 in.), slump 75–100 mm (3–4 in.), w/c = 0.4, and a minimum Portland Cement Type II content of 400 kg/m^3 (674 lb/yard^3). A superplasticizer (Mel Crete) was used for the required workability (especially when silica fume was added) with the same w/c ratio in all mixes. The modified mortars were obtained by replacing the cement with the same weight of polymer resins.

For each of the above six repair materials, a corresponding mortar bonding agent was used over the boundary areas. The sand used for all six bonding agents was compatible with ASTM C144 [18]. The sand/cement ratio was 1:1 and the w/c was 0.4. The silica fume content in the bonding agents were 0%, 5%, 7%, and 10%, corresponding to the same values in the repair materials. The bonding agent was applied to the interface areas using a brush.

The average thickness of the bonding agent was 3 mm for cementitious and about 1–2 mm for polymer materials. For the cementitious agents, the mix proportion for water/Type II cement/sand was 1:6:2.5, respectively. Sand and cement were dry mixed; water and polymer were mixed together and were added to the dry mix. In the case of modified bonding agents, the resin content of the bonding agent was 20% for SBR and 50% for K100 adhesive. The resin content of the K100 repair material was kept at 10% as stated earlier. During the first 7 days, the cementitious specimens were moist cured at 20 °C (68°F) and after that they were kept at the same temperature and 50% humidity. The specimens were typically removed from the humidity room and allowed to dry for a day prior to testing.

Table 2
Chemical analysis of Portland cement and silica fume

Chemical ingredient	Portland cement (%)	Silica fume (%)
SiO_2	20.52	91.1
Al_2O_3	5.5	1.55
Fe_2O_3	4.3	2.0
CaO	62.78	2.24
MgO	1.6	0.60
NaO_2	0.5	–
K_2O	0.4	–
Ignition loss	1.74	2.10
Free lime	0.84	–
SO_3	1.44	0.45

Table 3
Properties for SBR

Physical state	Milky white liquid
Total solids (by weight of polymer)	40%
Specific gravity	1.01
pH	10.5
Mean particle size	0.17 μm

5.3. Test results

All 164 composite or continuous-bond specimens reported in this article were loaded statically at the age of 28 days. The adverse effect of additional long-term deformations was neglected for this study. Each group of specimens is identified with two characters. The first character or number refers to the repair material and the second character to the interface surface preparation (L for low roughness and H for high roughness). Table 1 gives the test results, including the mean bond strengths, COVs, and the percentage of the specimens that failed by bond failure.

For pull-off tests and continuous interface, the average of two tests is reported. For all other cases, the mean values and COV for a group of four identical specimens are given. The results show a COV varying from 6.1% to 15.8% with an average value of 9.8%. It is further noted that the average COV for Bi-Surface shear tests is 10.6% compared to 9.3% for the other two tests. However, considering all Bi-Surface shear tests reported here and elsewhere [7], the COV for this test was 9.6% which compares favorably with the other tests. All of these COVs are reasonable considering the types of tests and materials and attest to the reliability of the tests.

The failure modes were characterized by the location of the failure in the specimens. Bond failure is defined when the plane of failure is along the interface surface. Some of the specimens failed by partial failure of either the old concrete or the newly added repair material. Fig. 5a shows a slant shear specimen failed in bond and Fig. 5b shows a specimen in which the failure plane passed through a portion of the interface and repair material. The numbers of the specimens that failed in bond are listed in Table 1. As can be seen, all pull-off and splitting prism specimens failed in bond. One group tested in Bi-Surface shear and eight groups tested in slant shear had failure modes other than bond.

The bond strength for all methods, except for the splitting, was calculated by dividing the maximum load at failure by the bond area; that is, for the slant shear test, the bond area is a sloping surface. The splitting tensile strength was calculated by the following equation:

$$\sigma = 2P/\pi A \qquad (1)$$

where σ = splitting tensile strength, MPa (psi); P = applied load, N (lbf); and A = area of bond plane, mm^2 (in.^{2}).

For continuous-bond specimens, i.e., specimens that were monolithically cast in a single stage, there is no predefined interface plane. Therefore, bond failure calculations do not have any physical significance and were not reported. However, to allow comparison of the results of repaired specimens with a monolithic sample, an equivalent bond strength for these specimens was calculated by dividing the applied force by the corresponding noncontinuous bond area values, e.g., sloping area in the case of slant shear test.

Fig. 6 shows a comparison of the measured bond strength by different methods for both low- and high-roughness specimens. The slant shear gave the highest strength for all repair materials and surface preparations. This can be attributed to the high compressive stresses that exist in slant shear test. These compressive stresses produce higher interlock and friction forces that increase the shear failure load. The Bi-Surface shear test resulted in much lower bond strengths compared to the slant shear but higher than those of the splitting and pull-off tests. The bond strength mea-

a) Bond failure b) Non-bond failure

Fig. 5. Slant shear specimens after failure.

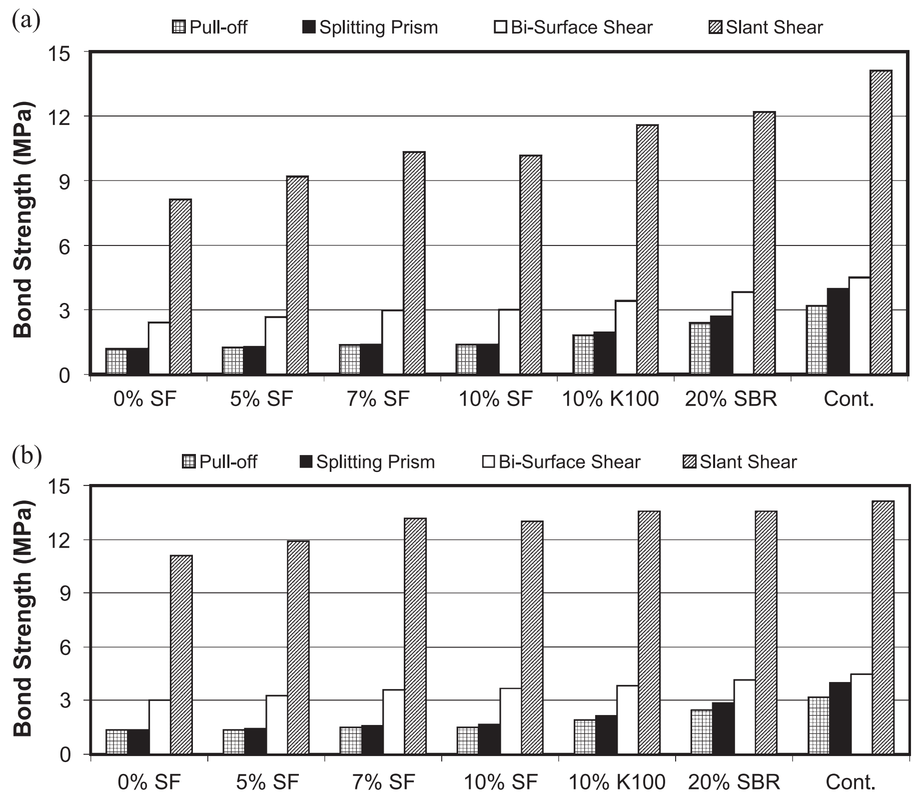

Fig. 6. Measure bond strength by different methods: (a) low roughness and (b) high roughness.

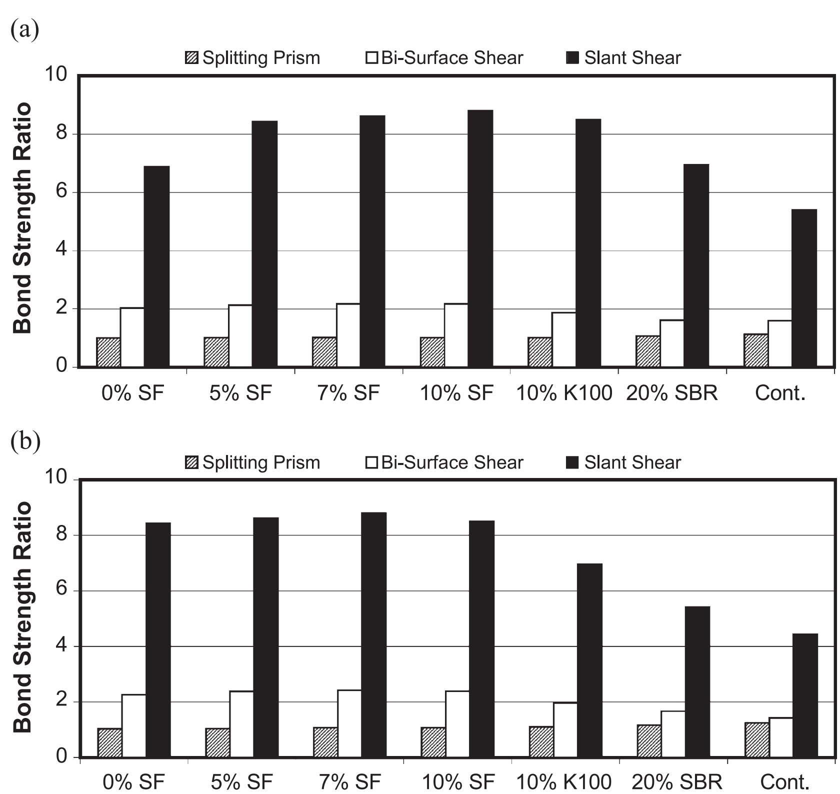

Fig. 7. Ratios of measured bond strength by different methods to those of pull-off test: (a) low roughness and (b) high roughness.

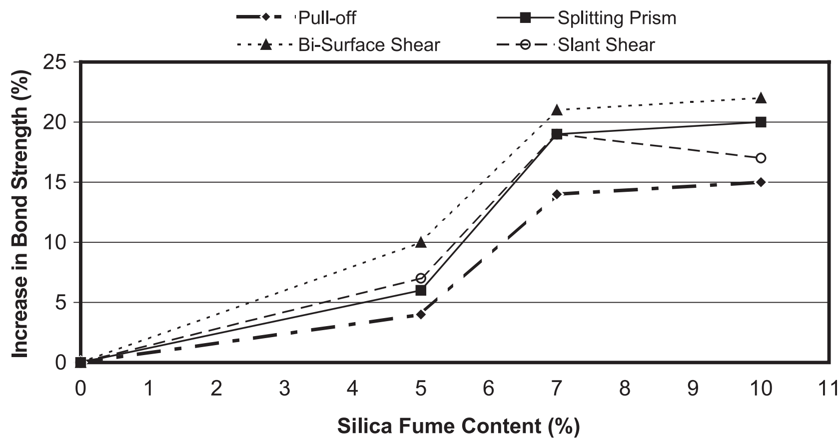

Fig. 8. Percentage of increase in bond strength for various silica fume contents (high roughness).

sured by the splitting prism and pull-off tests were very close and lower than the other two methods.

Fig. 6 also shows that regardless of the test method used, the continuous specimens had the highest bond strength. In other words, none of the repair materials reached the bond strength of continuous samples. It is noted, however, that some repair materials may result in bond strengths that are higher than that of the original specimen and the above conclusion is limited to the materials examined in this study. In general, the bond strength increased with the silica fume content and further increases were observed for the K100 and SBR mixes.

Pull-off test provides the most conservative bond measurement because it is not influenced by friction or other forces that are present in other methods. Having the lowest bond strength values, the pull-off test has been chosen as a base for comparison. Fig. 7 shows the ratios of the measured bond strength by different methods to those of pull-off test. The splitting, slant shear, and Bi-Surface shear tests for high-roughness surfaces resulted in bond strengths that were on the average 1.1, 1.8, and 7.30 times higher than the pull-off tests, respectively. This indicates that some tests, such as slant shear or Bi-Surface shear, result in significantly higher bond strength values. Therefore, when the interface is under a state of tension stress, results from slant shear or Bi-Surface shear should not be used, unless appropriate correction factors are applied to these results. Conversely, reliance on pull-off and splitting bond strengths for applications where the interface is subjected to shear or shear and compression can underestimate the true bond strength. As seen in Fig. 7a, a similar trend exists for specimens constructed with low surface roughness.

The effect of silica fume content on bond strength is shown in Fig. 8. Because the specimens with high roughness represent sand-blasted surfaces that are more common in construction, the results for low-roughness specimens have not been plotted here. It can be concluded that regardless of the test method used, addition of silica fume increases the bond strength by as much as 22%. However, the influence of silica fume appears to peak at 7% and any additional silica fume content does not increase the bond strength measurably. The improvements caused by the addition of silica fume were higher for those methods that cause shear stresses (i.e., slant shear and Bi-Surface shear tests), compared to those where tensile stresses are induced (i.e., pull-off and splitting). This demonstrates that adding silica fume is more effective under shear stresses than tension stresses.

Fig. 9 shows the increase in the bond strength for high-roughness specimens compared to those with the low

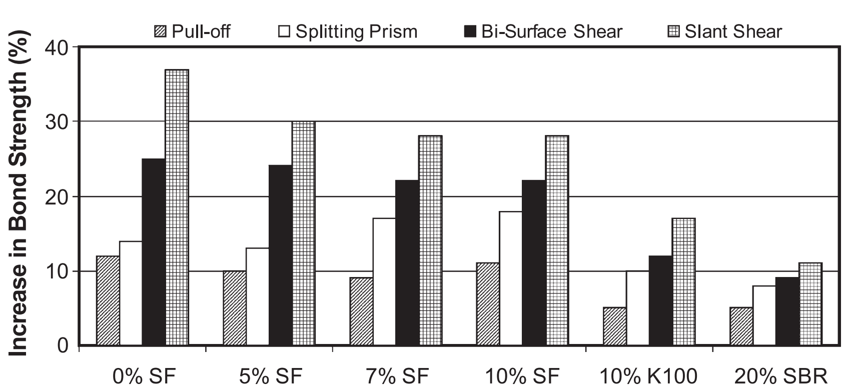

Fig. 9. Percentage of increase in bond strength for high roughness to low roughness surfaces.

roughness. Providing a rougher bonding surface resulted in an increase in bond strength for all six repair and bonding agent materials. These increases were on the average 9% for pull-off, 13% for splitting, 19% for Bi-Surface shear, and 25% for slant shear. This indicates that all methods are sensitive to the interface roughness; the Bi-Surface and slant shear methods are most highly sensitive, especially when cementitious materials are used. The data also demonstrate that for materials with low adhesion (e.g., cementitious materials), the influence of surface roughness is higher than that for polymer-modified mixes that have higher adhesion.

The ratios of bond strength of high-roughness repaired interfaces to that for the continuous samples are shown in Fig. 10. This comparison is important because in spite of the large differences that exist among the absolute measured bond strengths (Figs. 6 and 7), the value of each test can only be judged in terms of its ability to predict the strength of a monolithic sample tested under the same conditions. A ratio of one represents a repair material whose application does not introduce a new weak link in the structure. Regardless of the materials used, the bond strength decreases for various tests in the following order: slant shear, Bi-Surface shear, pull-off, and splitting (Fig. 10).

Considering cementitious materials, tests that fail under tension (i.e., pull-off and splitting) measured values that were 34–48% of the continuous samples with an average of 41%, while the other two tests (Bi-Surface and slant shear) gave much higher values (67–93% with an average of 81%). This clearly indicates that when cementitious materials are used for repair, the most conservative results are obtained when pull-off and splitting tests are employed. Furthermore, it is evident that the bond strength of cementitious materials under tension is less than 50% of the continuous samples. Therefore, in such applications, the use of polymer-modified or enriched-cementitious materials results in bond strengths that more closely represent a monolithic structure. Although the same trend exists for modified cementitious materials, the differences are not quite as large; e.g., 55–79% with an average of 67% for pull-off and splitting, versus 85–97% with an average of 93% for Bi-Surface and slant shear.

6. Summary and conclusions

The short-term bond strength of 164 specimens constructed with six different repair materials has been reported. The specimens were tested under four approaches, each representing a different state of stress. These included a new test proposed by the authors referred to as Bi-Surface shear. Based on the results obtained, the following conclusions can be drawn:

1. Bond strength is greatly dependent on the test method used. While the COV for each type of test was acceptable, the bond strengths from some tests were up to eight times larger than those obtained from others. It is imperative that the bond tests be selected such that they represent the state of stress the structure is subjected to in the field.
2. The measured bond strength decreases with the test method in the following order: slant shear, Bi-Surface shear, splitting, and pull-off.
3. Bond strength increases with silica fume content for all test methods. However, these beneficial effects are negligible beyond a silica fume content of 7%.
4. Rough surface preparation leads to higher bond strength. These increases ranged from 9% for pull-off to 25% for slant shear tests. The influence of surface roughness is more pronounced when the repair materials have low adhesion, e.g., cementitious materials.
5. For cementitious repair materials, pull-off and splitting tests predict bond strengths that are approximately 40% of the bond strength of a monolithic sample; Bi-Surface and slant shear tests predict values that are about 80% of the continuous samples.
6. For the modified-cementitious materials studied, pull-off and splitting tests predict bond strengths that are 67% of the bond strength of a monolithic sample; Bi-Surface and

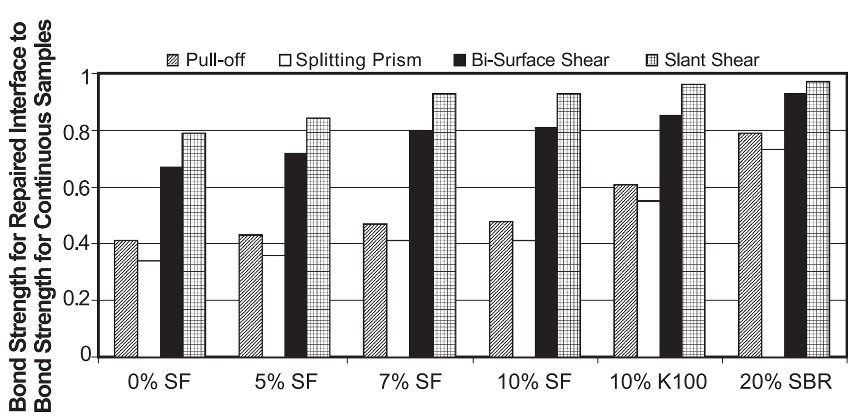

Fig. 10. Ratio of bond strength of repaired interfaces to that for continuous specimens (high roughness).

slant shear tests predict values that are 93% of the continuous samples.

7. The proposed Bi-Surface shear test is easy to carry out and provides consistent results. The test represents a state of shear stress on the interface.

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