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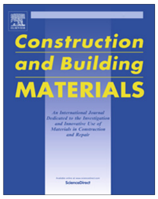

Further evidence of interfacial adhesive bond strength enhancement through fiber reinforcement in repairs

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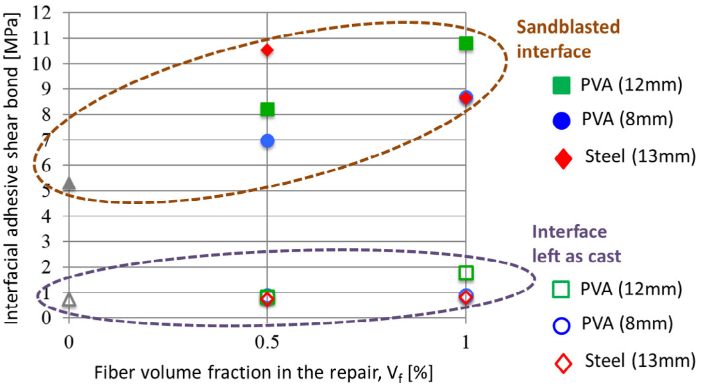
HIGHLIGHTS

- Adding steel or PVA fibers to a repair increases cohesive bond to the substrate.
- With 0.5% & 1% fiber volume fractions, cohesion strength is increased of up to 100%.
- Fibers' enhancement of substrate-repair bond requires proper interface roughness.

GRAPHICAL ABSTRACT



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ABSTRACT

While intensive structural and non-structural repair is required worldwide to compensate the current infrastructure deficit, repair effectiveness is jeopardized by poor durability, compatibility, and bond. Benefits of fiber reinforcement in concrete repairs are remarkable as durability is enhanced and the effect of poor compatibility can be mitigated. Furthermore, fibers' potential to improve concrete-concrete bond, a crucial property in repair applications, has been demonstrated. Only a few studies, however, are available on the effect of fibers on substrate-repair bond and additional analysis form different bond tests, fiber reinforcements, and substrate treatments are required to fully utilize such benefits in repair applications.

In this study, substrate-repair shear bond strength in fiber reinforced repair mortars is investigated. Based on previous encouraging results on 8 mm long Poly-Vinyl-Alcohol (PVA) fibers, PVA fibers with different lengths (8 and 12 mm) and 13 mm long steel fibers are compared. Two fiber volume fractions, equal to 0.5% and 1% are applied beyond the control condition (plain mortar). While results currently available are focused on roughened substrates, sandblasted substrates and substrates left as-cast are considered in these experiments. Substrate-repair bond strength is assessed through Modified Slant Shear Cylinder (MSSC) test with different bond plane inclinations, corresponding to different normal-shear stress ratios. Adhesion strength and friction coefficient, two parameters inherently characterizing substrate-repair bond, are assessed. The bond enhancing mechanisms offered by the different types of fibers and their correlation to surface treatment are discussed. Variations of indirectly determined coefficients are statistically validated through a permutation technique applied to the 170 samples tested overall.

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1. Introduction

Several countries are facing a remarkable infrastructure deficit, requiring extensive budget investment for maintenance, repair, rehabilitation, and retrofit. Lack of durability has not only been observed in concrete infrastructure, but also in repair interventions affected by substrate-repair debonding and poor compatibility, which intensify repair vulnerability to environmental attack and internal chemo-physical deteriorative processes [1,2]. Fiber reinforcement represents a viable way to enhance concrete durability. Fibers can improve crack growth, impact and fatigue resistance [3,4], control permeability under stress [5], and reduce bleeding [6], as well as shrinkage and thermal cracking [7–9]. Sporadic studies have shown that also substrate-repair bond is improved by the addition of fiber reinforcement to the repair material [10–14]. With substrate-repair interface representing the weakest link of repair systems, the ability of fibers to enhance not only mechanical properties and durability, but also interfacial bond, has generated increasing interest in their implementation for repair applications.

Banthia and Dubeau [10] tested the tensile bond between concrete and cement-based composites reinforced with carbon and steel micro-fibers, to assess their suitability as thin repairs. The authors performed closed-loop tensile tests on the interface and observed adhesion enhancement from 0.8 MPa (plain repair) up to 1.4 MPa when a 3% volume fraction of steel fibers was added to the mortar matrix. Lim and Li [11] studied the bond between concrete substrates and overlays made with Engineered Cementitious Composites (ECC); bending tests were performed, which resulted in a combined state of shear and tension at the interface. Higher bond strength was observed when ECC was employed, compared to other cementitious overlays; the improvement was attributed to the development of a crack trapping mechanism that arrested crack growth in ECC when the interfacial crack was deviated (kinked [11,15]) out of the bond plane. Zanotti et al. [12] tested the crack growth resistance of sandblasted interfaces in Mode-I (pure tension) and found that the addition of 8 mm Poly-Vinyl-Alcohol (PVA) fibers to the repair mortar enhanced interfacial crack nucleation and resistance to growth. Micro-crack deviation outside the interface was observed and the interfacial crack improvement was attributed to crack blunting as well as reduced shrinkage and operational damage. Wagner et al. [13] performed mechanical characterization of interfaces between concrete subgrade and strain hardening cementitious repair layers reinforced with 8 mm PVA fibers. The authors tested the interfaces in closed loop under wedge splitting and various combinations of shear and tensile stresses. In the wedge splitting test (tension), it was found that PVA fibers were effective only when surface roughness and bond strength were sufficiently high to allow crack formation in the fiber reinforced concrete. For combined shear and tension, conclusive result discussion was referred to ensuing inverse analysis. In this regard, Sajdlová and Kabele [16] have recently offered novel insights on the stability of Mode II crack propagation between two or more layers of materials with variable composition and microstructure.

It is evident that, while the studies presented above highlighted that fiber reinforcement can enhance interfacial adhesive bond, knowledge gaps remain and additional studies comparing different fiber reinforcements, repair matrices, and substrate treatments, as well as different interfacial stresses and repair size, are required before the repair sector can comprehensively master the bond advantages offered by fibers.

In particular, the results available focus on interfaces subjected to tension (pure or combined to shear), while the effect of fiber reinforcement on shear bond strength and correlated adhesive shear bond remains mostly unknown. Zanotti et al. [14,17] presented a study where interfacial bond was tested with a Modified Slant Shear Cylinder (MSSC) test under different combinations of shear and compressive stresses and cohesion and friction coefficients were extrapolated based on the Mohr-Coulomb approach. The research demonstrated that 8 mm PVA fibers enhance shear bond strength and adhesion in sandblasted interfaces [14]; alongside, additional questions were raised: what would be the effect of different fiber reinforcements? To what extent may sandblasting affect the adhesive shear bond amelioration conferred by fibers?

A new study is presented where the same testing technique adopted in [14], based on MSSC test, Mohr-Coulomb approach, and statistical validation through permutation analysis, was applied to compare the effects of three types of fibers, namely: 8 mm long Poly-Vinyl-Alcohol (PVA) fibers, 12 mm long PVA fibers, and 13 mm long steel fibers. The effect of PVA fiber length was assessed by comparing 8 mm and 12 mm long fibers. Steel fibers with similar length (13 mm) were also considered. Steel fibers and PVA fibers have rather different mechanical, physical, and chemical properties as well as different adhesion characteristics to the cement matrix. Therefore, different substrate-repair bond strengths and different substrate-repair slip resisting mechanisms can be expected. Beyond the plain mortar as control condition, 0.5% and 1% fiber volume fractions were employed.

Each repair mortar was applied on two types of surfaces, that is, sandblasted substrates and substrates left as cast (smooth interface). While there are several studies available on the effect of sandblasting on substrate-repair bond (such as [17–22] among others), their comparison within this context demonstrated the key-role played by substrate treatment in activating the shear bond enhancing mechanisms offered by fibers.

2. Materials and methods

2.1. Materials

In order to maximize compatibility and consistently with the previous investigation on 8 mm PVA fibers and sandblasted interfaces [14], the mix proportions shown in Table 1 were adopted. The effects of the following three types of fiber reinforcement were compared: Poly-Vinyl-Alcohol (PVA) fibers with two different lengths (8 mm and 12 mm) and 13 mm long steel fibers. Technical information on PVA and steel fibers is provided in Table 2.

2.2. Test set-up

The slant shear test consists of applying a compressive load to a cylinder where repair material and substrate are bonded together at a standard 30° inclination [23] (Fig. 1a), resulting in a combination of shear and normal stresses along the substrate-repair interface (Fig. 1b). Compared to the standard slant shear test, a modified version previously developed was adopted in this study [24]. This exact same testing procedure was adopted in [14], so that the previous results obtained with 8 mm PVA fibers on sandblasted interfaces can be compared. The main features of the test are summarized hereafter, while more details are provided in [24]. Three different bond plane inclinations, α, equal to 30°, 25°, and 20° were applied (Fig. 1c and d) rather than the standard 30° angle only [23]. The cylinder diameters were varied to keep similar interfacial areas and minimize size effects as the slant angle, α, changes. The distance between the edges of the cylinder and the bond plane was kept equal to the diameter to minimize the effect of loading plate-cylinder frictional stresses on the substrate-repair interfacial stresses.

Substrate-repair interfacial shear stresses are given by:

$$\tau_n = \frac{1}{2}\sigma_0 \sin(2\alpha) \tag{1}$$

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