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Interface evaluations of overlay-concrete bi-layer composites by a direct shear test method

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Abstract

Interface evaluations of four high-performance concrete overlays cast on top of one type of normal concrete substrate were made by a new direct shear test method. Two different surface preparations such as mechanical abrasion and chemical etching were followed to manufacture 64 overlay–substrate bi-layer specimens. This paper discusses the material properties and fabrication and evaluations of bi-layer specimens. Results show that successful interface bond characterization was possible through this direct shear apparatus. The test method seems to be suitable for screening and selection of various overlays for their compatibility with substrate concrete. However, some modification in the tool is needed for assessing the high-bond capacity interface. Effects of bonding slurry also needs further study.

Keywords: Bond strength; Concrete; Direct shear test; Interface; Overlay–substrate; Surface preparations

1. Introduction

In highway bridge construction, high-performance concrete (HPC) overlays are usually applied over normal concrete (NC) bridge deck substrates to significantly increase the service-life of decks. Overlays are placed as a leveling and high-quality riding surface. They are primarily used in rehabilitation projects after removal of the distressed surface layer. A thickness of 30–75 mm of HPC-overlay over NC-substrate is regarded as a much better cost-effective option than recurring repairing costs of solely NC decks without overlays. Typical types of HPC overlays include: silica fume modified concrete (SMC), latex modified concrete (LMC), fiber reinforced concrete (FRC), high-early strength concrete (HESC), polymer concrete (PC) and others [1]. The application of HPC-overlay has several advantages as a protective layer, including high compressive and flexural strength, enhanced toughness, and low-chloride permeability and shrinkage. However, a successful application of an overlay primarily depends on its ability to effectively bond to the substrate.

A review of current practices [2–9] reveals that the most critical problem with overlays is delamination due to bond failure at overlay–substrate interface. The interfacial bond surface is generally the weakest plane between two materials of a composite bi-layer system. The incompatibility becomes pronounced when overlays and substrates are made of two distinctly different materials. A well prepared and adequately treated substrate surface before pouring of overlays and correct choice of overlay types can minimize the delamination problem to a great extent. However it is desirable to have some evaluation techniques by which the interface could be characterized and tested properly. Published information [2–8] indicates that interface characteristics have been evaluated by several test methods, such as

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pipe-nipple grip and friction grip tension tests [2–4] on cored and cast samples, ASTM slant shear test on cored and cast samples [2,4], pull-out test in the field [5], and uniaxial tension test per Canadian Standards Association A23.2–M94 in a field simulated laboratory condition [7]. Though the results of all these test methods can be used to compare the relative bond strengths and as quality control measures, none of them [2–7] is representative of the actual nature of failure of interface. They measure the indirect shear strength of the interfacial zone. Since delamination of deck overlay is the result of propagation of failure mostly through the interfacial plane between two layers, an effective test method is one which measures the capacity to transfer the stress directly through the interface.

A few direct shear tests [8–10] were conducted to evaluate the interface performance. Dhir [8] investigated the effect of prevailing temperature conditions during the very early life of an overlay on the bond strength developed. In his study only normal concrete–concrete interface was studied. Shahrooz et al. [9] proposed a "guillotine" shear test method to evaluate the interface bond, but the "cutting" force was always applied directly at the overlay–base concrete interface, leading to biased results of interface strength and nature of failure. The strategic highway research program (SHRP) [10] interfacial bond test method is a direct shear test methods but in this test, fabrication and surface preparations are made in individual molds—not in a gang mold. This can affect the consistency in surface preparation if a large number of specimens are needed for screening and selection purposes. Shahrooz et al.[9] found that SHRP test is not sensitive enough to pick up the differences of bond strengths among different overlays.

In this study an effective test method was developed for HPC-overlay and NC-substrate bi-layer composites to evaluate the interface performance through direct shear without the load being applied directly at the interface. This was achieved by designing a compression loading test fixture analogous to the block-shear tool typically used for wood specimens to determine shear strengths of adhesive bond interfaces (ASTM D 905, standard test method for strength properties of adhesive bonds in shear by compression loading). Considering the present study as concrete–concrete interface, the proposed test fixture was designed much sturdier to provide lateral confinement of the concrete specimen to avoid tensile stresses within the material, while inducing shear failure of the interface. The sample preparation and testing method permitted consistent preparation for a particular surface condition.

The objective of this study was to evaluate the interface bond characteristics of four types of HPC-overlays cast on top of one type of NC-substrate, using a new shear test device. Two different surface preparations were made to observe the influence of surface characteristics on the interface bond response. The results reported include bond strength values and failure modes of the bi-layer composites.

2. Materials

The materials used were ASTM Type I cement, 12.5 mm nominal maximum size graded river gravel (specific gravity = 2.60), 4.75 mm nominal maximum size graded river sand (specific gravity = 2.71), commercial fibrillated polypropylene fiber (length = 19 mm, count = 33,000–55,000/gram, specific gravity = 0.91), Dow latex (solid content = 48%, specific gravity = 1.04), high-range water reducing admixture (HRWRA) (specific gravity = 1.21), air-entraining admixture (AEA), silica fume (specific gravity = 2.20), and ASTM Class F fly ash (specific gravity = 2.40). A commercial silicone based defoamer of 600 ml/m^3 of concrete was used along with the latex to control the undesirable air entrapment. Cement, sand, gravel, HRWRA, air-entraining admixture, silica fume and fly ash used in this study met their respective ASTM requirements.

3. Experimental program

3.1. Mixture selections

A total of four HPC-overlay concrete mixtures and one NC-substrate concrete mixture were prepared for the study. The choice and proportions of the mixtures were based on the specifications of West Virginia Division of Highways (WVDOH), other state highways, and published information [1]. The final mixtures were achieved after several trials in the laboratory. The four HPC-overlay mixtures were: latex-modified concrete (LMC), silica fume-modified concrete (SMC), silica fume-modified concrete with fly ash (SMC-FA) and fiber-reinforced concrete (FRC). The substrate concrete is a normal concrete usually used for conventional bridge decks. Table 1 shows the mixture proportions of HPC-overlay and NC used in this study.

3.2. Properties of overlays and substrate mixtures

Bi-layer specimens were made with each type of HPC and one type of NC. The mixtures are listed in Table 1. The basic fresh and hardened properties were determined in accordance with relevant ASTM standards and are given in Table 2. Compressive strengths of 101.6 mm diameter × 203.2 mm long cylinder specimens were measured at 28 days. Flexural strengths of 50.8 × 50.8 × 279.4 mm long prism specimens were measured under four point bending in an MTS machine at a constant displacement rate of 0.1 mm/ min. After

Table 1
Mixture proportions of HPC-overlays and NC-substrate (for one cubic meter of concrete)

Ingredients	NC	LMC[a]	SMC	SMC-FA	FRC
Cement (kg)	337	415	377	307	377
Gravel (kg)	1038	716	716	716	716
Sand (kg)	716	1038	1038	1038	1038
Silica fume (kg)	–	–	33	33	33
Fly ash (kg)	–	–	–	53	–
Fiber (kg)	–	–	–	–	1.82
Latex (kg)	–	126	–	–	–
Water (kg)	169	146	164	157	164
HRWRA (ml)	1310		7240	7240	7715
AEA (ml)	860		765	765	635
Water–cementitious material ratios[b]	0.5	0.35	0.4	0.4	0.4

NC = normal concrete, LMC = latex modified concrete, SMC = silica fume modified concrete, SMC-FA = silica fume modified concrete with fly ash, FRC = fiber reinforced concrete, HRWRA = high-range water reducing admixture, AEA = air-entraining admixture.

[a] In LMC mixture, silicone defoamer of 600 ml/m^3 was used.

[b] For each concrete, water–cementitious material ratio was calculated including the water from latex and HRWRA.

Table 2
Properties of HPC-overlays and NC-substrate

Mixtures	Air content (%)	Slump (mm)	Unit weight (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)
NC	7.1	160	2275	41.8	4.96
LMC	3.8	190	2355	47.6	9.07
SMC	7.0	140	2165	57.2	5.86
SMC + FA	8.0	180	2145	49.2	5.28
FRC	7.6	130	2130	60.7	6.86

casting the test specimens for both compression and flexure, they were stored within molds under wet burlap at temperature 23 ± 2 °C for 24–26 h, and subsequently immersed and cured in water (saturated with calcium hydroxide) at 23 ± 2 °C until the day of testing. Three replicate specimens were tested and the average values are reported.

3.3. Fabrication of specimens

A "butterfly" double wedge type symmetrical specimen was used with notches around the interface periphery. The specimen geometry and dimensions are shown in Fig. 1. In total 64 bi-layer composite specimens were fabricated. They included two different substrate surface preparations. All the substrates of 38 mm thickness were cast using NC (Table 1) in a wooden mold and vibrated by an external vibrator. Fig. 2 shows the substrate concrete cast in partitioned wooden molds. Fig. 3 shows the typical surface of an untreated specimen. After about 5–6 h (just before final setting of concrete) half of the substrates (32 substrates) were scarified mechanically with a steel brush and vacuuming to simulate similar field conditions. Fig. 4 shows the typical surface of a mechanically treated specimen. All the substrates were covered under wet burlap at a temperature of 23 ± 2 °C for 28 days, until the corresponding overlays were poured over them. The other half of substrates was etched with acid

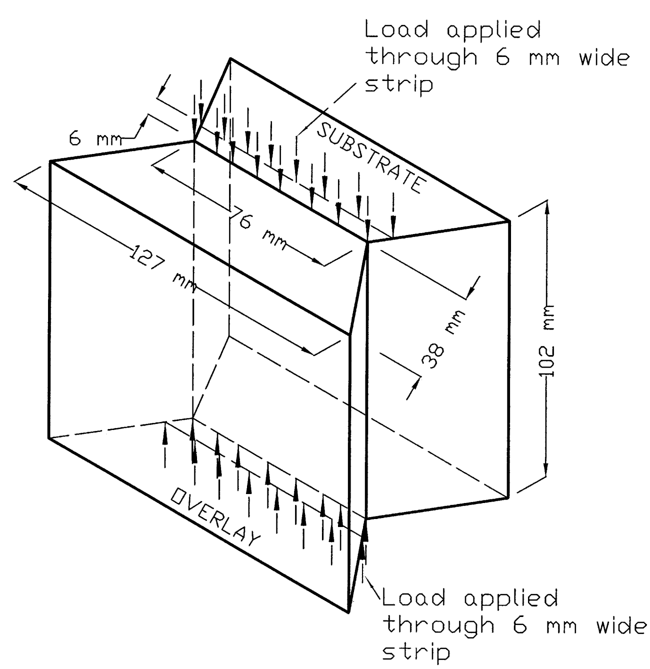

Fig. 1. Specimen geometry and dimension (not to scale) with loading scheme.

per ASTM D 4260 (standard practice for acid etching concrete), after 26 days of wet burlap curing. The acid was washed with water and subsequently tested per

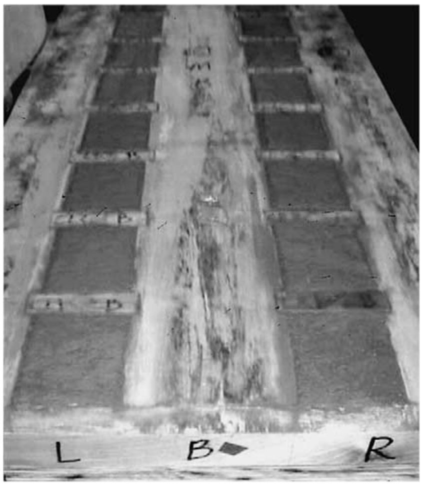

Fig. 2. Substrate specimens cast in partitioned wooden molds.

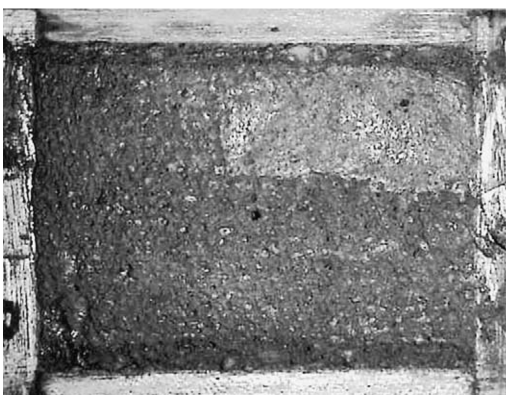

Fig. 3. Typical untreated concrete surface.

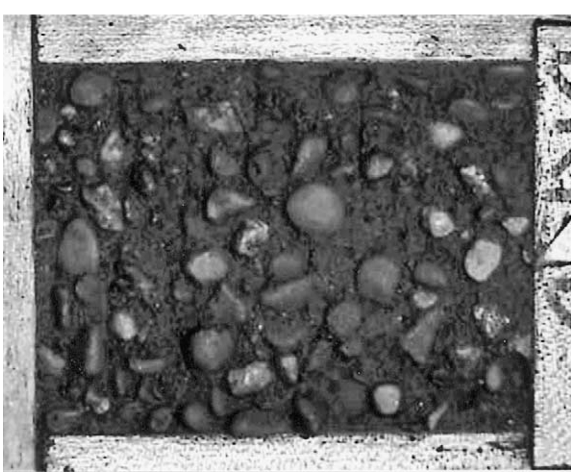

Fig. 4. Mechanically scarified surface.

ASTM D 4262 (standard test method for pH of chemically cleaned or etched concrete surface) to ensure that pH of concrete surface was above 7.0. Fig. 5 shows the typical surface of an acid treated specimen. After

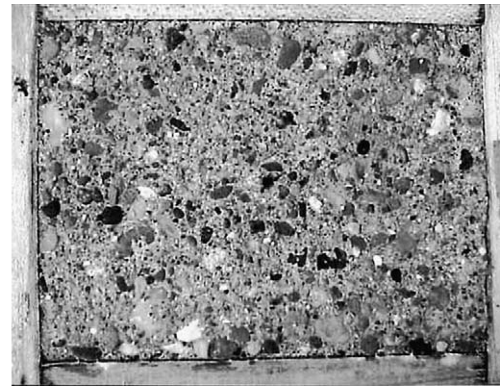

Fig. 5. Acid etched surface.

acid etching, the substrates were covered with wet burlap at temperature of 23 ± 2 °C until the overlays were poured over them. Before application of the overlay, bonding slurry made from the same overlay concrete by removing the coarse aggregate and adding about 60–70 gm of extra water for each kg of cementitious material was applied thoroughly and scrubbed into the surface. Due to low water–cementitious material ratio of HPC-overlay (0.35 and 0.4), they could not be spread thoroughly on substrate as bonding slurry. Therefore, extra water was needed to improve the consistency so that it may be applied and scrubbed easily. In case of FRC the fiber was not included in the bonding slurry. Four overlays LMC, SMC, SMC-FA and FRC (Table 1) of thickness 38 mm were placed in a wooden mould on the top of the substrate after applying a water-proof tape of 6.4 mm along the periphery of each substrate to form a notch. Then the entire set of bi-layer specimens were covered under wet burlap at a temperature of 23 ± 2 °C within the mould until 28 days, when all of them were demolded and covered in a plastic sheet to be tested within two days. For each overlay type, a total of 16 specimens were produced with eight specimens each for the two surface preparations.

3.4. Fabrication of the testing tool

The testing tool was designed as a block-shear apparatus analogous to the shearing tool used for testing adhesive joints of wood specimens by compression loading (ASTM D 905, standard properties of adhesive bonds in shear by compression loading). Since in the current study, the objective was to determine shear strength of concrete–concrete bi-layer specimens, a much sturdier design than ASTM 905 testing tool was required. Considering this the following fabrication of testing device was done: Testing device had three major components: (1) two side blocks with grooves; (2) four sliding type side blocks (two at each side), each with a dovetail tongue; (3) two stepped plates, with one each

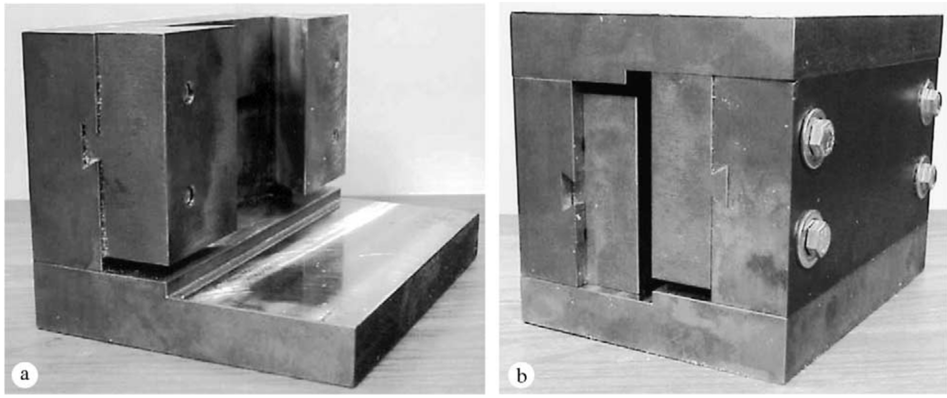

Fig. 6. (a) Bottom step plate, side plate and two sliding blocks (one half of tool). (b) Completed shear tool with both halves connected together.

for top and bottom. The components were joined together by steel bolts. The top and bottom plates were made stepped to enable the movement of the bi-layer specimen after failure. Figs. 6(a) and (b) show one-half of tool and completed shear tool respectively. The top and bottom stepped plates had threaded holes so that they could be fitted to the top and bottom grips of an MTS machine by suitable steel bolts (Fig. 7). The use of high-quality steel and robust design of the apparatus and heavy end plates prevented the bending of the entire device at a compression load as high as 20 kN. The siding side blocks held the concrete bi-layer specimen laterally (Fig. 8) and protected it from premature tensile cracking during testing, which was common due to the brittleness of concrete. The compressive load induced by the actuator of the MTS machine was transferred to the interface through the bi-layer specimen. Fig. 1 shows how the axial vertical loads were transferred through 6 mm wide strips which were made of thin steel and neoprene sheets. The device, therefore, transferred the direct shear load efficiently through the interface with eccentricity less than 10% while preventing stress concentration and tensile cracking of the concrete.

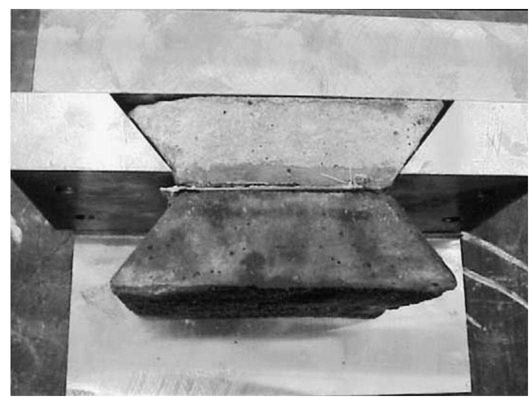

Fig. 8. Shear tool with specimen.

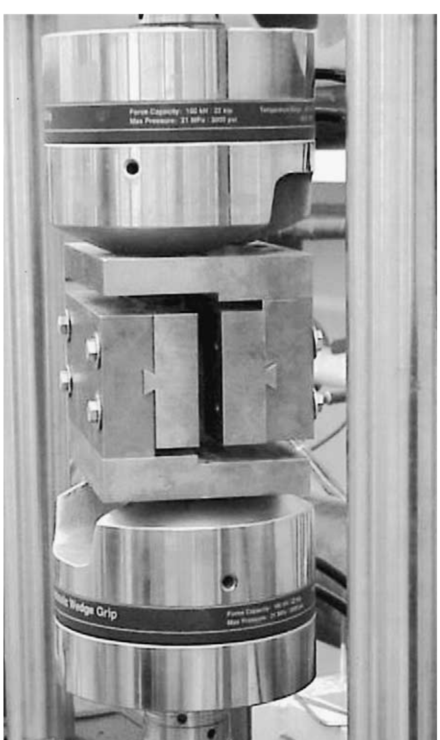

Fig. 7. Shear tool fixed on the MTS.

3.5. Testing of bi-layer overlay–substrate composites

A total of 56 bi-layer specimens out of 64 cast specimens were tested under shear loading at the overlay–substrate interface in a MTS machine, with a 100 kN load-cell capacity. Eight specimens were discarded due to manufacturing defects. Axial vertical compressive loads were applied through 6 mm wide strips (Fig. 1) which was made of thin neoprene rubber and steel sheet at the displacement rate of 0.5 mm/min in order to induce direct shear through the interface area of 5645 mm^2. The maximum load at failure and nature of failure of the specimens were noted for each case. The tests of 28-day old overlay and 56-day old substrate bi-layer

Table 3
Bond test results

Overlay types (1)	Surface treatment (2)	Number of specimens tested (3)	Average of maximum load at failure (kN) (4)	COV[a] (%) (5)	Interface[b] bond strength (MPa) (6)	Mode of failure (7)
LMC	Mechanical[c]	8	18.3	7.0	–	All through substrate
LMC	Chemical[d]	8	17.1	8.2	–	All through substrate
SMC	Mechanical[c]	8	10.4	7.6	1.8	6 through interface, 1 through substrate, 1 mixed mode[e]
SMC	Chemical[c]	1	9.0	NA	1.6	All through interface
		1	13.1		2.3	
SMC-FA	Mechanical[c]	7	13.5	9.4	2.4	All through interface
SMC-FA	Chemical[d]	8	11.6	11.8	2.1	All through interface
FRC	Mechanical[c]	8	11.8	7.3	2.1	6 through interface, 2 mixed mode[e]
FRC	Chemical[d]	7	8.5	8.5	1.5	7 through interface

[a] Coefficient of variation.
[b] Average bond strength of those specimens which failed through interface only.
[c] Scarified surface by mechanical abrasion.
[d] Acid-etched surface by chemical means.
[e] Failure through both interface and substrate.

specimens were completed within two days by a single operator. Table 3 shows the values and modes of failure for the specimens.

4. Results and discussion

4.1. Properties of overlays and substrate

Table 2 shows that air content of LMC is 3.8%, which is much lower than that for the other mixtures. Silicone type defoamer was used for LMC to reduce the excessive air entrapment, which is detrimental to its performance as overlay material. Knab and Spring [2] reported that in tension and slant shear tests of high air-content LMC and base concrete bi-layer system, the failure surface always propagated through high air-content LMC instead of base concrete, but in the case of normal air content LMC, the failure occurred preferentially through the base concrete, which is a desirable failure mode. In the current study, therefore, it was expected that low air content of LMC would enhance its performance as overlay material. The values are however sufficient to resist the damaging effect of freezing–thawing cycles in the field. For the other overlays the air contents are in the range of 7–8%, which ensure their durability against freezing–thawing. The high slump used for all the mixtures, such as 130–190 mm would be good for pouring, vibrating and finishing of the overlays in the field. The specification of several departments of transportation is within this range of values for slump and air content.

Since NC is used as the substrate for all bi-layer composites, it is important that both compressive and flexural strength values (Table 2) be high enough to ensure that the material will not fail prematurely under traffic loads. Also the concrete should be strong enough to withstand the abrasion due to mechanical and chemical surface preparation techniques. Among the overlay mixtures, FRC has the highest compressive strength and second highest flexural strengths, respectively 60.7 and 6.86 MPa, due to fiber addition. SMC-FA has slightly lower compressive and flexural strengths due to partial replacement of cement with fly ash; however, the values are acceptable for overlay material. Between the two most commonly used and effective overlay systems [1], namely LMC and SMC, the SMC has 20% higher compressive strength than LMC, but LMC has significantly higher flexural strength (about 55%) than SMC. Overall, all the mixtures developed in this study are of good and consistent quality in terms of their fresh and hardened concrete properties, which are prerequisites for the acceptance of the material in field applications and also for proper interface evaluations.

4.2. Direct shear test

Table 3 shows the results of bond tests of LMC, SMC, SMC-FA and FRC bi-layer composite specimens including the modes of failure. It is evident from the results that in all cases of LMC-substrate bi-layer specimens, the failure plane occurred preferentially through the substrate, for both types of surface treatment—mechanical and chemical. This is due to the effectiveness of the LMC-based bonding slurry with its high adhesion strength that did not allow the interface to fail. Further it may be stated that the shear strength of the interface is more than that of the substrate material (not measured). Fig. 9 shows a typical failure pattern of LMC-substrate specimen. Deming et al. [4] and Warner et al. [6] suggested that failure through the substrate concrete is always desirable, because it is an indicator that the

Fig. 9. Typical failure of latex modified concrete bi-layer specimen (substrate failed but interface intact).

overlay material is stronger than the substrate. In this study, the mechanical surface treatment performed slightly better than the chemical treatment. The coefficient of variation (COV) values for eight specimens each were 7.0% and 8.2% for mechanical and chemical treatment, respectively. Considering the manufacturing complexity and variations in material properties, the COV is not statistically significant. Knab and Spring [2] observed COV values of 4.7–10.1% on a similar material when tested by friction grip, pipe nipple and slant shear test. Kuhlman [3] observed a COV of 8.3% in his tensile bond test. The narrow range of COV values for the LMC-substrate in the present study is an indication of the consistent repeatability of the proposed shear test method.

For SMC, the failure was found to occur through the interface in eight specimens out of 10 tested. The interface failure plane occurred precisely through the substrate side of the bond line, which is expected due to the relatively lower strength of NC. Fig. 10 displays a typical interface failure of SMC. The effect of chemical versus mechanical treatment could not be evaluated because of only two specimens with chemical treatment being available for testing in case of SMC. The interface strengths of 1.8 MPa (mechanical), and 1.6 and 2.3 MPa (chemical) are comparable with other published results [2–5,8] with some variations due to differences in geometry of specimens, test methods including load transfer, bonding agents and surface preparations. The COV for the eight SMC (mechanical) specimens is 7.6% which demonstrates the consistency of the present test method.

Table 3 further shows that SMC-FA had bond strengths of 2.4 and 2.1 MPa respectively for mechanical and chemical treatments. The mechanical treatment performed marginally better than the chemical treatment. All of 15 specimens failed through the interface, with the failure plane consistently occurring through the bond line of the substrate side (Fig. 11). Comparisons of shear bond strength of SMC-FA with SMC alone reveal that replacement of cement with fly ash did not negatively affect the bond strength; rather the bond strength of SMC-FA (mechanical) was higher than of SMC (mechanical) by 32%. This may be due to additional pozzolanic reactions by fly ash in the bonding slurry of SMC-FA. The COV values are 9.4% (mechanical) and 11.8% (chemical) for test data of seven and eight specimens each, respectively. This further demonstrates the consistency of the test method adopted.

The interface shear strengths of FRC are 2.1 and 1.5 MPa respectively, for mechanical and chemical treatments. Thus, in this case also, the mechanical treatment performed better than the chemical treatment. The observation agrees well with Wells et al. [7], who evaluated the bond strength of concrete overlays utilizing four different surface preparations by uniaxial tension test. In their study for the cement–silica fume bonding grout, the bond strengths of handwire-brushing case (mechanical) and shot blasting case (mechanical) were higher than a brooming and vacuuming, or thorough cleaning process. For all cases in the present study except LMC, a similar bonding grout was used, and the chemical etching treatment may be thought to be similar

Fig. 10. Typical failure of silica fume modified bi-layer specimen (failure on substrate side of specimen).

Fig. 11. Typical failure of silica fume-fly ash modified bi-layer specimen (failure on substrate side of specimen).

Fig. 12. Typical failure of fiber reinforced concrete bi-layer specimen (failure on substrate side of specimen).

to the brooming and vacuuming (a thorough cleaning) process [7] since both of these methods do not alter the surface roughness much. In 13 specimens out of total of 15 specimens, the failure plane occurred through the interface. Some fiber bridging was observed at the interface after failure. The failure plane passed entirely through the bond line of the substrate side (Fig. 12). The COV values are 7.3% and 8.5% for mechanical and chemical treatment, respectively. It is observed that the addition of fibers by itself did not improve the interface strength. It is, however, evident that the bonding slurry/grout played a significant role in defining the interface behavior. Thus, the use of the same bonding slurry as used for SMC resulted in bond strengths of similar values.

Among all the published information, only Dhir et al. [8] reported shear bond test results for both laboratory and field overlay–substrate systems. They obtained a wide range of values from 0.42 to 2.90 MPa depending on the location of sampling. Their data showed that laboratory bond strengths were much higher than the field values and in the range of 2.50–2.90 MPa. The present test method is also a shear bond test and shows a comparable range of values with [8]. Except for LMC showing bond strength higher than the material strength of substrate concrete, the other overlay–substrate combinations exhibited bond strengths in the range of 1.5–2.4 MPa. These values are above the generally accepted bond strength of concrete resurfacing material, which is approximately 1.38 MPa [8]. The bond strength values obtained from the present study are also above the bond strength requirement by the Canadian Standards Association (CSA), A23.1–M94, which is 0.90 MPa. General comparisons of average maximum load capacity (average of mechanical and chemical) of all specimens indicate that LMC-substrate could transfer a maximum average load of 17.7 kN, followed by SMC-FA-substrate of 12.55 kN, SMC-substrate of 10.8 kN and FRC-substrate of 10.15 kN. In general, the "mechanical" type of surface preparation was superior to the "chemical" type irrespective of overlay mixtures.

The range of COV values for the entire study is 7.0–11.8%, which seems to be reasonable considering the variability of production of cementitious composite materials. The reported COV values for tensile bond tests and slant shear tests of portland cement concrete and latex-modified concrete repairing materials by other authors [2,3] lie in the range of 4.8–8.3%. The present slightly higher COV values indicate relatively larger scatter in our test data compared to reported tensile bond test (pipe nipple) and slant shear test. This larger variability may be due to the effect of using the bonding slurry with extra water added to the mixture, which was done to ensure a better spreading ability of the slurry on substrate. This process might have caused some variability in the production of the bi-layer composite specimens. However from the consistency obtained in the interface failures through the relatively weaker bond line on the substrate side of the majority of the bi-layer specimens (except LMC-substrate), and from the comparable bond strength data obtained with respect to published information, we can infer that the present new direct shear bond test is a promising method for evaluating overlay–substrate bond characteristics.

5. Conclusions

A successful interface bond characterization was possible through a new direct shear apparatus. This test method seems to be highly suitable for screening and selection of various overlays for their compatibility with substrate concrete. Precision of the test method is evident from the reasonably low COV values obtained, though there are opportunities to improve the quality control of specimen preparations. The proposed test method is also effective for the evaluation of bond strength of a number of commonly used overlay materials, which is evident from the consistency of test results and mode of failure. However, some form of modification is needed to eliminate the rotation of tool for evaluation of interface strength of high-bond capacity material such as LMC or polymer modified concrete, or for bi-layer materials where improved surface preparation techniques such as hydro demolition or scabbling are used to achieve strong interface. The effect of the bonding slurry on interface strength needs to be investigated more comprehensively. Suitability of the present test method for field investigation needs further development.

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References

[1] Halvorsen GT. Bridge deck overlays. Concr Constr 1993;6:415–9.
[2] Knab LI, Spring CB. Evaluation of test methods for measuring the bond strength of portland cement based repair materials to concrete. Cem, Concr Aggregates 1989;1:3–14.
[3] Kuhlmann LA. Test method for measuring the bond strength of latex-modified concrete and mortar. ACI Mater J 1990;4:387–93.
[4] Deming BM, Aktan H, Usmen M. Test for polymer overlay interface on concrete. In: Basham Kim D, editor. Proc. ASCE materials engineering congress. Specialty Conference, Infrastructure: New Materials and Methods for Repair, San Diego, California. ASCE. p. 709–15.
[5] Hindo KR. In-place bond testing and surface preparation of concrete. Concr Int 1990;4:46–8.
[6] Warner J, Bhuyan S, Soma WG, Hindo KR, Sprinkel MM. Surface preparation for overlays. Concr Int 1998;5:43–6.
[7] Welles JA, Stark RD, Polyzois D. Getting better in concrete overlays. Concr Int 1999;3:49–52.
[8] Dhir MP. A study on the effect of temperature variations on the bonding of concrete overlays. J Am Concr Inst 1984;2:172–9.
[9] Shahrooz BM, Gillum AJ, Cole J, Turner A. Bond characteristics of overlays placed over bridge decks sealed with high-molecular-weight methacrylate. Transportation research record J Transportation Res Board 2000:24–30 [Record no. 1697].
[10] SHRP-C-361. Strategic highway research program. Summary report. Mechanical behavior of high-performance concretes, vol. I. Washington, DC: National Research Council; 1993. p. 93–8.