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ARTICLE

Shear bond between existing concrete and high-strength fiber reinforced overlay: Influence of substrate strength and interface roughness

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Abstract

Bonded concrete overlays are widely used for strengthening and repair of concrete members. The aim of a concrete repair is to restore the load-carrying capacity and stiffness of a concrete member, and to extend the service life of a structure. The bond between substrate and overlay is one of the main factors concerning the serviceability of a composite member consisting of concrete of different ages. This paper aims at better evaluating, through an extensive experimental program, the shear bond strength between existing concrete and a subsequently applied fiber reinforced overlay. The main purposes of this test program are to study the influence of the substrate strength and of the substrate surface roughness on the interface bond strength between a substrate and overlay concrete. A refinement of a novel bond test, proposed by some of the authors of this paper, is also implemented. Results indicate that there is an increase in the bond strength with an increase in the substrate compressive strength. On the other hand, the results suggest that, for the substrate strength classes investigated, the surface roughness does not influence the interface bond strength.

KEYWORDS

experimental tests, high strength overlay, interface bond strength, steel fiber reinforced concrete, substrate strength, surface roughness

1 | INTRODUCTION

Appropriate bond of a repair material to concrete is crucial in the application and performance of concrete repairs.[1] The interface between a fiber reinforced overlay and existing concrete (substrate) plays an important role in the overall success of repair and rehabilitation work. Due to the differential shrinkage between the new overlay and the existing concrete, the interface is generally expected to withstand significant and sustained bond stress. Good adhesion is a key factor for contributing to both the stiffness and load carrying capacity of the element.

Bond strength is the stress required to separate substrate and overlay. Testing the bond strength provides information on the overall location of failure; that is, "substrate," "interface," or "overlay" failure.[1]

The bond strength of composite materials has been investigated over the last few years. Many studies have been reported in the literature on the test methods used to determine the bond between concrete substrate and repair material.[2–15] Existing tests to determine the bond between concrete substrate and repair material can be divided into several categories.[9] Silfwerbrand et al.[16] noted that the results depend to a large extent on the test method used. For that reason, the effect of various test methods on the interface bond strength between concrete substrate and repair materials has been studied.[8,9,17,18] Robins and Austin[12] found that the strength and integrity of the bond depend on the physical and chemical characteristics of the overlay, on the condition of the substrate such as surface roughness and soundness, and on the subgrade properties. Randl and coworkers[19] found that the use of high strength concrete for the overlay is beneficial to bond strength. Similar results, experimentally found by Júlio et al.,[20] indicate that increasing the compressive strength of the overlay, in relation with the compressive strength of the substrate concrete, improves the bond strength. Bonaldo et al.[21] demonstrated that the substrate mechanical properties influence the interface bond strength.

The surface preparation and the cleaning of the concrete substrate are considered the most crucial step in a concrete repair project. Surface preparation includes the removal of damaged and/or deteriorated parts of the old concrete and the removal of loose particles and contaminants on the surface.[15] The method of substrate-surface preparation influences to a large extent its roughness. Tschegg et al.[14] compared different roughnesses and found better bond characteristics for the rougher interface. Other studies reported that bond test results have shown that surface roughness has only a minor influence on tensile bond strength.[22,23] Silfwerbrand[22] compared interface strength resulting from different surface treatments and different roughness; he concluded that there is a roughness threshold value beyond which further improvement in roughness does not seem to enhance bond strength. Beushausen[23] argued that the tensile pull-off test methods are not very susceptible to the effects of surface roughness. He stated that it appears reasonable to assume that the interface roughness has an influence on shear bond strength. Zanotti and co-workers[24] carried out an experimental study on the influence of fibers on the mechanical properties of the interface; bond strength was assessed by means of slant shear tests with different slants on repair mortars with different contents of polyvinyl alcohol (PVA) fibers. Shear-normal stress interaction diagrams, adhesion strength and internal friction were obtained.

From the mentioned literature survey, it emerges that most of the studies on bond strength regard, above all, the testing methodology. In addition, several experimental tests have been performed not considering the concrete substrate strength. However, the latter should play a major role by considering that most of the existing structures to be repaired were made by low-strength concrete (except infrastructures such as bridge girders). In fact, as already mentioned, the shear critical crack may occur at the interface, or in the overly (which is unlikely) or in the subgrade concrete. The interface roughness plays a major role only when the shear critical crack develops through the interface. Moreover, among recent published studies,[25–27] Chilwesa et al.[25] investigated the influence of substrate surface roughness on interface bond strength through a new bond test setup and highlighted some limitations of the bond test methods. It should eventually be observed that most of these studies generally do not consider high or ultra-high performance fiber reinforced concrete (HPFRC or UHPFRC) as a repair material.

In order to shed some new lights on the overlay bond, this paper presents a series of bond tests on prismatic specimens with the purpose of evaluating the shear bond strength between a low-strength existing concrete and HPFRC overlay. In this work, the test setup has been improved with respect to previous research[25] and a wider spectrum of materials has been considered.

Two series of specimens with two different repair materials were tested. To assess the influence of the substrate strength and of the substrate surface roughness, both series were characterized by three different exiting concretes and three different roughnesses. The main results of the tests will be presented and discussed.

2 | EXPERIMENTAL PROGRAM

In order to investigate the shear bond strength between existing concrete and HPFRC overlay, three different concrete substrates and two different repair materials were considered. The experimental program consisted of two series of specimens (that depend on repair materials): series S1 and series S6. Both series were characterized by three different substrates and three different roughnesses. There were four specimens for each one. This resulted in a total of 72 specimens tested in the program.

Specimens were constructed at Mapei S.p.A.—Cafiero (Milan) and the tests were conducted at the laboratory for testing materials of the University of Brescia.

2.1 | Specimens geometry

All members consisted of two substrate prisms, each measuring 200 × 100 × 100 mm^3, on the sides of which overlay prisms (300 × 100 × 100 mm^3) were cast such that four contact surfaces between two materials were created (Figure 1). The contact surfaces area measured 100 × 100 mm^2. The contact surface on each substrate

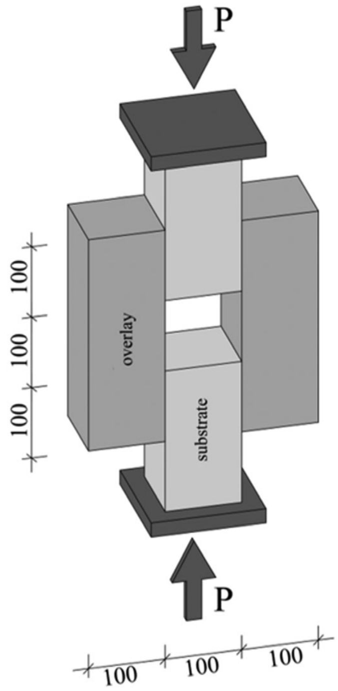


FIGURE 1 Geometry details of the test specimens (dimensions in mm).

TABLE 1 Classification of surface roughness, Model Code 2010.[28]

Roughness classification	Average roughness, R_t (mm)
Smooth	<1.5
Rough	1.5–3.0
Very rough	>3.0

prism had to be prepared to ensure good roughness prior to casting of the overlays. Figure 1 illustrates the specimen geometry and interface detailing specimen for the interface bond test.

In order to study the influence of the substrate surface roughness on the interface bond strength, three different roughness indexes were investigated:

- Smooth surface;
- Rough surface;
- Very rough surface.

The smooth surface specimens were obtained by using a Bosch GSS 2300 Professional Orbital Sander. A needle gun scaler was used in the preparation of the rough and very rough surface specimens. The roughness of the samples was measured by a profilometer (Barton's comb).

Table 1 reports the average roughness of the specimens and the classification of surface roughness according to *fib* Model Code for Concrete Structures 2010 (MC2010),[28] which provides detailed design recommendations for interface shear transfer, as well described in reference 29. The standard deviation and coefficient of variation were not provided by the producer.

The casting process began with the preparation of the substrate prism, which incorporated 6 mm (Ø6) longitudinal rebars and stirrups. The substrate prisms were cast at least 45 days prior to casting the overlay. The substrate prisms were subjected to the required treatment method to obtain the needed surface roughness parameter. Then, the prisms were thoroughly cleaned with compressed air to remove dust and residual materials; moreover, the substrate surface was moistened to obtain a condition of "saturated surface dry" (SSD). This procedure was done by wetting the surface until it was saturated, and letting it dry just enough to remove excess moisture. The SSD condition ensures that there is no free water at the surface and moisture loss by the overlay to the substrate.

The specimens were stored in water at a temperature of 23.0 ± 2.0°C until the time of testing (28 days).

2.2 | Materials

Three types of concrete with different strength classes were chosen for the substrate and two types of HPFRC were selected for the overlay.

Regarding the substrate concrete, the three materials chosen are representative of a spectrum of material often adopted for the construction of RC residential buildings. They were: C12/15, C16/20, and C20/25, according to both MC2010[28] and Eurocode 2[30] designation.

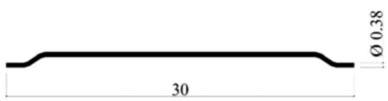
Concerning the HPFRC overlay, the two commercial products selected were: Planitop HPC Floor and Planitop HPC Floor 46, henceforth PHF and PHF46. The selected materials are representative of typical structural repair materials employed to reinforce slabs, columns, and beams. Both materials are a high performance fiber reinforced cementitious mortar. The maximum size of aggregate is 1 mm for the material PHF and 6 mm for PHF46. The steel fibers adopted are hooked and have a length $l_f = 30$ mm, an aspect ratio $l_f/d_f = 79$, a volume content $V_f = 0.96\%$, and a tensile strength $f_y = 3070$ MPa. Table 2 reports the properties of steel fibers adopted for all test specimens. In order to reduce the probability of cracking phenomena due to shrinkage, after casting each specimen was stored in water at a temperature of 23.0 ± 2.0°C up to the time of testing.

The mean uniaxial compressive strength ($f_{cm,cube}$) of the overlay was evaluated from six concrete cubes measuring 150 mm, following the guidelines given in UNI EN 12390-3.[31] All the specimens were stored in water at a temperature of 23.0 ± 2.0°C and were tested at 28 days (when bond tests began). The cylindrical mean compressive strength (f_{cm}) was conventionally assumed as $0.83 \cdot f_{cm,cube}$. The mean tensile strength (f_{ctm}) and the mean secant elastic modulus (E_{cm}) of the concretes were both calculated according to Eurocode 2[30] as $f_{ctm} = 2.12 \cdot \ln(1 + (f_{cm}/10))$ and $E_{cm} = 22 \cdot (f_{cm}/10)^{0.3}$. Table 3 gives the values ($f_{cm,cube}$ and f_{cm}) for all cubes tested.

According to the European Standard EN 14651,[32] 12 (150 × 150 × 500 mm^3) notched beams were tested under the three-point bending test for evaluation of the tensile behavior of fiber reinforced concrete. The tests provided the flexural tensile stress–CMOD (crack mouth opening displacement) curves, which enable determining the residual strength parameters required by MC2010[28] to characterize the post-cracking behavior of SFRC.

As summarized in Table 3, the residual strength parameters include the limit of proportionality f_L (i.e., the highest flexural tensile strength detected for CMOD ranging from 0 to 0.05 mm) and the residual flexure strengths f_{R1}, f_{R2}, f_{R3}, f_{R4}, corresponding to different CMOD values of 0.5, 1.5, 2.5, and 3.5 mm, respectively. The stress–CMOD curves are reported in Figure 2.

TABLE 2 Properties of steel fibers.

Fiber shape	Hooked-end
Material	High carbon, cold drawn steel
Tensile strength (MPa)	≈3070
Length, l (mm)	30
Diameter, Ø (mm)	0.38
Aspect ratio, l/Ø	79
Fiber designation	RC-80/30 BD
Fiber view	

2.3 | Test setup and instrumentation

Figure 3a illustrates the setup for the interface bond test: the interface shear force was introduced via a compression load applied to the specimens using two steel plates at both ends. At specimen-to-steel plate interfaces, a thin layer of neoprene was used to prevent contact problems pertaining to any possible uneven surfaces and to equally distribute the total vertical load (P).

Figure 3b shows the specimen prior to the application of the load. As shown in Figure 3, a resistive clip gauge and 11 LVDTs were used for experimental measurements. The clip gauge (front side) and a vertical LVDT (back side) were placed in the middle of the specimen to monitor the relative displacement (vertical and horizontal) between the substrate prisms. In particular, eight vertical LVDTs

TABLE 3 HPFRC properties.

Material ID	PHF	PHF46
Uniaxial compression test on cubes (compressive strength)		
# of cubes	6	6
$f_{cm,cube}$ [MPa]	118.2 [119.5–116.6] (0.01)	110.5 [115.1–106.6] (0.03)
f_{cm} [MPa]	98.1	91.8
f_{ck} [MPa]	90.1	83.7
f_{ctm^2} [MPa][a]	5.05	4.92
E_{cm^2} [GPa][a]	43.6	42.8
Three point bending test (3PBT)		
# of prisms	12	12
f_L [MPa]	7.33 [6.51–8.45] (0.10)	7.52 [6.81–8.07] (0.06)
f_{R1} [MPa]	12.54 [10.49–15.44] (0.13)	11.90 [9.56–14.78] (0.14)
f_{R2} [MPa]	12.70 [11.12–15.53] (0.10)	12.65 [10.37–15.92] (0.12)
f_{R3} [MPa]	11.46 [9.83–14.15] (0.11)	12.04 [9.86–14.80] (0.13)
f_{R4} [MPa]	9.91 [8.59–12.20] (0.11)	10.19 [8.50–13.51] (0.14)
FRC class[b]	8c	8c

Note: [min–max] minimum and maximum values are reported in square brackets. (CV%) coefficient of variation reported into round brackets.
[a]Calculated according Eurocode 2.[30]
[b]FRC classification according fib Model Code 2010.[28]

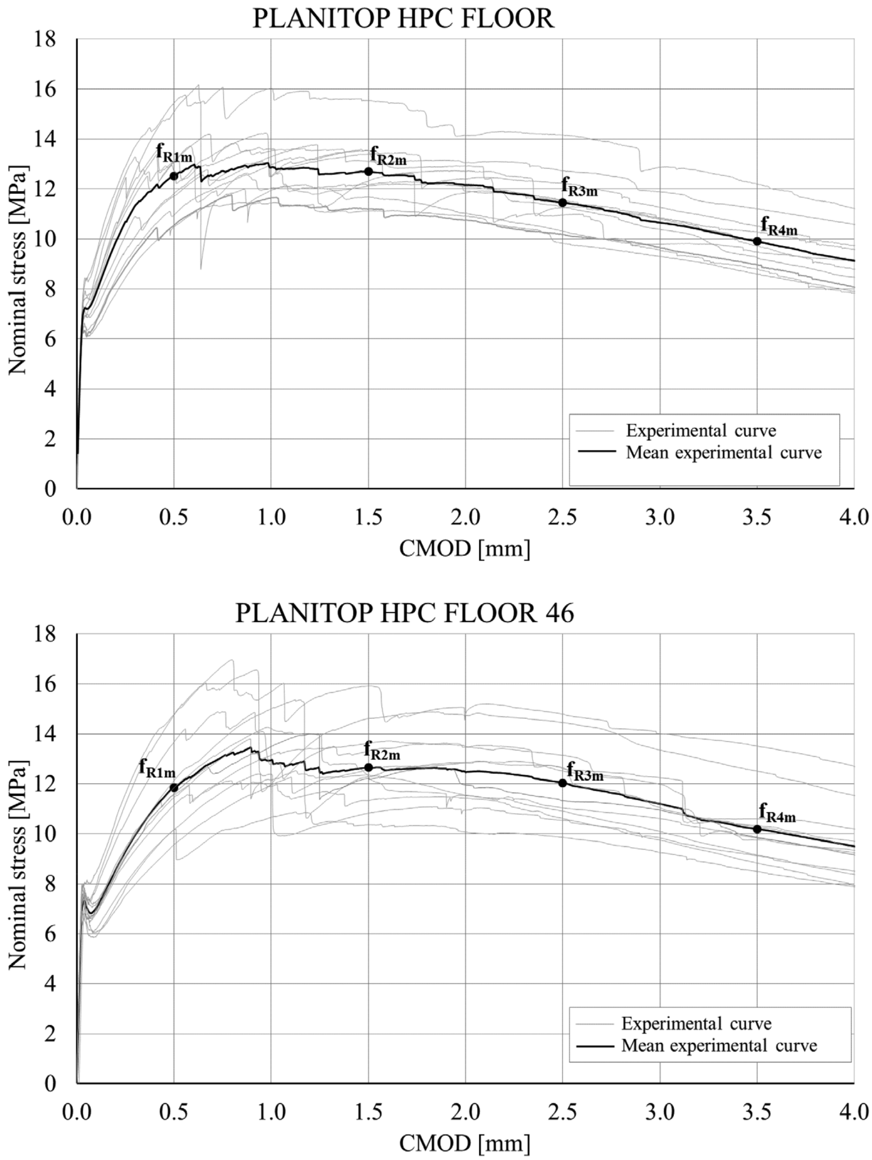


FIGURE 2 Nominal stress versus CMOD curves for PHF Floor and HPC Floor 46.

were placed across each contact surface (front and back side) to measure the relative displacement between substrate and overlay concrete that is, the slip. Two horizontal LVDTs were located across the contact surface on the front side to measure the horizontal crack opening displacement (COD) between substrate and overlay concrete.

This setup is an extension (and improvement) of the one recently proposed Chilwesa et al.[25] In the previous arrangement, the relative displacement between the substrate prisms was measured with the clip gauge only; here, a further LVTD was adopted. Moreover, the two horizontal crack opening displacements (COD) between substrate and overlay concrete were not implemented. In addition, a broader range of low substrate concrete classes was herein investigated to fit better with actual cases in typical retrofitting interventions.

Tests were performed under displacement control by using a INSTRON 1274 Universal Testing Machine, by monotonically increasing the displacement. Three different speeds were utilized: 0.02 mm/s (elastic range), 0.01 mm/s (intermediate range), and 0.005 mm/s (pre-peak until failure). This type of displacement control was performed by the resistive clip gauge. Data were detected and stored by a data acquisition system.

The average shear stress across an interface deflection was calculated with the following equation:

$$\tau_a = \frac{P}{2A}, \tag{1}$$

where τ_a is the average shear stress; P is the maximum achieved load; A is the interface contact area (10,000 mm^2).

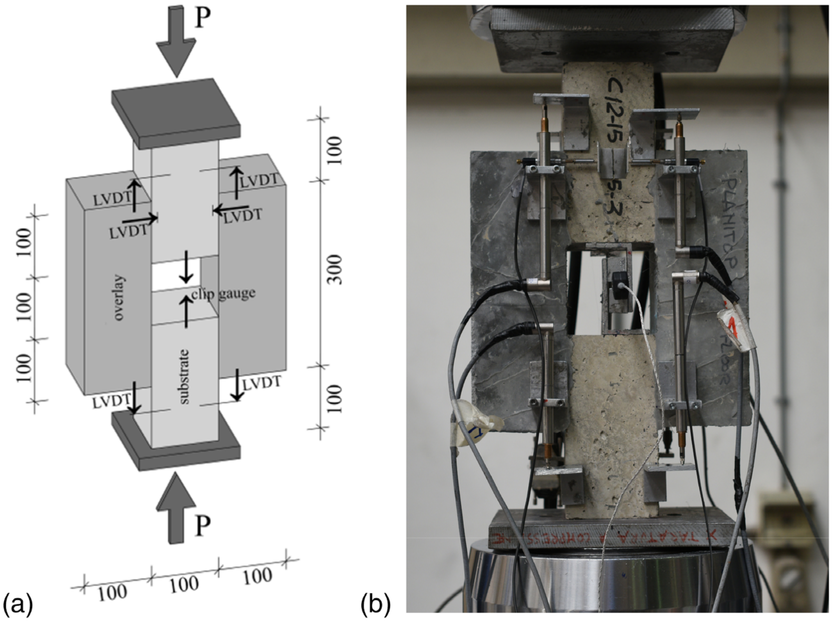


FIGURE 3 Schematic (a) and actual view (b) of the test setup (dimensions in mm).

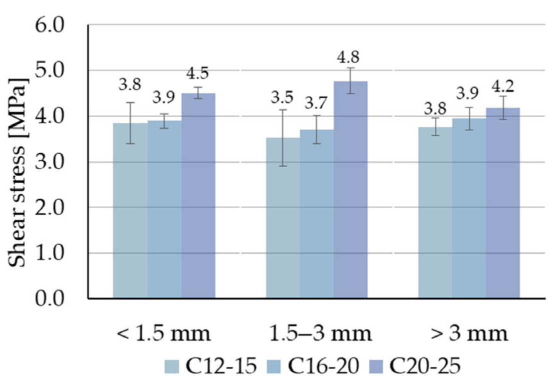


FIGURE 4 Summary of shear bond strength for PHF specimens.

3 | EXPERIMENTAL RESULTS AND DISCUSSION

The major objectives of the bond tests were the investigation of the influence of the substrate compressive strength on the bond strength, and the evaluation of the possible influence of the substrate surface roughness on interface bond strength. The following sections give the results of these tests. The results presented herein concern the average shear stress (given by Equation 1) and the slip (tangential displacement).

3.1 | Influence of substrate strength

The results are presented for each surface preparation method, that is, smooth, rough, and very rough specimens. The experimental results are divided in the two series: S1 and S6 where the specimens of the series S1 are characterized by the PHF repair material, while the series S6 by the PHF46.

3.1.1 | Overlay PHF

Figure 4 illustrates the results of bond tests for all the concrete substrates tested. It may be observed that C12/15 and C16/20 specimens recorded similar shear bond strength. The results show that there is an increase in the bond strength with an increase in the substrate compressive strength. For smooth and rough specimens, the increase is higher than for very rough specimens.

In the smooth specimens, the percentage increase is 2.6% between C12/15 and C16/20; 18.4% between C12/15 and C20/25; and 15.4% between C16/20 and C20/25. For the rough specimens, the percentage increase is 5.7% between C12/15 and C16/20; 37.1% between C12/15 and C20/25; and 29.7% between C16/20 and C20/25. For the very rough specimens, the percentage increase is 2.6% between C12/15 and C16/20; 10.5% between C12/15 and C20/25; and 7.7% between C16/20 and C20/25. Table 4 gives the shear stress results for each substrate strength, with indication of minimum and maximum values in square brackets and the corresponding COV in the round brackets.

Figures 5 and 6 present the three typical failure mode (interface failure, failure close to the interface, substrate failure), and the frequency at which it occurred.

TABLE 4 Mean shear stress from shear bond tests for each substrate strength, PHF specimens.

PHF specimens	C12/15	C16/20	C20/25
Mean shear stress τ_a (MPa)			
Smooth	3.8 [3.3–4.3] (0.12)	3.9 [3.8–4.1] (0.04)	4.5 [4.4–4.7] (0.03)
Rough	3.5 [2.7–4.1] (0.18)	3.7 [3.4–4.1] (0.08)	4.8 [4.4–5.0] (0.06)
Very rough	3.8 [3.9–4.5] (0.06)	3.9 [3.7–4.2] (0.06)	4.2 [3.9–4.5] (0.06)

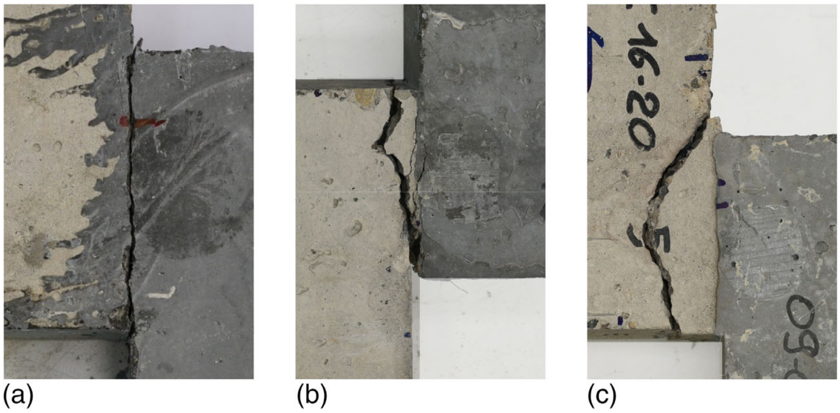


FIGURE 5 Typical failure mode for PHF specimens: (a) failure at the interface; (b) failure of the substrate concrete in regions close to the interface; (c) substrate failure.

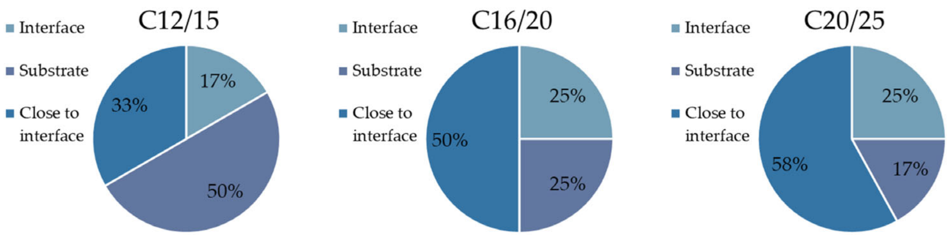


FIGURE 6 Percentage at which a type of failure occurs.

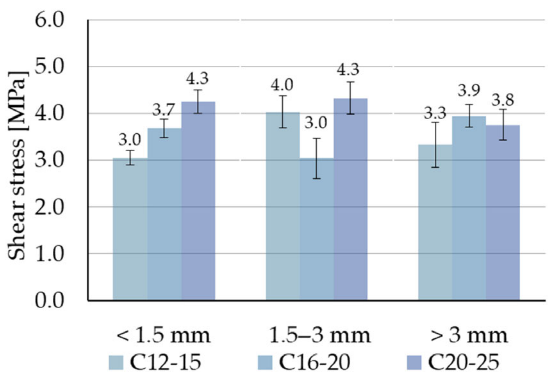


FIGURE 7 Summary of shear bond strength for PHF46 specimens.

3.1.2 | Overlay PHF46

Figure 7 shows the results of bond tests for all the concrete substrates tested, which conforms the increase of bond strength with an increase in the substrate compressive strength. The highest increase in shear stress is in the smooth specimens. It can be noted that for the C16/20 specimens with intermediate roughness, there is high dispersion in the results. In the smooth specimens, the percentage increase is 23.3% between C12/15 and C16/20; 43.3% between C12/15 and C20/25; and 16.2% between C16/20 and C20/25. For the rough specimens, the percentage increase is −25.0% between C12/15 and C16/20; 7.5% between C12/15 and C20/25; and 43.3% between C16/20 and C20/25. For the very rough specimens, the percentage increase is 18.2% between C12/15 and C16/20, 15.2% between C12/15 and C20/25, and −2.6% between C16/20 and C20/25. Also, for the PHF46 overlay, the increase for the very rough specimens is lower than for the smooth and rough specimens. Table 5 summarizes the shear stress results for each substrate strength. For specimens characterized by PHF46 repair material, the failure modes were the same as reported in Figure 5, while in Figure 8 the frequency at which the failure mode occurred are reported.

As a final consideration, compared to the tests presented in reference 26, the push-out tests led to similar load transfer scenarios while the slant shear tests provided much higher bond strength. Therefore, the shear

PHF46 specimens	C12/15	C16/20	C20/25
Mean shear stress τ_a (MPa)			
Smooth	3.0 [2.9–3.2] (0.05)	3.7 [3.4–3.9] (0.05)	4.3 [4.1–4.6] (0.06)
Rough	4.0 [2.6–3.6] (0.08)	3.0 [2.6–3.6] (0.14)	4.3 [3.9–4.9] (0.08)
Very rough	3.3 [2.9–3.9] (0.14)	3.9 [3.2–4.0] (0.06)	3.8 [3.3–4.2] (0.09)

TABLE 5 Mean shear stress from shear bond tests for each substrate strength, PHF46 specimens.

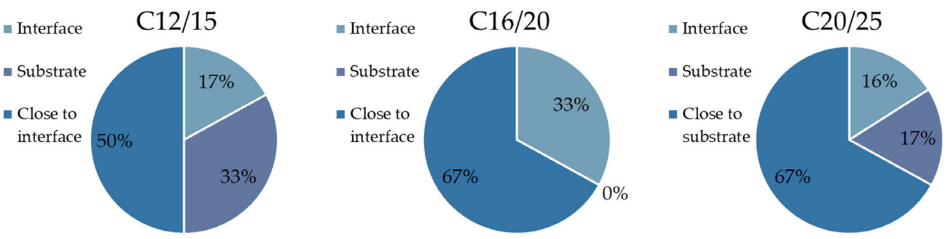


FIGURE 8 Percentage with which a type of failure occurs.

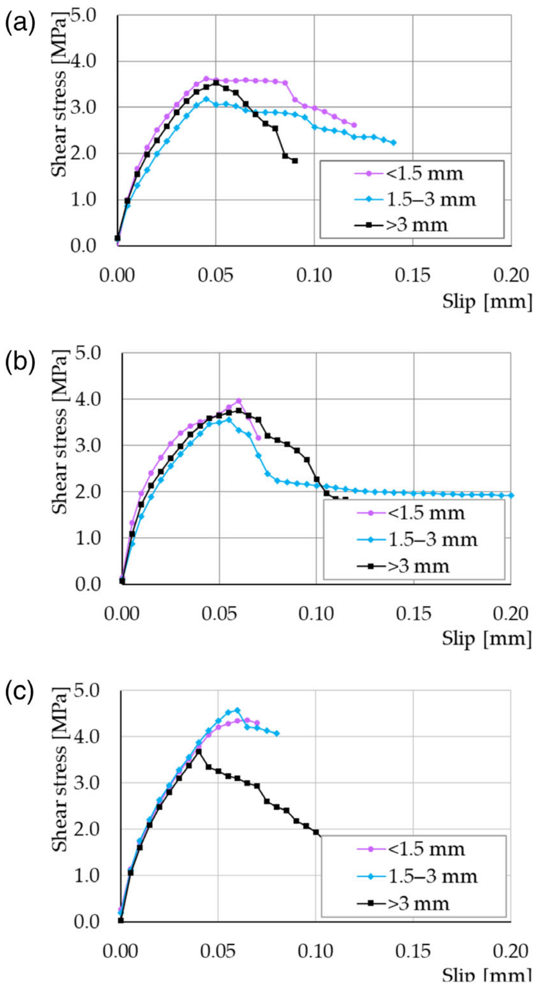


FIGURE 9 Average shear stress versus interface slip curve for PHF series: (a) substrate C12/15; (b) substrate C16/20; (c) substrate C20/25.

bond results based on the push-out setup are on the whole well comparable to the tests herein performed (for the C20/25 substrate class).

3.2 | Influence of surface roughness

This section presents the results on the influence of substrate surface roughness on interface bond strength. The results of the bond tests are presented in the form of average shear stress versus slip (tangential displacement) curves. The average shear stress versus slip graph represents the response of the interface to loading. The experimental results are given for the repair material PHF and PHF46. In the first case (PHF), Figure 9 illustrates the results for the specimens with C12/15 substrate (a), C16/20 substrate (b), and C20/25 substrate (c). Each curve represents the main curve of four identical specimens. The curves show that the slope in the pre-peak region is characterized by a very steep slope. After the peak stress, a low softening behavior is observed.

For the PHF46 overlay, Figure 10 illustrates the smooth specimens (a), the rough specimens (b), and the very rough specimens (c).

In both series, S1 and S6, despite the different roughness, it can be seen that the graphs are similar in terms of the pre-peak slope and the post-peak softening behavior. Moreover, from the experimental curves of both series, it can be observed that the increase in substrate surface roughness did not produce a significant increase in the area under the stress–displacement graph in the post-peak region, which represents the ability of the element to absorb more energy and offer a more ductile behavior. Thus, it can be affirmed that there was not a clear increase in ductility as a result of surface preparation.

Furthermore, focusing on slips values lower than 0.002 mm, it can be seen that, although slips were almost zero, in most of cases the shear stresses reached values up to 0.1–0.3 MPa.

It should be observed that, despite the different surface preparation method, the failure always localized

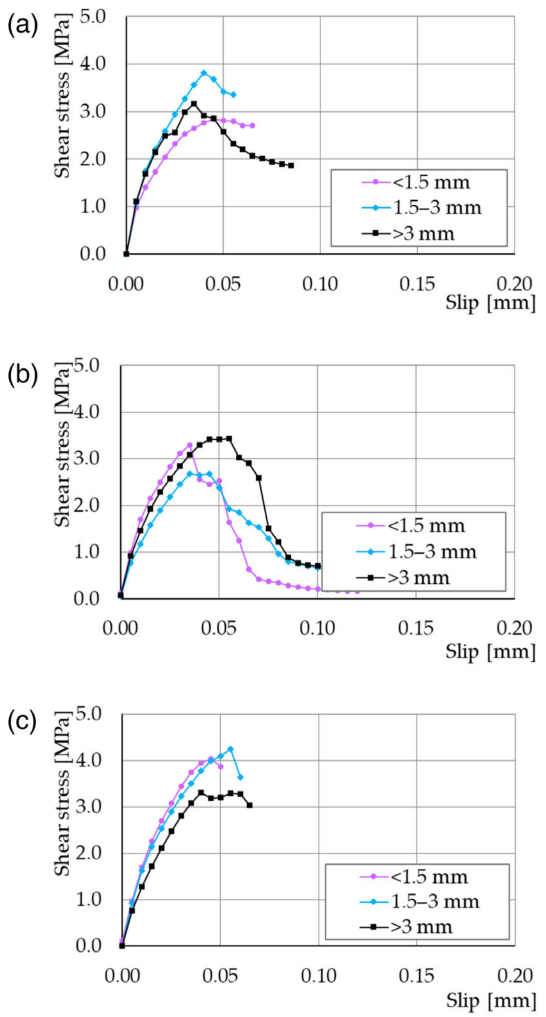


FIGURE 10 Average shear stress versus interface slip curve for PHF46 series: (a) substrate C12/15; (b) substrate C16/20; (c) substrate C20/25.

(partly or, in some cases, completely) in the substrate, due to its rather lower compressive strength. It is important to note that this failure stress would be the bond stress only if the failure develops completely at the interface. In all other cases, the failure stress is only a lower bound of the bond strength.[16] Therefore, in both series, when the crack does not develop at the interface, the bond experimental strength represents a lower bound of the interface strength. As a further consequence of that, the values recorded by the two horizontal measurements (COD) are not significant for this experimental program and, therefore, are not reported in this paper.

4 | CONCLUDING REMARKS

The results of 72 specimens subjected to bond tests have been presented in this paper. Comparisons have been made among samples with different substrate compressive strengths and different substrate surface roughnesses.

Based on the experiments and discussion reported herein, the following main conclusions can be drawn:

- The novel and simple test for evaluating bond strength, recently introduced by Chilwesa et al.,[25] was improved and implemented. It can be further confirmed that this test is an easy tool for measuring interface bond strength.
- The dominant failure mode was characterized by substrate failure or failure in regions close to the interface of the substrate concrete regardless of the substrate strength, surface roughness or material repairs. Therefore, the failure stress obtained from this experimental program may be assumed as a lower bound of the interface bond strength. This means that, when using high strength concretes as an overlay for retrofitting classical low strength existing structures, provided that a minimum surface treatment is carried out, the interface is rarely the weakest component of the composite structures, as the failure is more likely to develop in the substrate.
- The influence of the substrate compressive strength seems to be a significant parameter affecting the shear stress between concretes with different ages. In particular, the highest increase in bond strength is noted for substrate C20-25. The effect of substrate compressive strength is much more important for smooth and rough specimens, where the biggest increases in shear stress are observed.
- With the increase in surface roughness, a corresponding increase in the area under the stress–displacement graph in the post-peak region was not observed. The ductility did not increase with the increase of the substrate roughness.

It is important to underline that these conclusions purely refer to the substrate compressive strength ranges investigated. Additional tests that consider a higher substrate compressive strength (i.e., in the case of bridges) could potentially lead to a shear failure at the interface, and to a more refined bond experimental model for a wide range of composite elements.

NOMENCLATURE

A	interface contact area
CMOD	crack mouth opening displacement
COD	crack opening displacement
d	effective depth
d_f	diameter of the fiber

E_{cm}	mean Young's modulus of concrete
f_{cm}	mean cylindrical compressive strength of concrete
$f_{cm,cube}$	mean cubic compressive strength of concrete
f_{ctm}	mean tensile strength of concrete
f_L	mean value of the limit of proportionality of concrete
f_R	mean post-cracking residual strength of SFRC
f_{su}	mean ultimate strength of reinforcing steel
f_y	mean yielding strength of reinforcing steel
l_f	length of the fiber
P	applied load
δ	slip between substrate and overlay
τ_a	average shear stress

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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