BOND STRENGTH BETWEEN SHOTCRETE OVERLAY AND REINFORCED CONCRETE BASE

OF THE SAINT JOHNS RIVER POWER PARK COOLING TOWER

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Composite concrete construction is typically two or more separately fabricated elements functioning as one element because of composite action between the elements. Bonded concrete construction achieves composite action by adhesion and interlock between the elements and without reinforcement between the elements. It is generally accepted that the structural performance and durability of bonded concrete construction is a function of the adhesion and interlock between the elements as well as the strength and durability of the elements.

Standard tests typically used to measure bond strength include the tensile bond test (ASTM C1583[1]) and the slant shear test (ASTM C882[2]). The slant shear test requires specimens that are prepared in the laboratory and can be useful for approving concrete materials and adhesives. A slant shear bond strength of 1500 psi (10.3 MPa) has been used for approval of some materials. However, the test is not suitable for use with a performance specification, which requires tests on samples from constructed structures. The tensile bond test has been used since the 1960s to determine the bond strength of polymer overlays and has been used for approximately 30 years to measure the bond of concrete overlays.[3-5] The test is typically conducted on bonded concrete elements but can be conducted in a lab using cores removed from the structure. The bond strength required for good performance is a function of the stress on the bond interface and as long as the bond strength exceeds the bond stress, composite action is maintained. Given the difficulty of designing for bond stress, minimum bond strength values ranging from 100 to 250 psi (0.7 to 1.7 MPa) have been cited in specifications. ACI 548[6] currently recommends minimum bond strength of 250 psi (1.7 MPa) for polymer overlays.

Structural designers typically use shear strength when designing for composite action and tensile bond strength is of little value unless it can be correlated to shear bond strength. A number of different shear tests have been used to measure bond strength but there is no ASTM standard for a shear bond strength test.[7] Because a shear bond strength test result is a function of the test method as well as the test sample, there is no industry standard for the minimum shear bond strength recommended for composite action and performance.

STUDY SITE

The Saint Johns River Power Park Cooling Tower is a reinforced concrete structure that received a shotcrete overlay approximately 3.5 to 6.4 in. (89 to 163 mm) thick in 2011. Prior to applying the shotcrete, the surface was mechanically (grit) blasted (15 lb [6.8 kg] handheld concrete breaker and abrasive blast) or hydroblasted to provide a prepared surface that would achieve good bond strength. Tensile bond tests were performed to measure the bond strength. The tensile test results were typically less than the 250 psi (1.7 MPa) specified, raising some concern that the bond strength may not be adequate.[8] A guillotine shear jig was used to measure the shear bond strength of 17 cores removed from the areas where tensile bond tests had been conducted. The jig had been used in the 1980s to measure the shear bond strength of bridge overlays.[3-5]

OBJECTIVE

The objective of this study was to conduct and evaluate shear tests to provide shear bond strength values that were representative of the shear bond strength between the overlay and the base, to provide values that could be compared to values used in the design for composite action in the cooling tower, to correlate the shear values with the tensile values, and to help develop a much-needed test method for shear bond strength that may become an industry standard.

METHODOLOGY

Tensile bond tests were conducted in accordance with ASTM C1583[1] on areas that had been either mechanically blasted or hydroblasted. Seventeen test results were reported (Test 1), along with a second test (Test 2) at five locations.

Seventeen 2.75 in. (70 mm) diameter cores were removed from the cooling tower for use in conducting guillotine shear tests. Guillotine shear tests were conducted using the following procedure developed at the Virginia Transportation Research Council.

The thickness of the overlay was measured at four locations spaced 90 degrees apart around the circumference of the overlay. The overlay thickness varied from approximately 3.5 to 6.4 in. (89 to 163 mm) and typically varied by 0.25 to 0.75 in. (6 to 19 mm) around the circumference. An average overlay thickness was determined based on the four measurements on each core. The guillotine shear jig has a steel guillotine that is 3 in. (76 mm) thick with a 2.75 in. (70 mm) diameter half circle cut into the guillotine that is placed over the core (Fig. 1). The core is supported by a steel front frame that is 2 in. (51 mm) thick with a 2.75 in. (70 mm) diameter circle cut into the frame. A slice was cut from the top of each core to provide an overlay for testing with an average thickness of 2.56 in. (65 mm). The cut core is placed into the hole in the front frame and a 0.44 in. (11 mm) thick wood spacer is placed between the top of the core and the back inner wall of the shear jig to ensure the average center of the bond interface is aligned with the front edge of the guillotine and the inside front face of the support frame. The guillotine is placed into the jig and lowered onto the core. The wood spacer is removed. An aluminum spacer sheet approximately 1/32 in. (0.8 mm) thick is placed on top of the guillotine. The jig is positioned between the heads of the universal testing machine and the guillotine is centered under the upper head.

The core is subjected to a load applied at the rate of 4000 lb per minute, which equals 11.2 psi per second (77 kPa/s). The rate was selected because the shear bond strength is typically at least twice the tensile bond strength. ASTM C1583[1] requires a constant loading rate of 5 ± 2 psi per second (35 ± 15 kPa/s) for tensile bond strength tests. The core is loaded to failure and the failure load is recorded. The core is removed; the failed surfaces are examined; and the areas that failed in the overlay, bond interface, and base are estimated and recorded. The failed section of overlay is placed in the jig so that approximately half of the specimen is in the frame and half is under the guillotine. The overlay is loaded to failure to estimate the shear strength of the overlay. The failure load is recorded. The failed section of the base is placed in the jig so that approximately 2.5 in. (64 mm) of the bottom of the base is under the guillotine. The base is loaded to failure to estimate the shear strength of the base. The failure load is recorded. The failure shear stresses are computed by dividing the failure loads by the core cross-sectional area computed using the core diameter of 2.75 in. (70 mm). The shear bond strength, overlay shear strength, and base shear strength at failure are recorded.

BOND STRENGTH TEST FOR OVERLAYS

GUILLOTINE SHEAR TEST OF CORE

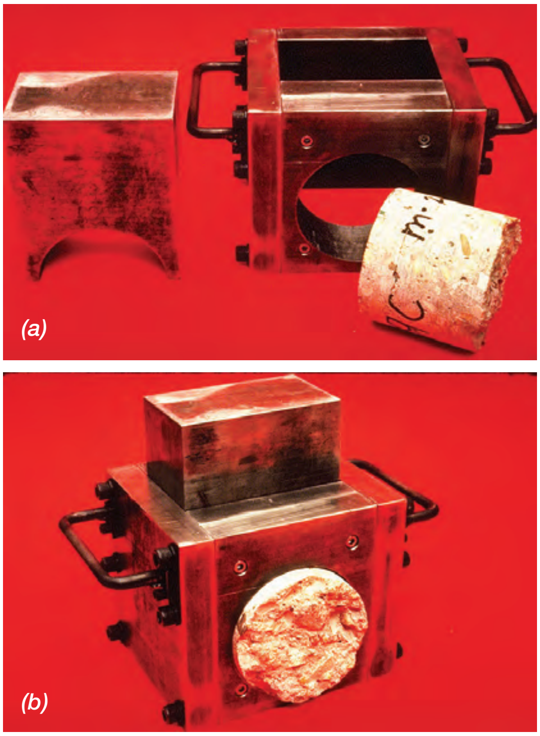

Fig. 1: Guillotine shear jig—(a) guillotine, base, and core; and (b) core ready to be loaded

RESULTS

Tensile bond strength test results are shown in Table 1. The average tensile bond strength for the hydroblasted substrate based on Test 1 is 145.9 psi (1.01 MPa) with a standard deviation of 58.4 psi (0.40 MPa). The average for Test 2 is 132.3 psi (0.91 MPa) with a standard deviation of 13.9 psi (0.10 MPa). The average tensile bond strength for the mechanically blasted substrate based on Test 1 is 139.9 psi (0.96 MPa) with a standard deviation of 22.1 psi (0.15 MPa). The one result for Test 2 on a mechanically blasted substrate was 139.1 psi (0.96 MPa). Based on all test results, the tensile bond strength is about the same for both hydroblasted and mechanically blasted methods of surface preparation at 142.0 psi (0.98 MPa) and 139.8 psi (0.96 MPa), respectively.

Guillotine shear bond test results are shown in Table 2. The average shear bond strength for the hydroblasted substrate is 1047.7 psi (7.22 MPa) with a standard deviation of 313.3 psi (2.16 MPa). The average shear bond strength for the mechanically blasted substrate is 972.7 psi (6.71 MPa) with a standard deviation of 245.3 psi (1.69 MPa). The shear bond strength is similar for both methods of surface preparation. The ratio of shear to tensile bond strength is 7.38 and 6.96 for hydroblasted and mechanically blasted surfaces, respectively. The average shear bond strength for both substrates is 1016.8 psi (7.01 MPa) with a standard deviation of 281.4 psi (1.94 MPa).

TABLE 1: TENSILE BOND STRENGTH TEST RESULTS FROM COOLING TOWER (REPORTED BY STRUCTURAL)

Core locations			Tensile bond strength, psi		Substrate surface preparation	Core removal type*
Tower	Zone	Panel	Test 1	Test 2		
1	C	34CF	65	111.6	Hydro	Full depth
1	C	32CF	138.4	140.4	Hydro	Broke off
1	C	32CF	138.4	140.4	Hydro	Broke off
1	A	10M	168.6		Mechanical	Broke off
1	A	10N	159		Mechanical	Full depth
1	A	10Q	111.3	139.1	Mechanical	Full depth
1	A	12N	139.1		Mechanical	Broke off
1	A	12N	139.1		Mechanical	Broke off
1	A	12P	111.3		Mechanical	Full depth
1	A	12Q	150.6		Mechanical	Full depth
2	C	28BT	251.8		Hydro	Broke off
2	C	26BT	85.6		Hydro	Broke off
2	C	29BT	201.1		Hydro	Full depth
2	C	29BR	128.5	136.7	Hydro	Full depth
2	C	36BT	209.1		Hydro	Full depth
2	C	34CA	104		Hydro	Full depth
2	C	34BW	137.4		Hydro	Broke off

*Cores either failed in the substrate near the bottom of the drilled core hole (full depth) or the failure intersected the bond interface (broke off).
Note: 1 psi = 0.00689 MPa.

TABLE 2: SHEAR BOND INTERFACE STRENGTH TEST RESULTS AND PERCENT FAILURE IN OVERLAY, BOND INTERFACE, AND BASE FOR 2.75 IN. (70 MM) DIAMETER CORES FROM COOLING TOWER

Panel	Load, lb	Stress, psi	OL, %	Bond, %	Base, %	Overlay (OL) thickness values = average, in.
34CF	4980	838	85	5	10	6.25, 6.5, 6.25, 6.5 = 6.38
32CF	5270	887	70	0	30	6.13, 5.63, 5.25, 5.63 = 5.66
32CF1	8700	1465	20	10	70	6.75, 6.31, 6.43, 5.88 = 6.34
10M	6560	1104	70	30	0	4.63, 4.38, 4.5, 4.25 = 4.44
10N	4250	716	70	0	30	4.38, 4.69, 4.88, 4.5 = 4.61
10Q	7100	1195	95	0	5	4.25, 4.5, 4.31, 4.13 = 4.30
12N	7380	1243	70	0	30	4.5, 4.5, 4.38, 4.63 = 4.50
12N	5200	875	0	10	90	4.13, 4.38, 4.19, 4.0 = 4.17
12P	3590	604	50	20	30	4.94, 4.69, 5.0, 5.25 = 4.97
12Q	6370	1072	70	0	30	4.5, 4.75, 4.88, 4.38 = 4.63
28BT	8920	1502	100	0	0	3.63, 3.38, 3.63, 3.38 = 3.50
26BT	3520	593	60	0	40	3.69, 4.5, 4.0, 4.44 = 4.16
29BT	4120	694	70	0	30	4.63, 4.0, 3.38, 3.5 = 3.88
29BR	5470	921	0	80	20	3.13, 2.5, 2.5, 3.13 = 2.81
36BT	7340	1236	60	0	40	4.25, 3.0, 4.0, 4.25 = 3.88
34CA	7540	1269	70	0	30	4.0, 3.69, 3.5, 3.38 = 3.63
34BW	6370	1072	60	0	40	4.25, 4.38, 4.56, 4.63 = 4.45

34CF: Frothy area approximately 0.25 in. (6 mm) thick located above bond interface approximately 1 in. (25 mm) long. Flaw/space in overlay approximately 0.13 to 1 in. (3 to 25 mm) above bond interface approximately 2 in. (51 mm) long.
32CF: Flaw/space in base approximately 0.25 to 1 in. (6 to 25 mm) below bond interface approximately 1.13 in. (29 mm) long. Flaw/space at bond interface approximately 1.25 in. (32 mm) long.
32CF1: Frothy area approximately 0.75 in. (19 mm) thick located above bond interface approximately 0.75 in. (19 mm) long.
10M: Flaw/space in overlay approximately 0.5 to 1 in. (13 to 25 mm) above bond interface approximately 2.25 in. (57 mm) long.
10Q: No space between saw-cut top of overlay and rear wall of jig.
12N1: Failed just below the bond interface (thin film of base) over 80% of the area.
28BT: Failure follows contours of concrete but overlay is bonded to concrete with a thickness ranging from a thin film to >1.25 in. (32 mm).
29BT: Frothy layer approximately 0.5 in. (13 mm) thick between base concrete and quality overlay. 70% failure is between top of frothy layer and quality overlay.
29BR: 80% bond failure follows the contours of the bond interface with a thin layer of overlay paste bonded to the base concrete.
Note: 1 lb = 0.454 kg; 1 psi = 0.00689 MPa; 1 in. = 25.4 mm.

TABLE 3: OVERLAY AND BASE SHEAR STRENGTH TEST RESULTS FOR CORES FROM COOLING TOWER

Panel	OL load, lb	OL stress, psi	Base load, lb	Base stress, psi
34CF	9150	1541	6260	1054
32CF	3000	505	3760	633
32CF	9470	1594	7760	1306
10M	6860	1155	4560	768
10N	6070	1022	5240	882
10Q	8210	1382	5140	865
12N	6830	1150	6160	1037
12N1	6700	1128	7850	1322
12P	6420	1081	6550	1103
12Q	6660	1121	6180	1040
28BT	2860	482	4380	737
26BT	5920	997	5380	906
29BT	6460	1088	4380	737
29BR	4010	675	4580	771
36BT	4240	714	5970	1005
34CA	5280	889	6380	1074
34BW	5480	923	6310	1062

Notes: All base failures shear through the coarse aggregate;
10M—hammer used to insert base core into jig; 1 lb = 0.454 kg; 1 psi = 0.00689 MPa.

Overlay and base shear strength test results are reported in Table 3. The average shear strength of the overlay is 1026.3 psi (7.08 MPa) with a standard deviation of 315.3 psi (2.17 MPa). The average shear strength of the base is 958.9 psi (6.61 MPa) with a standard deviation of 196.0 psi (1.35 MPa). The average shear strength for both the overlay and base is 992.6 psi (6.84 MPa). The average shear bond strength for both methods of surface preparation is 1016.8 psi (7.01 MPa). Bond strengths are as high as can be expected based on the shear strengths of the overlay and base. Based on these results, the guillotine shear bond test has the potential to be a standard because the test can provide an indication of shear bond strength and how it compares to the shear strengths of the base and the overlay which, along with surface preparation, influence the shear bond strength.

Figure 2 shows the correlation between the shear bond strength and tensile bond strength. One curve is a linear best fit and the other is a linear best fit forced through zero. The R^2 values (R^2 is the coefficient of (multiple) determination, meaning that it is the proportion of the total variation in the dependent variable Y that is explained by the regression of Y on the explanatory variable(s)—that is, the Xs) are not good for either fit. There is not a good correlation between shear bond strength and tensile bond strength.

Figure 3 shows the correlation between the shear bond strength and the overlay shear strength. The R^2 value is terrible. There is not a good correlation between shear bond strength and the shear strength of the overlay.

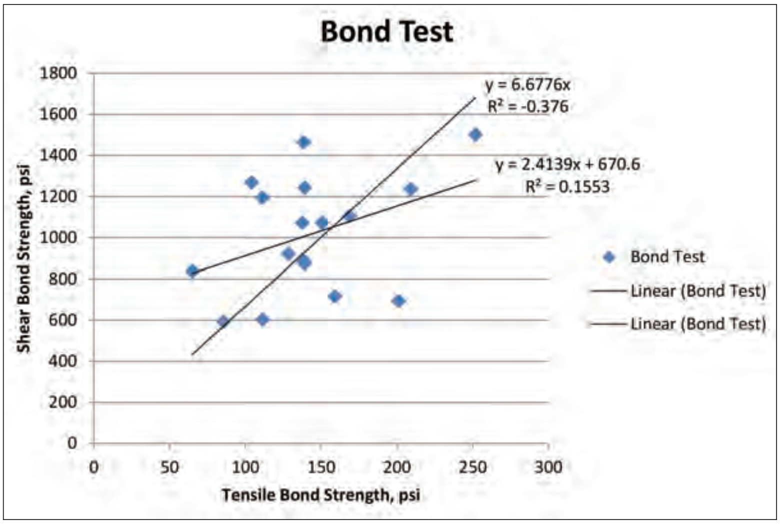

Fig. 2: Shear bond strength versus tensile bond strength, psi (Note: 1 psi = 0.00689 MPa)

Figure 4 shows the correlation between the shear bond strength and the base shear strength. The best-fit curve provides the anticipated result that the shear bond strength increases as the shear strength of the base concrete increases. The R^2 value is better than for the curves in Fig. 2 and 3 but is still not good. There is not a good correlation between shear bond strength and the shear strength of the base.

DISCUSSION

The tests conducted for this study indicate that tensile and shear bond test results have a high variability. The variability is likely caused by differences

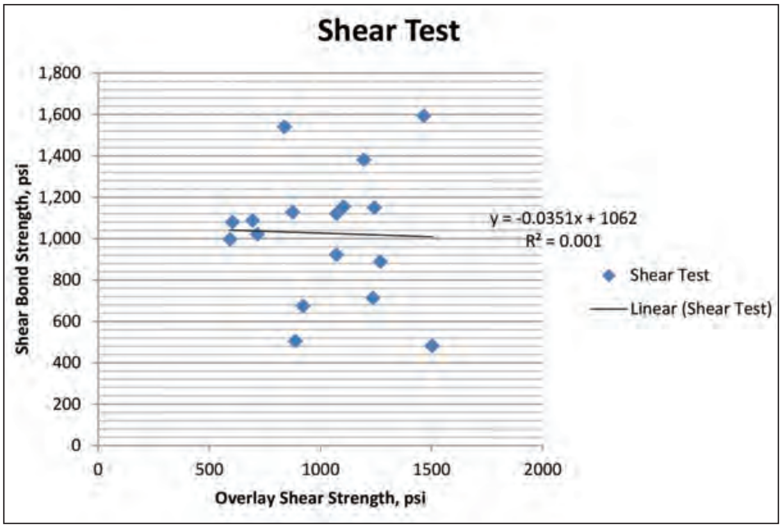

Fig. 3: Shear bond strength versus shear strength of overlay, psi (Note: 1 psi = 0.00689 MPa)

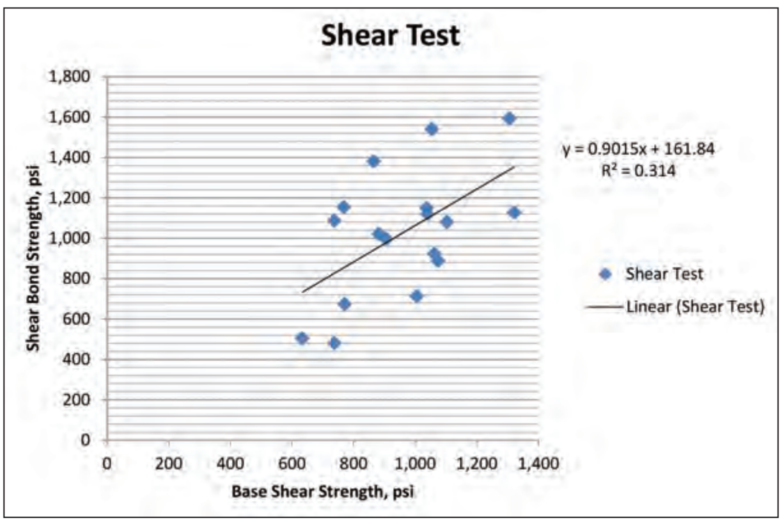

Fig. 4: Shear bond strength versus shear strength of base, psi (Note: 1 psi = 0.00689 MPa)

among the compressive, tensile, and shear strengths of the aggregates and cement paste and the interaction, adhesion, and bond strength between adjacent ingredients. When a core is tested in tension, all ingredients are pulled in tension; the weakest ingredient fails first and significantly influences the tensile bond strength. When a core is tested in shear, all ingredients are loaded in a combination of tension, shear, and compression, and because of interactions between the stresses caused by these loads, one or a combination of the weakest ingredients may begin to fail and cause further failure. Failures likely occur at locations where the stress exceeds the strength. Studies done in the 1980s when polymer overlays were placed on shotblasted surfaces indicted the shear bond strength was about three to four times the tensile bond strength.[3,4] These surfaces had macro texture depths of about 0.06 in. (1.5 mm).[9] As the texture increases, the shear bond strength increases relative to the tensile bond strength because the shearing interaction between the ingredients increases. Hydroblasted surfaces have a high macro texture and the shear bond strength typically increases with texture. The shear bond strength of the overlay at the cooling tower was about seven times the tensile bond strength. A good correlation between shear and tensile bond strength would not be expected unless the surface texture is similar for specimens tested by both methods. Shear bond tests should be used to measure shear strength for compliance with shear design requirements. Tensile bond tests should be used to measure the bond strength of overlays placed on surfaces with low macro texture, as is typically achieved by shotblasting the surface before placing the overlay. The macro texture of the prepared surfaces on the cooling tower was high, and high shear bond strengths were obtained as compared to tensile bond strengths. The agreement between the shear bond strengths and the shear strengths of the base and overlay provide an indication that surface preparation was very good and shear bond strengths were as high as could be expected.

CONCLUSIONS

1. The tensile bond strength was essentially the same for both hydroblasted and mechanically blasted methods of surface preparation: 142.0 psi (0.98 MPa) and 139.8 psi (0.96 MPa), respectively.
2. The shear bond strength was similar for both hydroblasted and mechanically blasted methods of surface preparation: 1047.7 psi (7.22 MPa) and 972.7 psi (6.71 MPa), respectively.
3. The ratios of shear to tensile bond strengths were similar for both hydroblasted and mechanically blasted surfaces: 7.38 and 6.96, respectively.
4. The average shear strength for the overlay and base was 992.6 psi (6.84 MPa) and the average shear bond strength was 1016.8 psi (7.01 MPa). Bond strengths are as high as can be expected based on the shear strengths of the overlay and base.
5. There is not a good correlation between tensile and shear bond strength tests.
6. The ratio between shear and tensile bond strength is about 3 to 4 for surfaces with a macro texture of 0.06 in. (1.5 mm) and increases as the macro texture increases to a ratio as high as 7.
7. Shear bond strength increases as the shear strength of the base concrete increases but the correlation is not good.
8. The guillotine shear bond test has potential to be a standard.

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