Use of sand coating to improve bonding between GFRP bars and concrete

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Abstract

Glass fiber-reinforced polymer bars are currently used to reinforce concrete in an attempt to overcome the corrosion issue encountered with ordinary steel. Different types of surface treatment were applied to the smooth rods in order to enhance bonding with concrete. Experimental results show that using bars coated with coarse sand notably improve the bond strength. The influence of granulometry sand, rebar diameter, length embedded, and concrete strength are analyzed. Rebars coated with finer sand lead to a stronger chemical adhesion with concrete. However, the effect of friction and interlocking forces produced by coarse sand prevails over the chemical adhesion in the pull-out test.

Keywords

Strengthening, bond strength, surface treatment, pull-out test, FRP reinforcement

Introduction

The use of fiber-reinforced polymers (FRP) as reinforcement in concrete structures is considered to be a possible alternative to steel in those situations where corrosion is present. FRP bars have many distinct advantages over steel reinforcement; including a high strength-to-weight ratio, high durability, easier handling due to their light weight, high tensile strength, excellent fatigue characteristics and electromagnetic neutrality.[1]

Typical applications of FRP composites include rehabilitation projects, including column strengthening,[2,3] seismic retrofitting,[4,5] repair of corrosion-damaged columns,[6,7] as well as improvements in strength and stiffness of deteriorated structures by the use of CFRP composites.[8–10] Also, FRP composites can be used as internal reinforcements for concrete bridge decks.[11,12]

In order to be widely accepted in the construction industry, all aspects of the structural behavior of FRP rebars must be studied to guarantee their safe application. Since several types of FRP bars are commercially available, with varying compositions and surface treatments, the interface bond of FRP-bar concrete is complex and quite different from that of steel reinforcement.

It is well known that the behavior of the interface between the FRP and the concrete is the key factor controlling debonding failures in FRP-strengthened reinforced concrete (RC) structures. The bonding between concrete and reinforcing bars is one of the key aspects with regard to both reinforced and prestressed concrete structures.[13] The mechanics of bond stress transfer between FRP reinforcement and concrete has been investigated by many authors.[14–18] These authors have investigated several kinds of bars, characterized by the differences in quality and quantity of fibers, and also by the different shapes of the outer surface.

It was observed that the bond between FRP reinforcement and concrete depends on several factors. These include friction due to surface roughness of FRP rebars, the mechanical interlock of the FRP rebars against the concrete, the chemical adhesion,

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the hydrostatic pressure against the FRP rebars due to the shrinkage of hardened concrete and the swelling of FRP rebars due to temperature change and moisture absorption.[19–22] Other research works studied the use of sprayed short glass fiber with thermosetting resin over the surface of bars as an effective way to transfer load from concrete.[23,24] Lee et al.[25] have also investigated the effect of adhesive type, adhesive layer thickness, and overlap length. It was found that the joint strength was slightly depend on adhesive type, decreased with adhesive layer thickness, and increased with overlap length. An approximate adhesive layer thickness between 0.2 and 0.5 mm maximizes the joint strength.[25]

Tang and Balendran[26] studied the bond performance of glass fiber-reinforced polymer (GFRP) bars in polystyrene aggregate concrete (PAC). The bond performance was studied with varying polystyrene aggregate content, concrete strength, embedment length, shape and surface treatment of the bars. The sand-coated GFRP bar gave the highest bond strength attained. In particular, the bond strength was found increased with the compressive strength and concrete density of PAC, but the rate of increase decreases with the increase in concrete strength.[26]

Ahmad et al.[27] presented the bond between carbon FRP bars included with concrete. They studied two types of surface, smooth and sand coated through pull-out test, examining the effect of parameters of embedment length, bar diameter and concrete age. Robert and Benmokrane[19] studied the effect of bond aging of glass FRP embedded in concrete. Their rebars presented a coating of sand particles of a specific grain-size distribution that enhances the bonding potential. Baena et al.[21] studied the bond behavior between concrete and commercial carbon fiber- and glass FRP, both with a sand-coated surface. Davalos et al.[20] performed an extensive study to evaluate the FRP bar degradation of interface bonds with high-strength concrete. They used different types of FRP bars: helically wrapped, sand-coated, and roughened by sand-blasting to produce deformations. The published papers did not take into account the effect of the sand granulometry on the bond strength.

The goal of this article is to explore the influence of granulometry of the sand on the interface bond between FRP bars and concrete, in order to increase the load transfer by means of producing better interphase.

Experimental

In this study, GFRP bars made of orthophthalic polyester resin reinforced with glass fiber, with a content of 60% wt, were used. Bars with two nominal diameters (ø) 9 and 16 mm were used. The tensile strength and Young's modulus were determined according to ASTM 3916, obtaining 770 MPa and 44.5 GPa for 9 mm bars and 680 MPa and 41.4 GPa for 16 mm bars, respectively. The smooth rods were coated with sand of two different granulometries. Sand granulometry was determined by sieving, according to ASTM C 778-02. Essentially, this process measures the maximum diameter of a sediment grain. The sand retained in sieve N°16 (mean size of the grain: 1.2 mm) was used as coarse sand, and the sand retained in sieve N°50 (mean size of the grain: 300 µm) as fine sand. Epoxy resin was used as the adhesive (diglycidyl ether of bisphenol A with $n = 0.14$ – DGEBA) and tetraethylene amine as catalyst (TETA), from Distraltec S.A. According to ASTM A 775 (specification for epoxy-coated reinforcing steel bars), the coating thickness should be in the range of 130–300 µm. The rebars were cleaned with sandpaper to remove the rust on their surface before coating. The coating was applied to the surface of each rebar by a paint brush, and then the coated rebars were cured under 120°C for 4 h and 140°C for 2 h, the glass temperature transition (T_g) was 110°C.

The FRP bars were embedded in two different types of concrete in order to study the influence of the matrix type: one named conventional concrete (CC), which had a mean compressive strength at 7 days of 23.5 MPa, and the second one named high resistance concrete (HRC), with a mean compressive strength at 7 days of 56 MPa. The concrete used for the pull-out test specimens was prepared in the laboratory and the composition is given in Table 1. The composition of CC includes Procemplast P (from BASF), which is a concrete plasticizer that improves the workability. The composition of HRC includes Glenium C-315 (from BASF), a high-range water-reducing admixtures, which permit improve the workability of low water/cement ratio giving a high-performance concrete.

The pull-out tests were performed according to ACI 440.3 R-04 standard (Figure 1). The pull-out specimens were prepared with a cylindrical mold with a diameter of 100 mm and height of 200 mm. The FRP bars were concentrically embedded in the concrete cylinders. In order to control the bond length, the FRP bar was prepared with a bond breaker, which consisted of soft plastic tubing inserted around the bar to prevent contact of FRP with concrete. The length of the bars studied were 5 and 10 times the bar diameter, from now on the shorter (×5) or longer (×10) length. The concrete cylinder specimens, with embedded FRP, were removed from the metallic molds 1 day after casting, and then placed in a curing tank for 6 days before they were tested. It was observed that the strength reached after 7 days is enough to analyze the bond behavior between

Table 1. Composition and characteristics of concrete

Composition for 1 m^3	CC	HPC
w/c ratio	0.5	0.3
Water (kg/m^3)	143	135
Cement (kg/m^3)	280	457
Sand (kg/m^3)	894	705
Gravel (kg/m^3)	1104	1157
Procemplast (mL)	0.96	–
HWR (mL)	–	2.2
7-days, compressive strength (MPa)	23	56

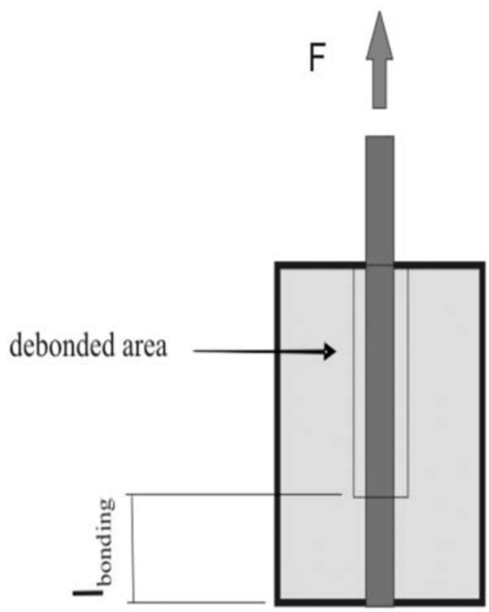

Figure 1. Pull-out setup.

the bar and concrete. Table 2 summarizes the different test conditions. The code has the following structure: 9S5-CC. The first number is the nominal diameter (9 or 16 mm); the first letter can be S, F, or C depends on the bar surface: Smooth, Fine Sand or Coarse sand; the second number indicates the embedment length, which can be 5 or 10 times the diameter; the rest of the code indicates the type of matrix, i.e. CC and HRC.

It is well known that the stress distribution is not constant along the embedment length. However, an average bond stress was defined as:

$$\tau = \frac{P}{\pi d_b l_b}$$

where P is the tensile load, d_b the rebar diameter, and l_b the embedment length.

After the pull-out test, splitting tensile strength tests of the cylindrical concrete specimens were performed according ASTM C496 in order to carry out a visual examination of the actual bond failure mode. Each bond strength value represents the average of three specimens tested.

Results

Influence of the concrete strength

Figure 2(a) and (b) shows the bond stress–slip relationship obtained for the rebars of 9 mm with different treatments included in both types of matrix. The bond–slip curves for each specimen were plotted using experimental results obtained directly from the slip measurements at the free end (bottom LVDT). Only one representative curve for each configuration is reported in Figure 2. The curve of smooth bar included in CC presents an initial linear increase in the bond stress, up to 1 MPa. The load transfer is provided by a weak chemical bond and friction, which depends strongly on the transverse pressure. Then, the bond stress increase slowly and the principal mechanism that resists the slip is friction; later on the friction diminishes as the rebar is pulled further out and the contact surface is damaged (see later).

The sanded bars presented very different behavior: the curve can be clearly divided in two parts. The first one includes an apparently linear increase until reaching maximum bond stress, where the chemical bond is the main resisting mechanism that provides load transfer. The second part is characterized by a softening, where friction is the more active bond mechanism. The residual bond stress value (post peak) represented the 40% of the peak bond value for the bar coated with fine sand and 70% for that coated with coarse sand.

In the case of high-resistant concrete (Figure 2(b)), the smooth bars present a similar bond stress–slip relationship than that seen in the CC. For sanded rebars, once the maximum peak value of bond stress–slip is reached, a sudden drop in the bond strength is observed. The residual bond stress value is the same for both systems (6 MPa), independent of the type of coating of the bars.

Regarding concrete strength, the maximum bond strength values reached by the sanded bars included in HRC are higher than that in CC. The high radial confinement pressure caused by the autogenous shrinkage of HRC during curing (due to the large quantity of cement) improved the friction bond.[27] Independent of the bar diameter, the higher strength of the matrix leads to a higher bond stress when the rebar is sand-coated (Figure 2(c) and (d)).

Table 2. Specimens notation of GFRP bars

Specimens notation	Nominal diameter (mm)	Embedment length (mm)	Surface	Type of concrete	Specimen N° 1	2	3	Average bond strength (MPa)	S^2 (%)[a]
9S5-CC	9	5φ	Smooth	Conventional concrete	0.94	1.03	1.15	1.04	1.11
9S5-HRC	9	5φ	Smooth	High-resistance concrete	1.29	1.21	1.91	1.47	14.68
9F5-CC	9	5φ	Fine sand	Conventional concrete	8.57	8.26	9.14	8.66	19.92
9F5-5HRC	9	5φ	Fine sand	High-resistance concrete	10.28	10.56	9.74	10.19	17.37
9C5-CC	9	5φ	Coarse sand	Conventional concrete	10.15	10.35	9.75	10.08	9.33
9C5-HRC	9	5φ	Coarse sand	High-resistance concrete	13.95	13.18	13.43	13.52	15.43
16S5-CC	9	5φ	Smooth	Conventional concrete	2.65	2.21	2.28	2.38	5.59
16S5-HRC	16	5φ	Smooth	High-resistance concrete	0.87	0.96	1.11	0.98	1.47
16F5-CC	16	5φ	Fine sand	Conventional concrete	8.1	7.88	8.34	8.11	5.29
16F5-HRC	16	5φ	Fine sand	High-resistance concrete	8.57	8.33	8.02	8.31	7.60
16C5-5CC	16	5φ	Coarse sand	Conventional concrete	8.92	9.12	8.51	8.85	9.67
16C5-HRC	16	5φ	Coarse sand	High-resistance concrete	10.15	10.02	10.57	10.25	8.26
16S10-CC	16	10φ	Smooth	Conventional concrete	1.22	0.74	1.51	1.16	15.12
16F10-CC	16	10φ	Fine sand	Conventional concrete	3.88	4.53	4.34	4.25	11.17
16C10-CC	16	10φ	Coarse sand	Conventional concrete	4.35	4.52	5.34	4.74	28.02

Notes: [a]Variance.

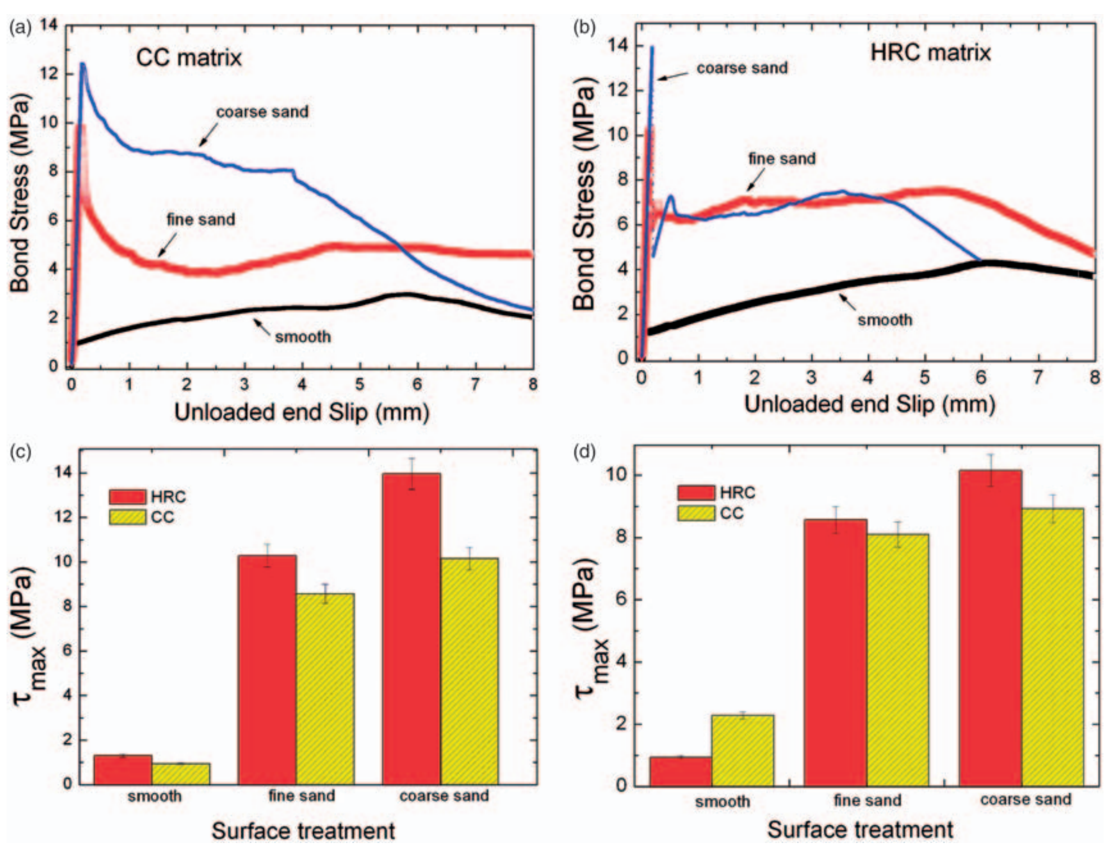

Figure 2. Representative bond–slip curves for unloaded end rebars of 9 mm included in (a) CC, (b) HRC, (c) τ_{max} for rebar of 9 mm included in both cement matrix, and (d) τ_{max} for rebar of 16 mm included in both cement matrix. Embedded length, 5 diameter.

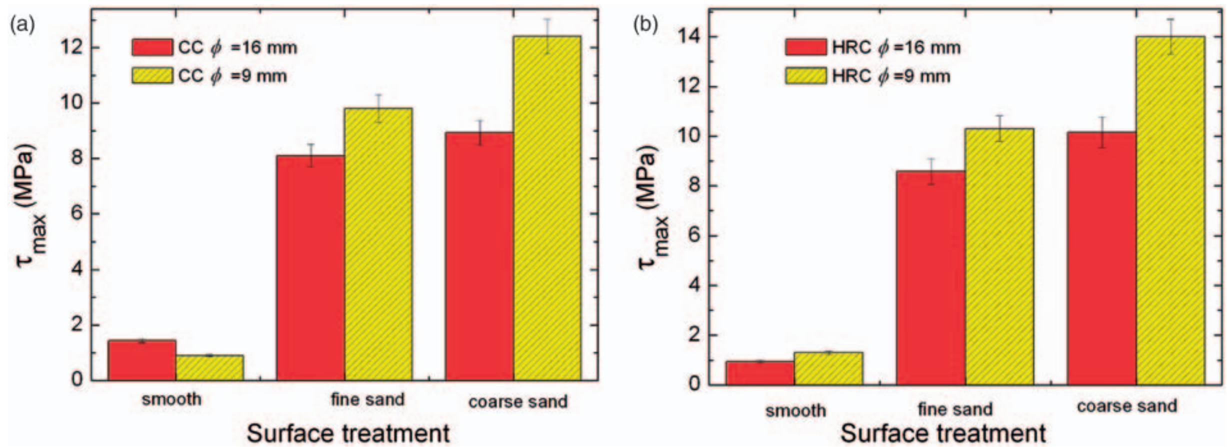

Figure 3. Effect of bar diameter on bond strength: (a) CC and (b) HRC.

Effect of bar diameter

Figure 3 displays the average bond stress obtained for the rebars of 9 and 16 mm including both CC and HRC matrices (Figure 3(a) and (b), respectively), which allows us to evaluate the effect of bar diameter on bond strength.

It is well known that the stress distribution is nonlinear along the bar during pull-out test.[28] In agreement with other authors,[29–31] the results obtained demonstrated that larger bar diameters lead to lower bond strength, regardless the strength of concrete (Figure 3). This nonlinear distribution is more evident in the case of the larger embedment lengths needed for larger diameters, which could explain the bond strength's dependence on rebar diameter. Also, it is affected by Poisson's ratio effect where the substantial elongation of the bar throughout the embedment length leads to a reduction in friction (a decrease in radial interface pressure with increasing pull-out load). For higher diameters, the effect of the strength matrix on bond strength is less pronounced (Figure 2(d)).

Effect of length embedded

Figure 4 shows the average bond strength obtained for rebars of 16 mm included in CC matrix with two different lengths, those of 5 and 10 times the bar diameter. The bond strength for different lengths is strongly dependent on the surface type. The bond strength for smooth bars is the same for both lengths tested. In the case of sanded bars, the bond strength for the shorter length is twice that of the longer length. This could be explained by taking into account that in longer lengths, the nonlinear distribution of bond stresses along the FRP bars is more pronounced.

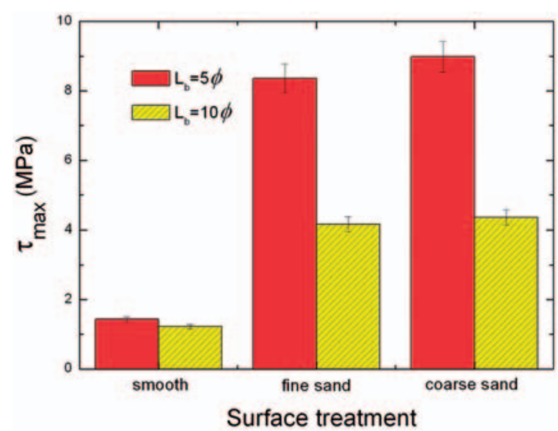

Figure 4. Effect of length embedded (L_b) on bond strength. Diameter of bar, 9 mm included in CC.

Effect of surface modification

Adding sand to the surface of the bars improves the mechanical behavior of coating as the sand itself provides higher friction and interlock forces. Regardless of the concrete strength, the use of coarse sand to cover the surface of rebars leads to a higher bond stress between sand and concrete. Coarser sand produces more interlocking forces and friction which leads to higher bond strength. This process is less pronounced in the fine sand treated bars.[32] This difference is more pronounced in the case of HRC.

This behavior can be explained taking into account the surface of the bars after pull-out test. Figure 5 shows samples containing rebars of 9 mm of diameter within CC matrix after splitting test. Figure 5(a)–(c) corresponds to smooth bars, coated by fine and coarse sand, respectively. All specimens tested under pull-out test failed by exhibiting slip through the

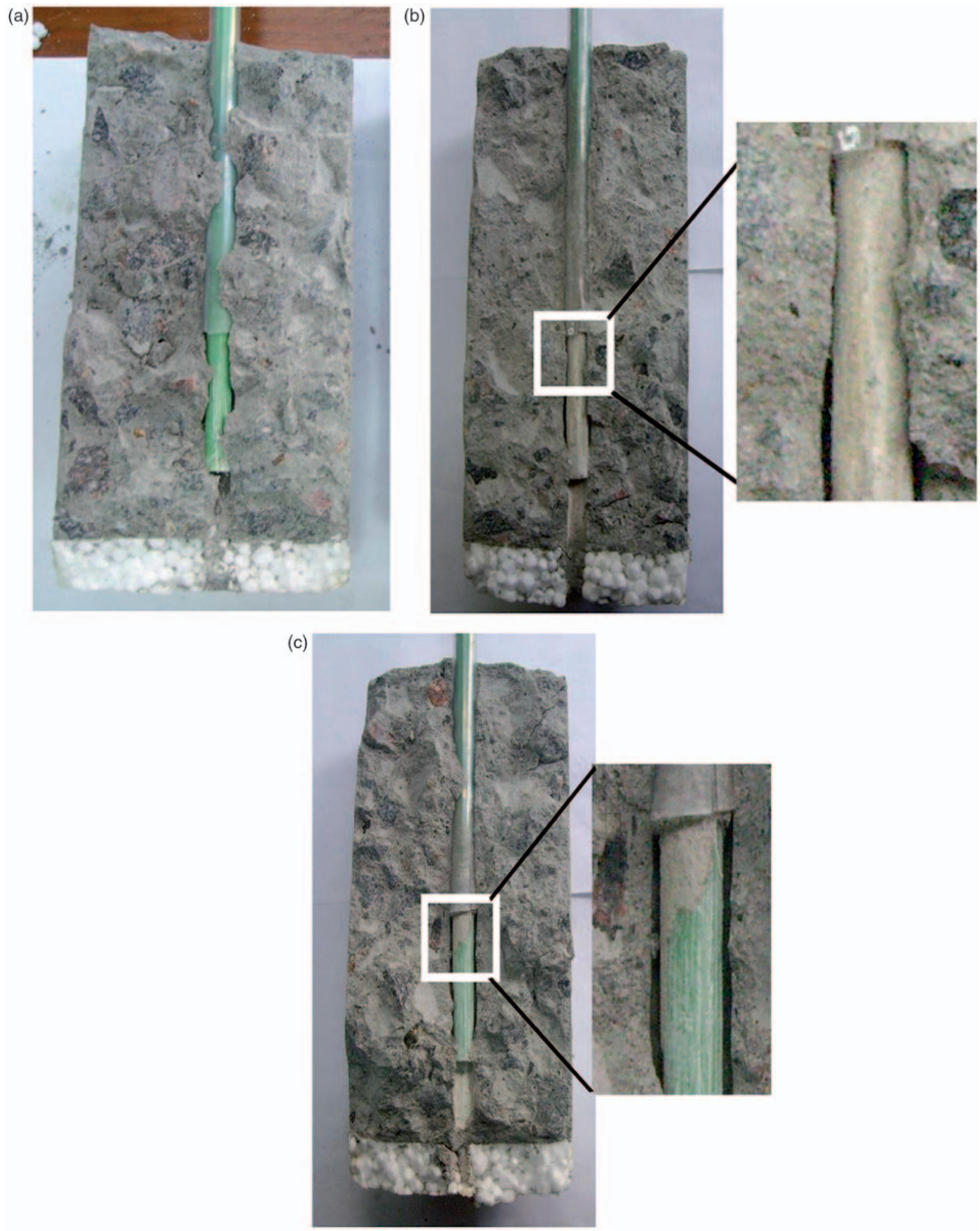

Figure 5. Photographs of samples submitted at splitting tensile strength of cylindrical concrete specimens: (a) smooth; (b) coarse sand; and (c) fine sand.

free-end. However, some relevant features can be distinguished between the different coatings. Figure 5(a) shows the effect of abrasion due to the action of aggregate against the smooth surface of the rebars. In Figure 5(b), it can be seen that the coating of fine sand on the bar is removed after the pull-out test, and in another case the coating of coarse sand remains bonded to the bar surface (Figure 5(c)). This suggests that the bond between the bar and concrete is stronger in the case of fine sand coating than the coarse (see magnification of Figure 5(b) and (c)). It is well known that silica sand absorbs very significant amounts of OH^- and Ca^{2+} from the cement solution, and releases very significant amounts of Si^{4+} into the cement solution and has little effect on the concentration of remaining elements.[33] The absorption of Ca^{2+} and OH^- by the silica sand probably indicates the formation of hydrated silicates. This chemical reaction is more pronounced in the case of finer sand due to the higher surface area exposed. This could be the reason for which the coating of fine sand is taken off after pull-out test.

In spite of the chemical adhesion being more pronounced in the case of the rebars coated with fine sand, for pull-out test, the more effective mechanism was the coating of coarse sand due to the interlocking and friction produced.

Conclusions

The experimental program aimed to investigate the possibility of using GFRP rods to strengthen concrete structural members. The following conclusions may be drawn.

- In the case of sanded bars, the bond strength for shorter lengths ($\times 5$) is twice that of those with a longer length ($\times 10$).
- Independent of the bar diameter, the higher strength of the matrix leads to a higher bond stress when the rebar is sand-coated.
- For thicker diameters, the effect of the strength matrix on bond strength is less pronounced.
- The absorption of Ca^{2+} and OH^- by the silica sand probably indicates the formation of hydrated silicates. This chemical reaction is more pronounced in the case of finer sand due to the higher surface area exposed. This could be the reason why the coating of fine sand is removed after pull-out test.
- The use of fine sand leads to a good chemical adhesion to the concrete due to higher surface area. However, the use of coarse sand produces higher bond strength between the rebar and the concrete due to friction and interlocking forces prevailing over the chemical adhesion mechanism.

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Conflict of Interest

The authors declare that they do not have any conflict of interest.

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