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Improving Bond Strength of Bonded Concrete Overlay by Adding Synthetic Discrete Fibers

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Abstract: There is an increasing use of Bonded Concrete overlay (BCO) in the repair or refurbishment of deteriorated concrete structures, and the addition of discrete fibers to the BCO improves its service life and reduces overlay thickness. Interface bond strength between the overlay and existing concrete is crucial for achieving the goal of concrete Structural rehabilitation. This work presents an experimental investigation of Splitting Tensile Bond Strength (STBS) and Direct Shear Bond Strength (DSBS) of BCO using two bond tests: a Splitting Tensile Bond Test (STBT) and Direct Shear Bond Test (DSBT). Four different types of synthetic discrete fiber and different fiber volume contents (0%, 0.5%, 0.8%, 1.0%, and 2.0%) were investigated, and seventeen different cases were prepared for each bond test. Results showed the interface bond strength to be significantly improved by the addition of synthetic discrete fibers compared to the concrete mix. In general, the addition of 1.0% of synthetic fibers to concrete led to an interface bond strength surpassing the minimum required. However, volume fraction dosage above 1.0% reduced the workability of the concrete mixture, leading to reduced bond strength.

Keywords: *Bond strength, repair, fibers, overlay, splitting tensile test,direct shear test*

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I. INTRODUCTION

In the United States, many deteriorated concrete structures within pavements and bridges are rehabilitated every year due to increased traffic loading. Thus, transportation agencies strongly desire high-performance repair systems to prolong the service life of existing concrete structures. Using BCO is more effective, environmentally friendly, and cost-effective than the complete removal and renewal of concrete structures and has become increasingly popular in the US over the past three decades [1, 2, 3, 4, 5]. The use of BCO adds crack control, greater capacity, better ride quality, and skid resistance to existing concrete structures and protects the structure from deleterious environmental effects [6, 7, 8]. The BCO thickness ranges between 125 mm and 500 mm and is fully bonded with the existing concrete structure; BCO should be only used when the existing concrete pavement is in relatively good condition. Therefore, BCO is not a suitable rehabilitation option when the existing pavement has structural deficiencies such as mid-panel cracks, pumping, or faulting [9, 10]. Performance data shows that BCO gives a low-maintenance service life. Most BCO lasts for 20 to 40 years, depending on conditions such as the pre-existing pavement condition, BCO type, and environmental and traffic features [10, 11].

A. *Fiber Reinforced Concrete in BCO*

Recently, the use of discrete fiber within BCO has become increasingly popular in concrete rehabilitation. The distribution of discrete fibers in the concrete matrix provides bridging forces across initiated cracks [10, 12]. Adding discrete fibers to concrete mixtures in this way improves flexural capacity, toughness, fatigue resistance, ultimate strain, and impact strength [13, 9, 14]. The type and volume content of discrete fibers determines the role of those fibers in a concrete matrix; typical fiber contents in concrete range from 0.01% to 3.0% [12]. There is a strong influence of synthetic discrete fiber dosage on the crack width and length by increasing the fiber dosage because of increasing concrete tensile strength [15, 16]. Proportions may vary with purpose; for example, a fiber content greater than 2.0% is not recommended for paving applications due to problems with workability [17, 18]. While steel fibers have long been used in paving applications, in the last three decades, synthetics fibers such as Poly Propylene (PP), Poly Vinyl Alcohol (PVA), and Poly Ethylene (PE) fibers have become predominant due to their ease of handling, better dispersion characteristics (i.e., less balling) and corrosion resistance [13, 10]. The most commonly used in concrete applications are PP fibers [19]. These are short in length (12.5 to 25.0 mm) and are longitudinally scored to split apart during mixing, which creates a more complex network of fibers throughout the matrix. Bothma [20] found the use of PP fibers improved post-crack ductility and first-crack strength of Fiber Reinforced Concrete (FRC) slabs compared to unreinforced slabs and increased the flexural capacity of concrete slabs in both elastic and plastic phases. Incorporating PP fibers within concrete overlays help to reduce shrinkage cracking due to its inert action in a cementitious environment; furthermore, it distributes very well within the concrete matrix and does not affect workability. Over the past twenty years, the use of PVA fibers in the production of FRC has been promoted [21, 22]. The main advantages of PVA fibers are a high aspect ratio, good chemical compatibility, high flexural strength, and high alkali resistance [23]. Noushini et al. [24] found the compressive, flexural, and tensile strengths of concrete to be increased with increasing PVA content.

B. *Interface Bond Strength of BCO*

It is common for BCO structures to fail early due to bond failure at the interface. The bond strength should be greater than the shear and tensile stresses at the bond interface due to applied loading. The mechanical properties of each layer, surface roughness at the interface, and curing conditions are factors that most influence bond strength. Over the past two decades, studies have focused on the traditional parameters affecting bond strength, such as the composition of each layer, curing time, and the preparation of the existing layers surface [25, 26]. Debonding failures in BCO have been observed as a loss of bonding due to excessive interface tensile and horizontal interface shear stresses [27]. Granju [28], Lange, and Shin [29] concluded that debonding failure was the result of normal interface tensile stress based on numerical modeling in conjunction with experimental measurements. Further, drying and thermal shrinkage in the concrete overlay led to high tensile stresses at edges and corners. Kim and Lee [30] found debonding failure in BCO resulting from both normal interface tensile stress and horizontal interface shear stress although tensile stress dominated over shear stress. Shear stress arising from the stopping and starting of vehicles may also cause debonding by horizontal traffic loading. Therefore, most BCO design is governed by tensile bond strength rather than shear bond strength.

Many tests can be used to evaluate bond strength between overlay and existing layers. Most researchers have classified such tests into three groups: tensile, shear, and compressive shear (slant shear) tests [31, 32]. The STBT, which is categorized as an indirect tension test, was adopted by the American Society for Testing and Materials and standardized as ASTM C496 [33]. The ASTM splitting standard test is used for homogeneous cylindrical specimens, but some researchers have used it with a composite specimen (two materials) to evaluate the tensile bond strength between layers. Ramey and Strickland [34] applied a splitting tensile test, testing composite concrete sections with an ASTM C496 splitting test of the concrete layer. They divided the sample into halves, overlay, and pre-existing layers and changed the sample shape from a cylinder to a prism. Geissert et al. [35] found prismatic composite samples gave more consistent results than cylindrical samples. The STBT is an efficient and reliable test since the interface is subjected to the maximum stress of the applied load [36, 37]. Momayez et al. [38] presented a composite splitting tensile test using prismatic samples of 75 mm wide x 150 mm high x 150 mm long, with a contact area of 150 mm x 150 mm, to establish the bond strength between two layers. According to the test features, the STBS of a composite sample can be calculated by Equation (1):

$$STBS = P/A \cdot \pi \quad (1)$$

Where:

STBST: is the splitting tensile strength, MPa, or psi.

P: is the maximum applied load, N or Ib.

A: is the contact area of interface, mm2 or in.2.

The DSBT was proposed and adopted by the Japan Society of Civil Engineers (JSCE) [39] and has been used by many researchers with samples of various dimensions. The DSBT provides pure shear stress at two areas of the interface and avoids bending problems that occur in other shear test methods, such as the Z-type, push-off, and FIP shear tests [40, 41]. Fig. 1 shows the features of STBT and DSBT. DSBS can be determined by Equation (2):

$$DSBS = P/2 \cdot A \quad (2)$$

Where:
DSBS: is the shear bond strength, MPa, or psi.
P: is the maximum applied load, N or Ib.
A: is the contact area of interface, mm2 or in.2.

Not all methodologies and procedures of BCO design specify minimum requirements for tensile or shear bond stresses, and few of the studies proposing them depend on experimental works or analytical analysis. Therefore, in this study, 0.9 MPa was adopted as a minimum shear bond strength according to the Canadian Standards Association [42]. According to the State of the Art Report from the RILEM Technical Committee 193-RLS [2], the tensile bond strength is around 50% of its shear bond strength. Therefore, tensile bond strength was adopted in this study as 0.45 MPa.

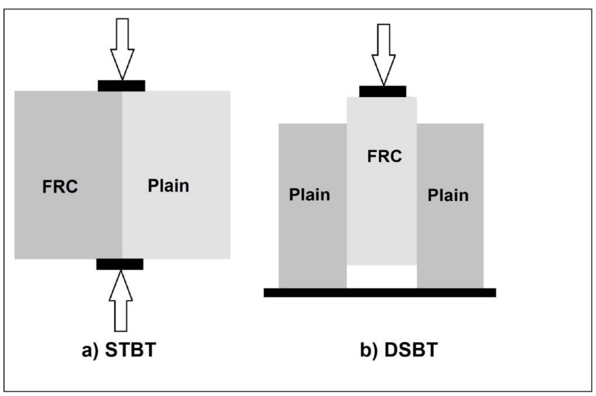

Fig. 1. Features of (a) STBT and (b) DSBT

C. Research objectives

A literature review was conducted, focusing on interface bond strength, which is the main factor in the success of BCO applications. Although many studies investigated the effects of traditional factors (mix proportions and properties, types of surface treatment, or curing types), there has been insufficient laboratory work to evaluate the improvement of interface bond strength by adding different types and amounts of synthetic discrete fibers. Therefore, the purpose of this research is to investigate the benefits of adding synthetic discrete fibers, of different types and volume contents, to concrete using two different bond test types, a STBT, and direct shear bond test.

Interface bond strength between existing and overlay concrete is a significant factor ensuring the durability of concrete repair and rehabilitation. The bonding behavior ensures that the overlay and existing layers behave as a monolithic system, which roles carry additional traffic and environmental loading. There are some applications that could be applied to this research in real-life applications. Repairing structure members such as columns in buildings and bridges is one of the implementations in this study. In a harsh environment such as a desert climate, temperature change increase stresses at the interface bond area, which leads to debonding in concrete overlays eventually. Therefore, it is very important to ensure the desired level of bond strength in the design process, and adding synthetic discrete fibers is one of the solutions to improve bond strength.

II. EXPERIMENTAL WORK

A. Methodology

To determine the interface bond strength of BCO, STBT and DSBT were applied. Prismatic composite samples, composed of two halves of overlay and existing layers, were used for STBT, while DSBT samples were composites of three parts, two layers of existing concrete and one overlay, as shown in Fig. 2

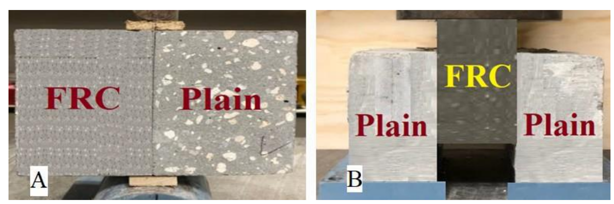

Fig. 2. Composite concrete samples of (A) STBT and (B) DSBT

B. Materials

Seventeen different cases were prepared for both tests, STBT and DSBT, as shown in Fig. 2 All cases included the same existing layer concrete mix and different concrete overlay mixes. The mixing design for concrete mixtures was adopted from the study of Suksawang et al. [43], given in Table 1. The materials used in the present study were as follows; type I Portland cement, which meets ASTM C150 [44]; a coarse aggregate of a maximum size of 9.5 mm with a relative density of 2.48; natural sand with a relative density of 2.63; type *F* High Range Water Reducing (HRWR) modified polycarboxylate based superplasticizer, which conforms to the requirements of the ASTM C494 [45], used as an admixture; and four types of discrete fibers; short PP, LPP, SPVA, and LPVA. The properties of these discrete fibers are summarized in Table 2.

TABLE 1
SUMMARY OF MIX PROPORTIONS (% BY VOLUME)

Case #	Cement	Water	Aggregate	Sand	Fibers
1	12.8	18.1	40.1	28.0	0.0
2+6+10+14	12.7	18.0	39.9	27.9	0.5
3+7+11+15	12.7	18.0	39.8	27.8	0.8
4+8+12+16	12.7	18.0	39.7	27.8	1.0
5+9+13+17	12.5	17.8	39.2	27.7	2.0

TABLE 2
PHYSICAL AND MECHANICAL PROPERTIES OF USED DISCRETE FIBERS

Property	LPP	SPP	SPVA	LPVA
Specific Gravity	0.91	0.91	1.3	1.3
Tensile Strength, (MPa)	300	480	1600	1000
Flexural Strength (GPa)	4.9	N.A	39	29
Length, mm	19.0	13.0	6.0	19.0
Equivalent Diameter, (Micrometer)	762	12	24	200
Melting Point, (C°)	160	160	225	225

C. Preparation and Testing of Samples

Prisms of the existing layer (75 mm width, 150 mm height, and depth) were cast in a timber mold and compacted using a small immersion concrete vibrator. All concrete prisms were set for twenty-four hours and covered with a plastic sheet. After that, all prisms were cured for twenty-eight days in a lime water tank. When all such prisms had been cast, cured, and treated, dust was removed with a high air pressure pump. Prisms of the existing concrete layer were then prepared to be cast with overlay layers. The interface surface was treated by wire-brushing method to achieve a clean surface, free of contaminants such as laitance, dust, and dirt. Overlay concrete mixes were cast in a timber mold, which included existing concrete samples. A small immersion vibrator was used to ensure a good, well-distributed bond. After casting, all specimens were set for twenty-four hours and covered with a plastic sheet before curing for twenty-eight days in a lime water tank. LPVA 0.5% samples in DSBS were unsuitable for use because they were weak and failed before testing; others failed due to failure in the existing layer or overlay but not within the interface, such as SPVA 2.0% in STBS. For the STBT, half of the sample comprised existing concrete only, and the other half had a concrete overlay, while the DSBT used two samples of existing concrete and one with a concrete overlay. Details are shown in Fig. 2 Tests were performed by using a (270 kN) compression machine. A constant loading rate (156 kN/s) was applied to the load.

TABLE 3
KEY FACTORS (VARIABLES) FOR STBT AND DSBT TEST CASES

Case #	Existing Layer	Overlay Layer	Case #	Existing Layer	Overlay Layer
1	Plain	Plain	10	Plain	0.5% SPP
2	Plain	0.5%SPVA	11	Plain	0.8% SPP
3	Plain	0.8%SPVA	12	Plain	1.0% SPP
4	Plain	1.0% SPVA	13	Plain	2.0% SPP
5	Plain	2.0%SPVA	14	Plain	0.5% LPP
6	Plain	0.5%LPVA	15	Plain	0.8% LPP
7	Plain	0.8%LPVA	16	Plain	1.0% LPP
8	Plain	1.0%LPVA	17	Plain	2.0% LPP
9	Plain	2.0%LPVA			

III. RESULTS AND DISCUSSION

A. Results of STBT

Table 4 shows the results of the using STBT for all cases. Assuming uniform tensile stress across the bond zone, the STBS was based on Equation (1). Clearly, the STBS for the plain concrete overlay is 0.3 MPa, which is below the minimum value (0.45 MPa) required. In general, adding any type of synthetic fibers to concrete led to achieving STBS above the minimum value. Fig. 3 shows that the addition of SPVA to concrete improved the STBS by more than 50%, 233% and 267% at SPVA contents 0.5%, 0.8% and 1.0%, respectively. Addition of LPVA to concrete increased the STBS by more than 67%, 167%, 233% and 200% at LPVA contents 0.5%, 0.8%, 1.0% and 2.0%, respectively. Meanwhile, adding SPP to concrete led to improvement in STBS by 67%, 100%, 200% and 150% at SPP content 0.5%, 0.8%, 1.0% and 2.0%, respectively. Adding 0.5%, 0.8%, 1.0% and 2.0% LPP improved STBS by 167%, 200%, 267% and 200%, respectively. For all fibers types, results show that the addition of 2.0% fibers to concrete decreased the STBS in comparison with 1.0% fiber content, since the resulting FRC mix gave low workability and high porosity. LPVA, which has a low fiber ratio aspect (length/diameter), showed a similar STBS to SPVA with a higher fiber ratio aspect.

TABLE 4
KEY FACTORS (VARIABLES) FOR STBT AND DSBT TEST CASES

Case #	STBS (MPa)	DSBS (MPa)	Case #	STBS (MPa)	DSBS (MPa)
1 (Plain)	0.3	0.2	10 (0.5%SPP)	0.5	0.5
2 (0.5%SPVA)	0.45	1.2	11 (0.8%SPP)	0.6	0.7
3 (0.8%SPVA)	1.0	1.4	12 (1.0%SPP)	0.9	1.6
4 (1.0%SPVA)	1.1	1.6	13 (2.0%SPP)	0.7	1.2
5 (2.0%SPVA)	N. A	1.1	14 (0.5%LPP)	0.8	0.7
6 (0.5%LPVA)	0.81	N. A	15 (0.8%LPP)	0.9	1.9
7 (0.8%LPVA)	0.8	0.5	16 (1.0%LPP)	1.1	12.2
8 (1.0%LPVA)	1.0	1.1	17 (2.0%LPP)	0.9	2.1
9 (2.0%LPVA)	0.9	1.2			

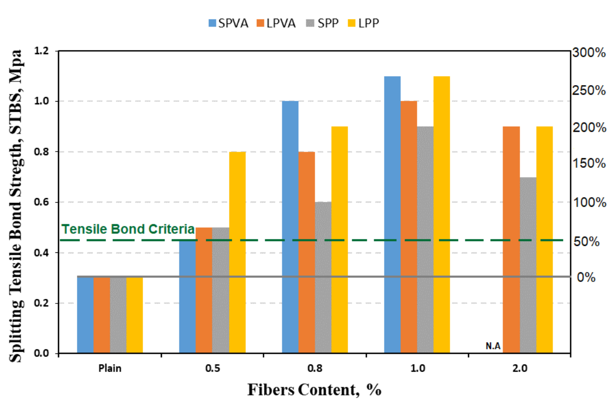

Fig. 3. Results of Results of Splitting Tensile Bond Test (STBT)

B. Results of Direct Double Shear Test (DSBT)

Table 4 shows the results of the DSBT for all cases in this experimental work. Assuming uniform, clear, direct shear stress across the bond zone, DSBS calculation was based on Equation (2). Generally, the STBS for the plain concrete overlay is 0.2 MPa, which is less than the minimum value required for DSBS (0.9 MPa); adding all types of synthetic fibers to plain concrete led to increased DSBS. Fig. 4 shows that addition of the SPVA to concrete improved the STBS by more than 600%, 700%, 800% and 550% at SPVA contents 0.5%, 0.8%, 1.0% and 2.0%, respectively. Meanwhile, addition of LPVA to concrete increased the STBS by more than 225%, 550% and 600% at LPVA contents 0.8%, 1.0% and 2.0%, respectively. It was found that adding SPP to concrete led to an STBS improved by 250%, 350%, 800% and 600% at SPP contents 0.5%, 0.8%, 1.0% and 2.0%, respectively. Adding 0.5%, 0.8%, 1.0% and 2.0% LPP improved STBS by 350%, 950%, 1125% and 1050%, respectively. For all fibers type, except LPVA, the addition of 2.0% of fibers to concrete reduced the DSBS (compared with the addition of 1.0% fiber content) since the FRC mix it yielded showed low workability and high porosity. SPVA, which has a high fiber ratio aspect, provided better STBS than LPVA, which has a lower fiber ratio aspect when added to plain concrete. As a result, using more than 1.0% of discrete fibers in concrete led to a DSBS above the minimum requirement of 0.9 MPa.

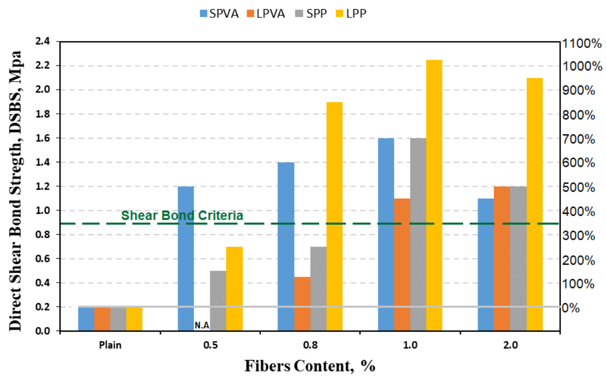

Fig. 4. Results of direct shear bond test

IV. CONCLUSION

Experimental work was conducted to assess the effects of different types and volume contents of synthetic fiber on interface bond strength. Splitting tensile bond and direct shear bond testing was performed to determine the interface bond strength. Based on the results, the following conclusions were drawn:

- Test results show that synthetic discrete fibers are very effective in improving the quality of the interface bond strength because the fibers distribute applied stress equally upon the interface, which delays failure.
- Adding 0.5% synthetic discrete fibers to concrete mix achieves the minimum tensile bond strength required.
- Direct shear bond testing showed that the addition of 0.8% discrete fibers could yield the minimum shear bond strength required.
- The use of high-volume fraction dosage (2% and more) of discrete fibers led to a lesser tensile or shear bond strength than was the case with 1.0%.

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