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Bonding in fabric–cement systems: Effects of fabrication methods

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Abstract

This paper compares the effects on the bond between fabric and cement matrix of three different processing methods: casting, pultrusion and vacuum condition. The fabrics included bonded glass mesh, woven polyvinylalcohol, and warp knitted weft insertion polypropylene. Pullout tests were performed to examine the bond between fabric and cement matrix. A microstructural analysis was conducted and correlated with pullout data. Improved bonding was obtained for fabric–cement composites produced with the pultrusion process, particularly for fabrics composed of multifilament yarns that have open junction points and no sizing to seal individual yarns. This improved bonding results from the impregnation of the fabric in the cement chamber during the pultrusion process, which filled the spaces between the filaments of the multifilament yarns.

Keywords: Processing; Pullout strength; Cement; Composite; Fabric

1. Introduction

Bonding at the fiber–matrix interface plays an important role in controlling the mechanical performance of cementitious composites. Several researchers have studied the bond characteristics of fiber–cement systems using analytical and experimental techniques [1–6]. The bonding of polymeric fibers with cement-based systems is relatively poor, which has limited the use of these ductile fiber systems. The use of polymeric fibers in the form of fabric can invoke geometrical interlock and improve the bond by mechanical means.

Several promising results with cement-based products reinforced with fabrics have been reported [6–13]. In addition to ease of manufacturing, fabrics provide benefits such as excellent anchorage and bond development showing a significant improvement over fibers [6,9]. Peled et al. [8] found that the flexural strength of cement-based composite products incorporating low modulus polyethylene fabrics is almost twice as high as that of composites reinforced with straight continuous polyethylene yarns. This was due to enhanced bonding between the fabric and the cement matrix, which depends mainly on the geometry of individual yarns within the fabric structure [6,8,9]. This paper examines that special fabric geometry and the proper infiltration of matrix between fabric components, which provides mechanical anchoring of the reinforcing yarns.

The pultrusion process is an efficient production method for fabric–cement composites that employs a simple set-up of low cost equipment [12–14]. During pultrusion, continuous reinforcements are impregnated in fresh matrix and then pulled through a set of rotating cylinders that apply pressure, remove excess matrix, and form fabric composite laminates. Recent publications discuss the development of this production method and some preliminary results [12,13].

Several studies have examined the effects of processing on interface characteristics [12–19]. Igarashi et al. [18] found that for a given processing method, materials, and fibers, increasing the processing time of the fresh mixture influences the fiber–matrix bond strength due to changes in the interfacial microstructure. Delvasto et al. [17], Peled and Mobasher [12] and Mobasher et al. [14] found that applying pressure to composites after casting increased the mechanical performance of cement composites. Peled and Shah [19] compared the properties of cast and extruded composites composed of similar matrices and fibers; they found significant effects due to the processing method. But, more information on the effects of processing on interface characteristics is needed to truly

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optimize the design, fabrication and performance of cement composites.

In this paper, pullout tests under different sample preparation conditions were used to determine the interfacial shear bonding. Samples were prepared using three different fiber types, three production methods, and two embedded fabric lengths. Pullout tests examined the bond between the fabric and the cement matrix. A microstructural analysis using a scanning electron microscope (SEM) was conducted on selected samples and correlated with the interfacial bond characteristics.

2. Experimental program

2.1. Fabric types

Three types of fabrics were used for this study: bonded, warp knitted weft insertion, and woven (Fig. 1); Table 1 presents their properties. In woven fabrics the warp and fill (weft) yarns pass over and under each other (Fig. 1a). The woven fabric in this study was made of 5.5 polyvinylalcohol (PVA) yarns per cm in each direction. In weft insertion warp knitted fabric, the yarns in the warp direction are stitched to straight yarns in the weft direction, which are the reinforcing yarns in the composite (Fig. 1b). The knitted fabric in this study was made from multifilament polypropylene (PP) yarns with 8 reinforcing yarns (weft) and 0.8 stitches (warp) per cm. In bonded fabrics, the warp and weft yarns are glued together at junction points (Fig. 1c). The bonded fabric studied here was composed of alkali resistance (AR) glass yarns, 4/cm in each direction, impregnated with a polymeric sizing.

Table 1
Properties of yarn made up the fabrics

Yarn type	Strength (MPa)	Modulus of elasticity (MPa)	Filament size (mm)	Number of filaments in a bundle	Bundle diameter (mm)
AR-glass	1276–2448	78,600	0.0135	400	0.27
PP	500	6900	0.04	100	0.40
PVA	920	36,000	0.025	200	0.93

2.2. Specimen preparation

Samples were prepared by three different methods, casting, pultrusion and vacuum processing, to evaluate the interaction between processing and interfacial bond development. Pultrusion is an impregnation process with a relatively flowable matrix. Normal casting also involves a relatively flowable matrix, but vacuum processing stiffens and de-airs the matrix. This variation in processing allowed a comparison of penetrability of paste and bonding due to paste rheology. In all cases, the matrix was made from cement paste with 67% cement, 6% silica fume and 0.2% superplasticizer (Rheobuild 2000, manufactured by Master Builders Technologies Ltd) with a 0.37 water/cementitious solids ratio by weight.

All processes involved a single layer of fabric being placed between two layers of cement paste within the mold. During casting a “clean” layer of fabric with a width of 10 mm was

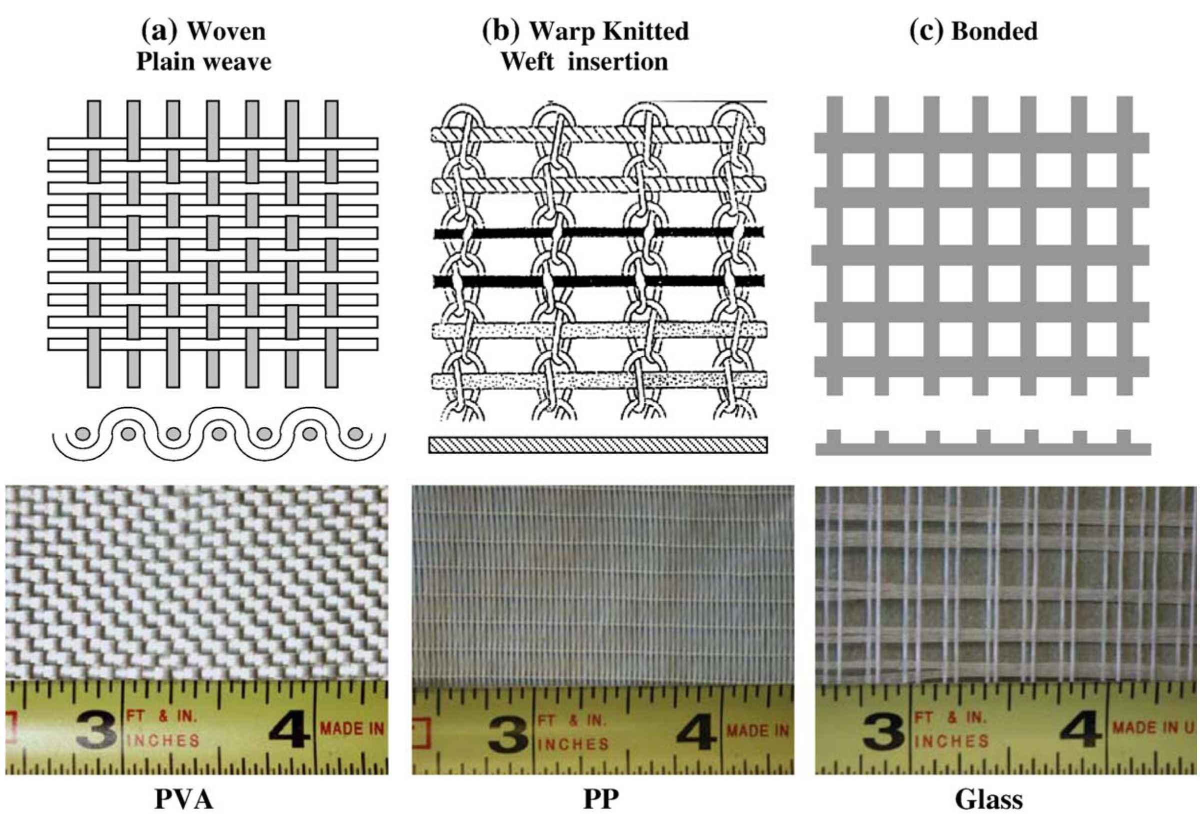

Fig. 1. The geometry of the fabrics: (a) woven PVA, (b) knitted PP, and (c) bonded glass.

embedded in the center of the cement paste matrix along the specimen length. In the pultrusion process similar single fabric layer was first impregnated in a cement paste bath using a set of rotating rollers (Fig. 2); the impregnated fabric was then embedded in the cement matrix. In the vacuum process, after the ingredients of the cement paste were blended in a stationary mixer, the fresh mixture was transferred to a vacuum chamber, and additional mixing was conducted under vacuum for 2 min. A "clean" single layer of fabric was then laid between two layers of the vacuumed paste as in the cast process. The vacuum process was performed for PP and glass fabrics only. A nominal tensile load of approximately 1.7 N was applied to keep the fabric parallel to the longitudinal axis. Tension was released 24 h after specimen preparation.

To study the effect of fabric structure on bond properties, individual PP yarns were also studied in pullout. In this case, individual yarns were extracted from the PP fabric and embedded in the cement paste matrix, using impregnated (pultrusion) and non-impregnated (casting) processes. Note that single yarn experiments were not performed for the vacuum process. Pre-tension was applied as with the fabric. Details of all specimen types, yarns and fabrics, are shown in Table 2.

All specimens were demolded after 1 day and cured in steam for 3 days at 80 °C and 100% RH (Relative Humidity) (these conditions yielded similar properties as did 28 days curing at room temperature [14]). After steam curing, samples were cut to a specified dimension using a water-cooled saw with a diamond edge blade and then stored at room temperature and humidity until testing at 7 days. All specimens (finished products) were 8 mm thick and 25 mm wide, with lengths of 7.6 mm or 12.7 mm. The length of the specimen was the embedded length of the fabric/yarn and the width of the embedded fabric was 10 mm in the cement matrix for all fabrics.

3. Testing

3.1. Pullout tests

Composite bond characteristics were evaluated with pullout tests of both fabrics and yarns. Pullout tests were performed in an

Fig. 2. The pultrusion set up.

Table 2
All specimen types

Reinforcement type	Process	Embedded length (mm)
AR-glass fabric	Cast	12.7
	Pultrusion	12.7
	Vacuum	12.7
PVA fabric	Cast	7.6
	Pultrusion	7.6 and 12.7
PP fabric	Cast	7.6 and 12.7
	Pultrusion	7.6 and 12.7
	Vacuum	7.6
PP single yarn	Cast	7.6
	Pultrusion	7.6
	Vacuum	7.6

Instron testing machine with a capacity of 4800 N at a crosshead rate of 0.25 mm/s. Tests continued until the entire embedded length was pulled out. Fig. 3 presents a schematic description of the test set-up. To compare the pullout behavior of fabrics with different densities, only 8 yarns (bundles) were pulled together out of each embedded fabric, i.e., in some fabrics not all the embedded yarns were pulling out. Note that in all fabrics, the perpendicular yarns were remained in the matrix after pullout process, i.e., only the longitudinal yarns along the pullout direction were extracted from the matrix. Straight PP yarns (not in a fabric form) were also included in the test program for comparison with the knitted PP fabric. Test results reported are average values for at least 6 specimens tested under the same conditions.

The load slip responses were used to calculate the nominal shear bond strength, τ_{nom}, using lower and upper bound estimates of bond strength. The lower bound was calculated using the external bundle surface perimeter and assuming very limited penetration of the cement matrix between the filaments of the bundle. This represents a single reinforcing yarn with a contact perimeter corresponding to the whole bundle contact area. The upper bound was calculated as the bond strength of a single filament, assuming complete penetration of cement matrix between the filaments of the bundle. Neither of these situations is generally valid in the actual composite, as the matrix partially penetrates between filaments. External bond strengths (lower bounds) were calculated to allow comparison of the different systems. By assuming a constant shear strength along the embedded length mainly due to friction, the nominal parameter τ_{nom} was calculated as follows:

$$\tau_{nom} = \frac{P_{max}}{n\pi dl} \quad (1)$$

where P_{max} = maximum pullout load of the bundle, n = number of bundles pulled out, d = equivalent bundle diameter, and l = bundle embedded length. This approach offers an "averaged" single parameter for the strength of the interface. The initial slopes of the pullout load–slip curves were calculated as well as the areas under the curves, referred to here as the toughness. The toughness values provide a measure of total energy consumption during pullout.

To achieve ease of handling as well as uniformity in load application, a 25.4 mm free length of fabric provided a buffer

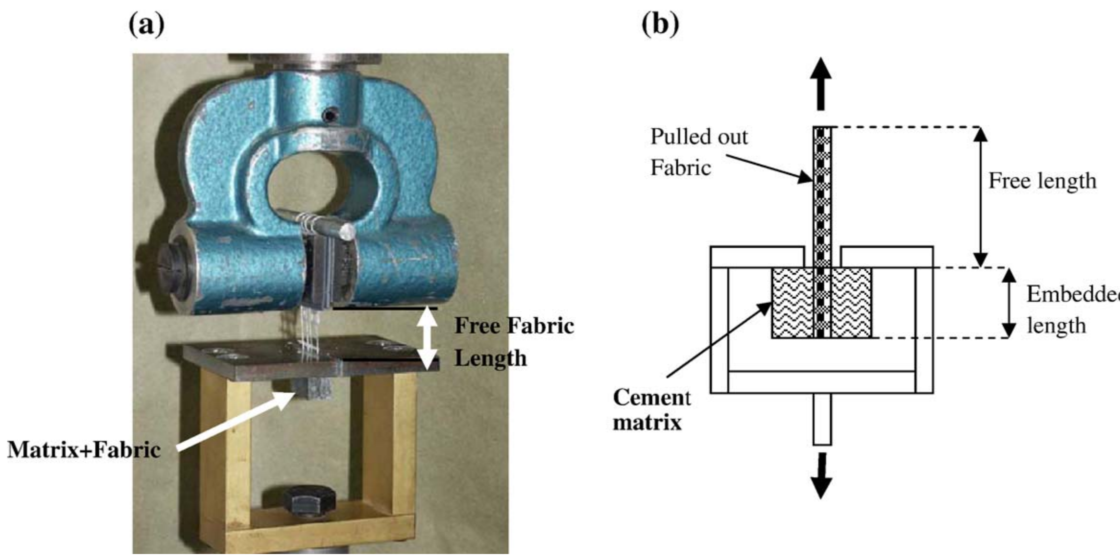

Fig. 3. The pullout set up.

between the pulled yarns and the grips (Fig. 3). The effect of the free fabric length on the bond stiffness was determined using several specimens of different fabric free lengths [20]. First, the slope of the ascending portion of the experimental pullout curve (the stiffness) was calculated for each specimen, refer as K. The compliance K^{-1} for each tested specimen was then plotted versus the free fabric length. Under the assumption of linear behavior, this response was extrapolated to a zero fabric length. The slope value of this trend line was used to calculate the free fabric displacement by multiplying it by the load. The ascending slope stiffness as well as toughness values of the different tested systems, presented in Table 3, were calculated based on this method. Since a constant free fabric length was used in the present discussion, the raw pullout curves, which include the fabric free length, are used in the comparative analysis of the different processing methods.

3.2. Microstructure characteristics

Composite microstructures were characterized using SEM; the microstructures were then correlated with mechanical properties. Prior to and after pullout tests, side sections of different specimens were obtained, dried at 80 °C, and gold-coated. Polished cross sections of the bundles in the cement matrix were also prepared and observed under SEM with similar condition. Microstructural features such as matrix penetration between the opening of the fabrics (between the yarns), between the filaments of the bundle, and between the stitches of the knitted fabric were evaluated for impregnated (pultruded), cast and vacuumed fabrics. Atomic elements near the filament–cement interface were also analyzed by X-ray under SEM. This analysis was carried out at the filament–cement interface near the bundle perimeter as well as at the inner area of the bundle, for fabric and individual yarns.

4. Results

4.1. Pullout behavior and bonding due to processing

Table 3 presents the average bond strengths, $\tau_{nom,}$ of the different fabrics and processing methods calculated from the pullout results. Among specimens prepared by the cast process, the glass fabrics exhibit the highest pullout loads and bond strengths. Average bond strengths (τ_{nom}) with

Table 3
Pullout results of the different systems (embedded length of PP and glass fabrics is 12.7 mm)

	Process	Ascending slope (stiffness) (N/mm)	Maximum load (N)	Toughness (N mm)	Bond strength, $\tau_{nom,}$ (MPa)
PVA fabric	Cast	47.94 (8.68)	145.92 (37.90)	477.52 (77.76)	1.54 (0.35)
	Pultruded	46.19 (8.83)	272.74 (15.51)	1539.98 (349.56)	3.20 (0.26)
AR-glass fabric	Cast	246.51 (58.33)	183.59 (18.02)	589.86 (227.43)	2.28 (0.16)
	Pultruded	218.45 (41.92)	145.50 (44.58)	368.78 (128.85)	1.76 (0.56)
	Vacuum	329.51 (47.24)	259.25 (31.31)	908.08 (167.13)	2.94 (0.33)
PP fabric	Cast	80.86 (38.73)	117.73 (49.87)	411.85 (236.14)	1.55 (0.62)
	Pultruded	93.54 (20.63)	239.34 (70.09)	1042.29 (410.45)	2.91 (0.67)
	Vacuum	111.76 (14.01)	125.15 (24.90)	425.23 (178.11)	1.67 (0.38)
PP single yarn	Cast	15.52 (3.48)	24.66 (15.29)	124.06 (92.73)	2.52 (1.53)
	Pultruded	18.80 (2.52)	27.44 (9.80)	136.33 (43.04)	2.85 (1.29)
	Vacuum	16.78 (3.31)	39.76 (10.96)	198.57 (42.34)	4.07 (1.09)

The numbers in brackets are the standard deviation values.

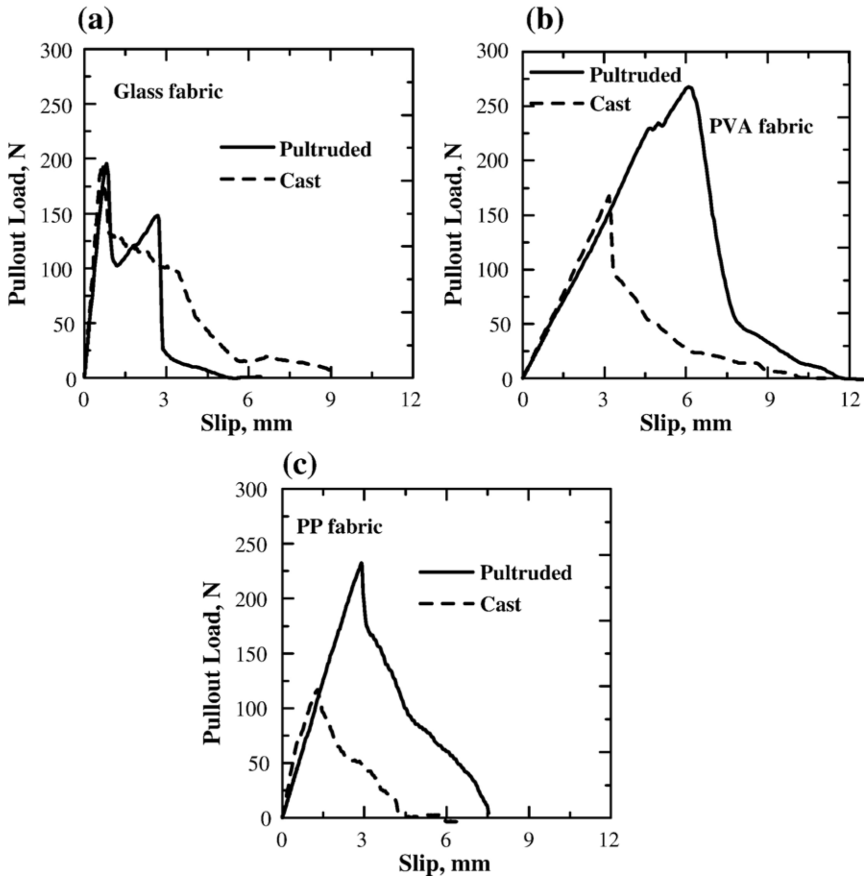

Fig. 4. Comparison of the pullout behavior of pultruded and cast systems: (a) glass fabric, (b) PVA fabric, and (c) PP fabric (7.6 mm embedded length).

values of 2.28 MPa, 1.54 MPa and 1.55 MPa were obtained for the glass, PVA and PP fabrics, respectively (Table 3). On the other hand, the highest bond strength for pultruded specimens is obtained with PVA, which has external bond values as high as 3.20 MPa. Pultruded specimens with PP and glass fabric have bond strengths of 2.91 MPa and 1.76 MPa, respectively.

The glass fabric systems also exhibit the highest initial bond stiffness regardless of processing method (Table 3). This may be due to the high modulus of elasticity of the glass fabric (Table 1). When processing methods are compared, the vacuum specimens exhibit the highest stiffness for both glass and PP fabric systems, due to the matrix characteristics, as the vacuuming reduced porosity and increased the stiffness of the hardened cement paste.

The toughness, or area under the load–slip curve, is similar for all fabrics for the cast process (Table 3). In pultruded specimens, however, the PP and PVA fabrics exhibit much higher toughness values, 1042 N mm and 1539 N mm respectively, than the glass fabric (369 N mm). This increased toughness implies improved energy absorption for the PP and PVA pultruded systems, leading to tougher behavior of cement composites made with these fabrics. Also, the pultrusion process significantly increases the pullout toughness for PVA and PP fabrics as compared to casting, increasing up to 1000 N m for PP and even higher for PVA (Table 3).

Fig. 4 compares the pullout behavior of the three fabrics in cast and pultruded (impregnated and non-impregnated) systems. Neither casting nor pultrusion appear to exert no significant influence on pullout resistance of glass composites (Fig. 4a). PVA and PP systems, on the other hand, exhibit improved properties when pultruded rather than cast (Fig. 4b and c), including bond strengths about twice that of non-impregnated cast fabric (Fig. 5a). Table 3 reveals only a marginal difference in bond strengths of pultruded and cast single PP yarn; the pultruded bond strength is about 10% higher (Fig. 5a). This suggests that the pultrusion process is beneficial mainly when fabrics are used.

In cast systems, a single PP yarn clearly develops a much stronger bond (2.52 MPa) with the cement matrix than does fabric made from same PP yarn (1.55 MPa) (Table 3). This suggests that the fabric is unable to properly bond with the cement matrix when the fabric is not impregnated prior to casting. Under a pultrusion system, PP fabric has slightly improved bonding compared with the single yarn (2.91 MPa vs. 2.85 MPa, respectively, Table 3). This suggests again that pultrusion is beneficial for fabric reinforcement, as it significantly affects the bond between the fabric and the cement matrix.

Fig. 5b compares the relative bond values of the two sets of the cast specimens, with and without vacuum. About a 30% improvement in bond strength is observed for the glass fabric system after exposure to vacuum. The glass vacuum specimen

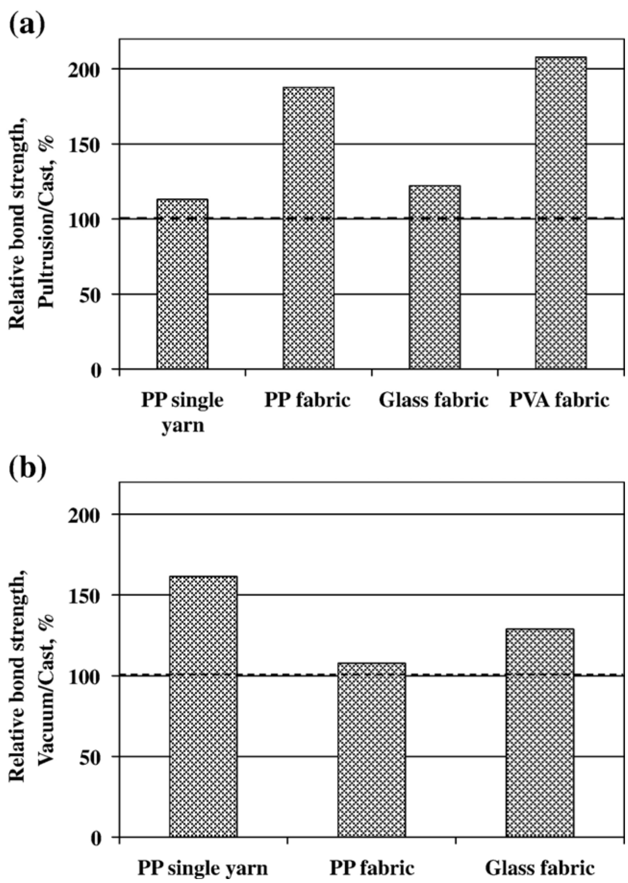

Fig. 5. Relative bond strength of (a) pultruded vs. cast and (b) vacuum vs. cast for the different systems.

exhibits also stronger bond strengths than that of the pultruded specimen (Table 3). Similar pullout resistance and bond strength values for PP fabric are observed for cast and vacuum specimens. The bond value of the PP fabric vacuum system, only 1.67 MPa, is significantly lower than that of the pultruded PP fabric system, 2.91 MPa (Table 3). This suggests that the vacuum procedure does not induce bonding of PP fabrics. The situation is different when comparing the single yarn PP systems; here as much as 50% improvement in bond strength values is seen (Fig. 5b). Moreover, the vacuum procedure provides stronger bond values with the single PP yarn than the pultruded yarn (Table 3).

The above trends may be attributed to the differences in the fabric–matrix interface developed and are discussed later (Section 4.3).

4.2. Fabric embedded length

The influence of the pultrusion process on bonding of PP and PVA fabrics is evident when examining the bond values as a function of embedded length. These, along with those for the cast process, are shown in Fig. 6. The PP system made with the cast procedure exhibits no significant difference in bond strength when the fabric embedded length increases from 7.62 to 12.7 mm (Fig. 6a). PP systems prepared with the pultrusion process, however, had a 40% greater bond strength for the shorter embedded length samples (Fig. 6b). The bond strength of PVA fabric also decreased as the embedded length increased (Fig. 6c). Only a few samples could be fully pulled out without fabric breakage.

Bond strength values, τ_{nom}, were calculated based on the maximum pullout load recorded during testing (Eq. (1)). Such calculations assume constant shear stresses, governed mainly by friction, along the fabric–cement interface. Results suggest that such assumptions are adequate for the cast process since no significant difference in bond strength values was observed for the short and long embedded lengths (Fig. 6a). This assumption might not be accurate for pultrusion process specimens, however, as the bond strength values were dependent on the fabric embedded length (Fig. 6b and c). This implies that shear stresses are not constant along the fabric–cement interface when the pultrusion process is used.

4.3. Microstructure characteristics

Fig. 7 presents AR-glass and PP fabric surfaces embedded in cement matrix by the pultrusion process. The nature and structure of these fabrics are completely different. The AR-glass fabric is coated with a polymeric sizing that leaves no spaces between the filaments for cement paste penetration (Fig. 7a and b). Moreover, the junction points are bonded, leaving no freedom of sliding between the two sets of yarns. Fig. 7c illustrates the bond at the junction point of an AR-glass fabric after the longitudinal yarn has pulled out and reveals severe damage at this zone. In addition, exposed filaments of the bundle show the absence of hydration product penetration. On the other hand, PP is a knit type fabric made of open filaments that allow hydration products to penetrate (Fig. 7d). The junction points are gently held by stitches that potentially allow sliding of the two sets of yarns. Note that PVA is a woven type fabric also made from open bundles with flexible junctions similar to PP. Fig. 7a and d also compares the open structure of the glass fabric with the much denser PP fabric. These differences in fabric nature, geometry, and openness as observed in Figs. 1 and 7, lead to the observed differences in bond properties (Table 3).

Fig. 8 presents SEM micrographs of PP fabrics embedded in the cement matrix through the three processing methods. The pultruded fabric exhibits good penetration of the cement matrix between the reinforcing filaments of the bundle (Fig. 8a). Hydration products are well dispersed between the stitches of the pultruded composite. The matrix fills the spaces between the filaments of the stitches as well as between the loops (Fig. 8b). Note that the stitches are perpendicular to the loading direction; adequate filling improves anchoring of the fabric and improves bond strength. The cast and vacuum composites have much poorer penetration that leaves empty spaces between the filaments of the bundle as well as within the loops (Fig. 8c–f). Similar to PP, the open filaments of PVA fabric allow the hydration products to penetrate between the yarns, only when pultrusion is used. These observations correlate with the improved bond strengths calculated for PP and PVA pultruded fabric systems and the relatively low

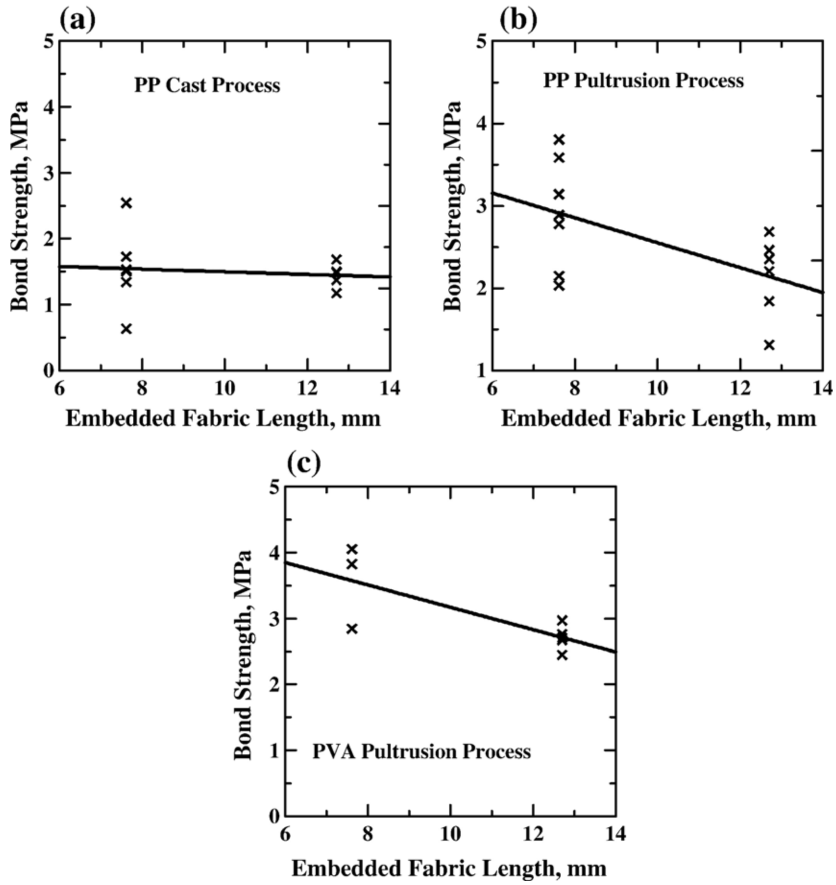

Fig. 6. Bond strength vs. embedded fabric length for various fabrics and processing: (a) PP cast, (b) PP pultrusion, and (c) PVA pultrusion.

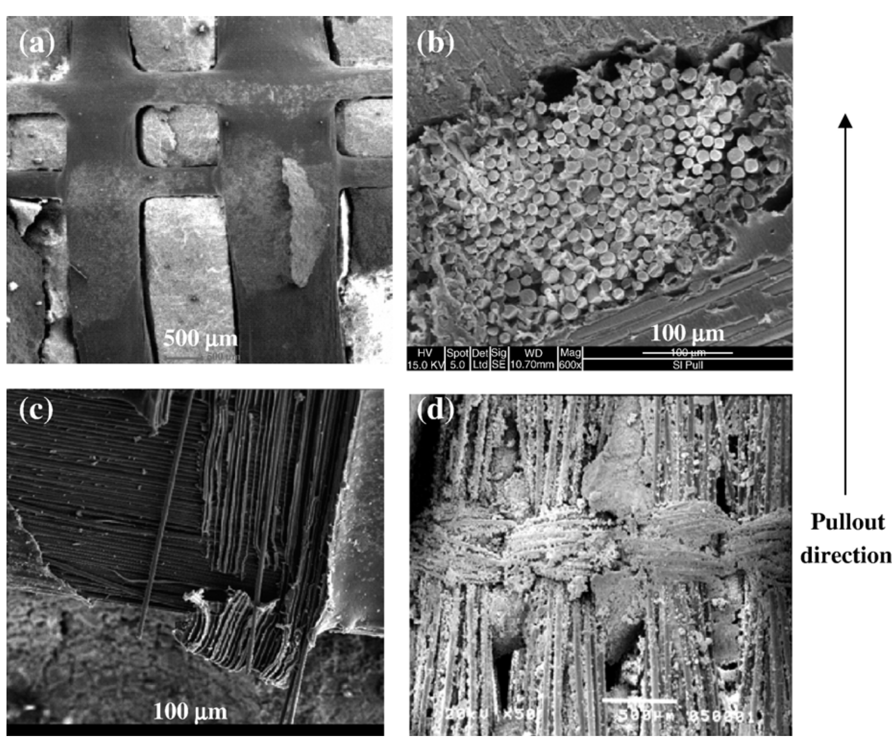

Fig. 7. SEM micrographs of the (a) side view of glass fabric, (b) cross section of glass fabric, embedded in cement before pullout, (c) side view of glass fabric after pullout, and (d) side view, PP fabric embedded in cement before pullout.

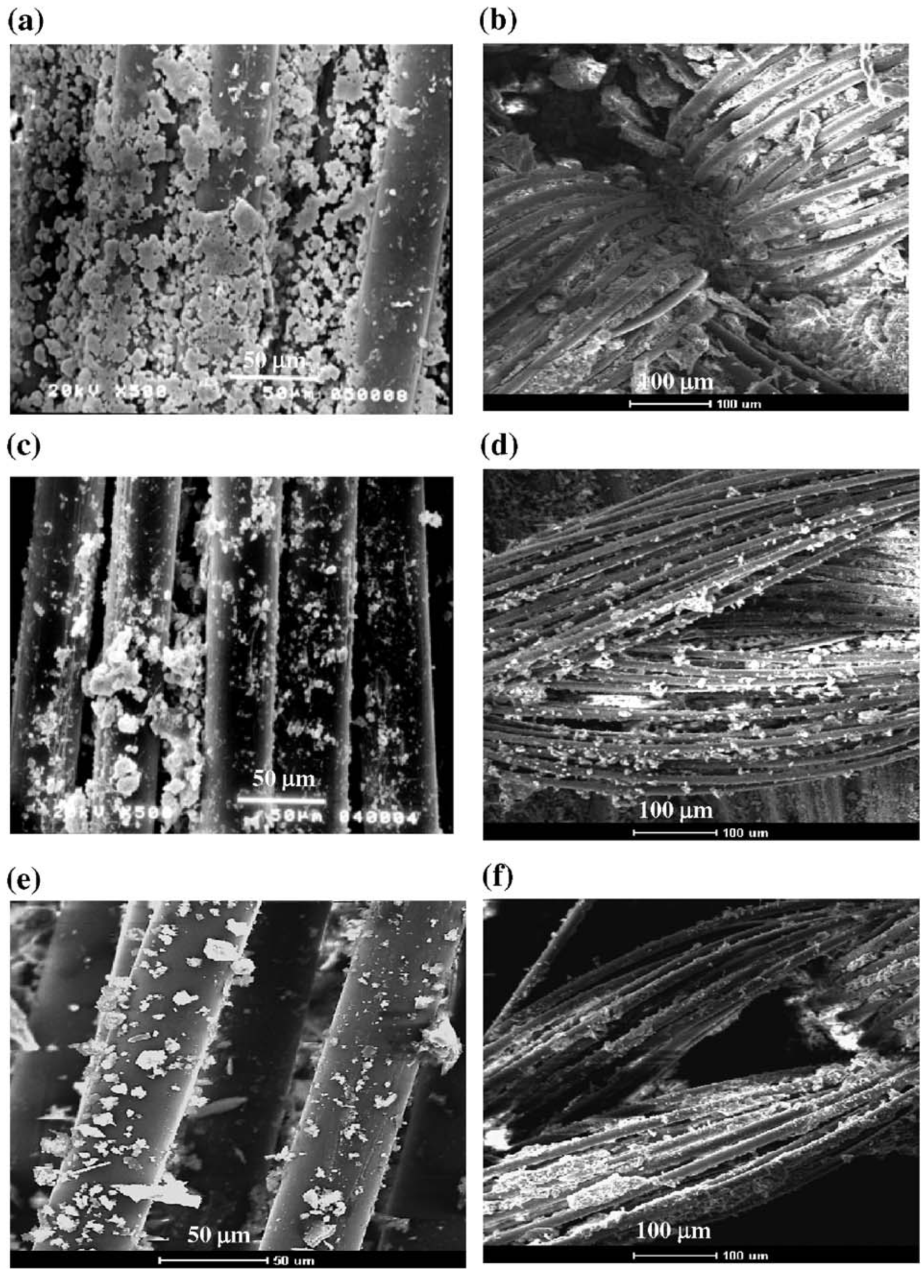

Fig. 8. SEM micrographs of the PP fabric prepared by different methods (a and b) pultrusion (c and d) cast, and (e and f) vacuum.

bonding of PVA and PP cast and vacuum fabric systems (Figs. 4 and 5).

Fig. 9 presents for the cast and pultrusion methods, the cross sections of the PP bundle as part of a fabric or as a single yarn embedded in the cement matrix. The atomic elements at different locations of the embedded bundle (the white arrows in the SEM micrographs) are also shown. The figure clearly shows much poorer penetration of the cement matrix between the filaments of the bundle in the cast composite (Fig. 9a) as compared to the pultruded bundle (Fig. 9b). Good matrix penetration is also observed with the single cast PP yarn (not in a fabric form, Fig. 9c). These observations explain the improved bonding of the pultruded PP system over the PP cast system, as well as clarify the similarity in bond strength values of the PP single yarn, pultruded and cast, and the pultruded PP fabric: 2.85 MPa, 2.52 MPa, and 2.91 MPa, respectively (Table 3).

The absence of atomic elements of the cement matrix between the filaments of the cast PP fabric bundle at its core region is obvious in Fig. 9d. Similar observations were also recorded for the pultruded fabric and cast single yarn systems at the black areas of the SEM micrographs. Cement matrix elements, such as Ca and Si, are observed in the open area between the filaments of the pultruded bundle system (Fig 9e). Similar observations also occurred at the bundle perimeter area of cast specimens, where paste penetration between filaments is relatively easy. The filaments closer to the bundle core represent a tighter, denser packing, and thus a different situation. A higher Ca/Si content is observed in this zone (Fig. 9f), suggesting

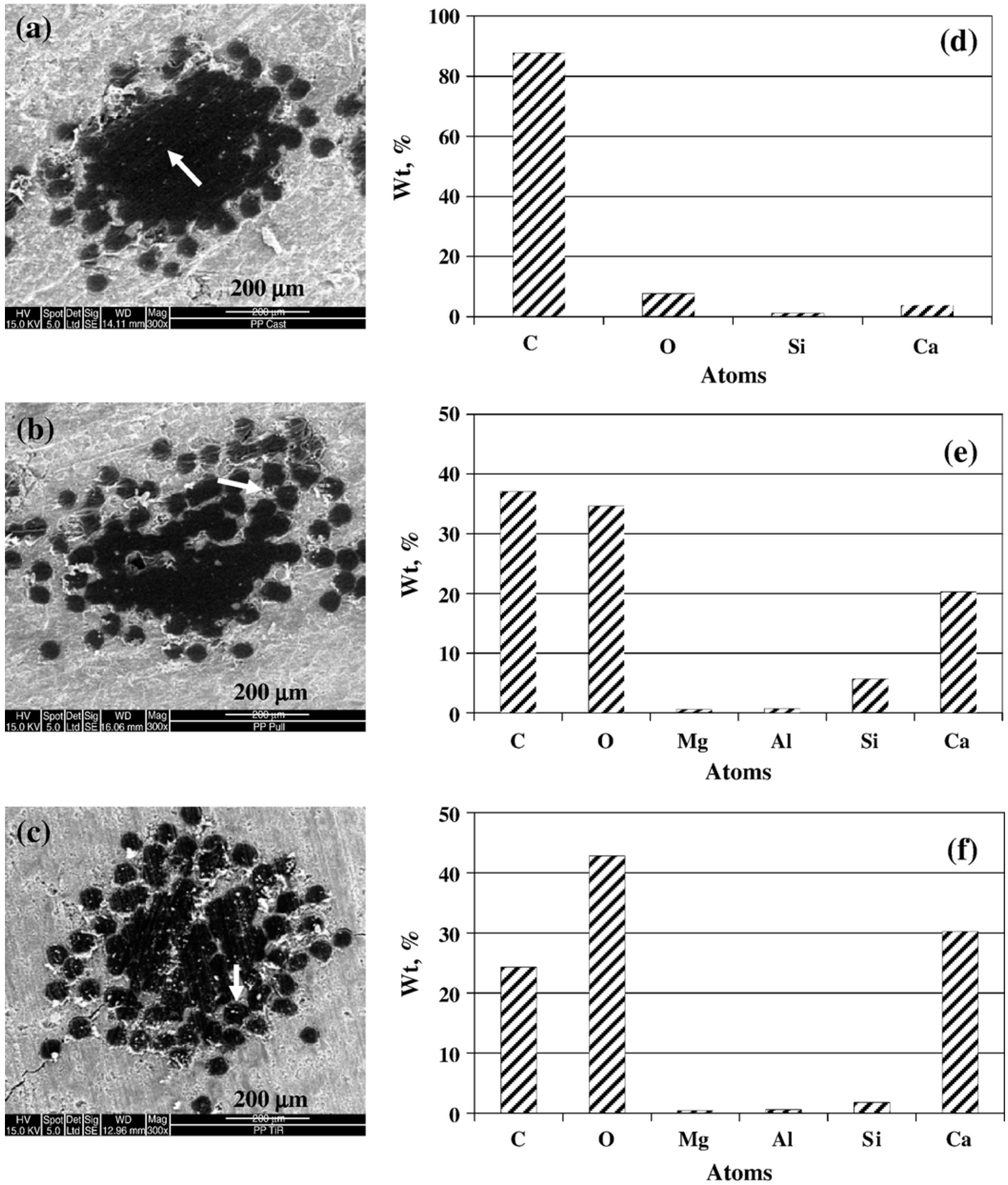

Fig. 9. Cross sections of the PP bundle in the matrix prepared by: (a) cast with fabric, (b) pultrusion with fabric, and (c) cast with single bundle (not in a fabric form), and (d, e, f) atomic elements at different areas of the embedded bundle (white arrows at the SEM micrographs).

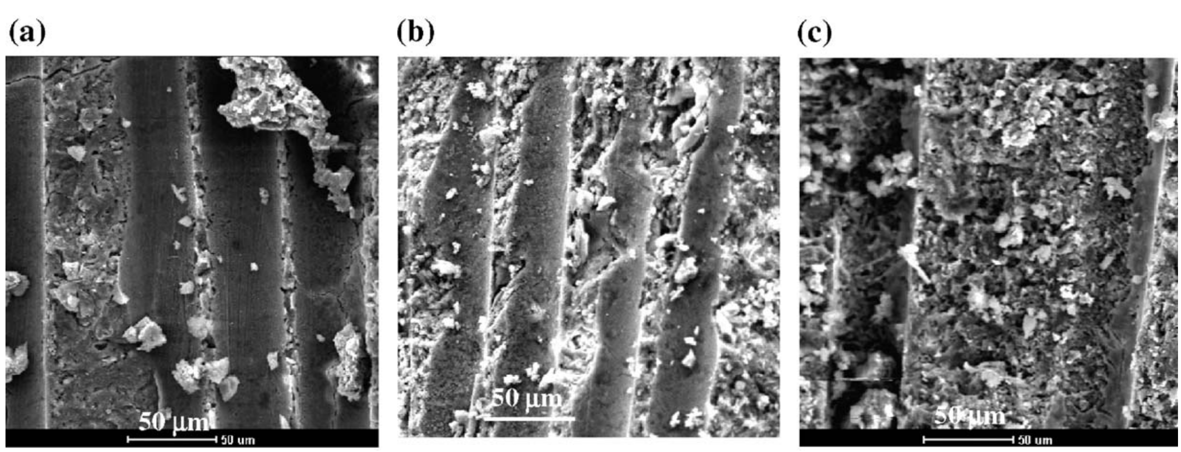

Fig. 10. SEM micrographs of the groove of the PP fabric after pullout prepared by (a) vacuum, (b) cast and (c) pultrusion.

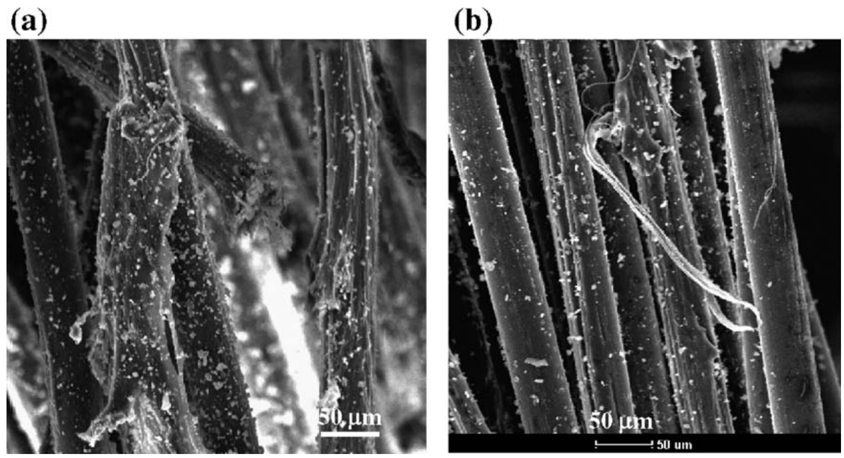

Fig. 11. SEM micrographs of bundle after pullout of: (a) pultruded, (b) cast.

precipitation of $Ca(OH)_2$ within the bundle at the expense of CSH. Such areas are frequently observed in the single PP cast yarn and pultruded fabric (Fig. 9c–b).

Fig. 10 presents the grooves of the PP filaments in the cement matrix of the pulled out fabrics for cast, pultruded and vacuum systems. As expected, dense matrix with low porosity is observed for the vacuum system (Fig. 10a), while the cast and pultruded systems have a more porous matrix (Fig. 10b–c). The cast system exhibits a relatively smooth surface of the filament groove (Fig. 10b), while the pultruded composite has a rough and damaged matrix at the filament–matrix interface (Fig. 10c). This suggests stronger bonding forces in the pultrusion than the cast system during the pullout process. Similar characteristics were observed with the PVA fabric. The vacuum system exhibits clear and smooth grooves of the filaments in the matrix (Fig. 10a), where a relatively strong and dense matrix at the filament–matrix interface may sustain greater forces. The relatively high forces developed during the pullout of the pultruded PP bundle can also damage the surface of its fibrils, as observed in Fig. 11a. Fig. 11b indicates less damage of the bundle fibrils with the cast system, suggesting lower interfacial forces and reduced bonding.

5. Discussion

This work studied the effects of bonding between fabrics and cement matrix by addressing four main areas: pultrusion vs. cast, vacuum vs. cast, fabric vs. its yarn, and embedded lengths. Results clearly show that pultrusion improved the bond strengths of the PP and PVA fabrics with the cement matrix as compared with casting, but the bond strengths of the pultruded and cast glass fabric systems were not significantly different (Figs. 4 and 5). These differences can be explained by SEM observations (Figs. 7–11). For the PP knit fabric, bulky stitches (Fig. 7d) that strongly hold the filaments in the bundle prevent open spaces between the filaments. Therefore, casting results in poor matrix penetration between the filaments (Figs. 8c,d and 9a), thus preventing their reinforcement potential. Impregnation of the matrix during pultrusion helps fill the spaces between the filaments of the bundled yarns (Figs. 8a and 9b) as well as the loops of the stitches (Fig. 8b) of the bundled knit fabric, leading to improved bonding (Fig. 4c). In addition, the surface condition of both the grooves at the matrix and the bundle surface after pullout (Figs. 10c and 11a) are evidence of intensive friction forces at the interface during pullout of the pultruded specimens. PVA fabrics exhibited similar behavior; the impregnation process (pultrusion) allows paste penetration between filaments as well as at junction points. The bundled yarns of the glass fabric were coated with sizing such that impregnation process (pultrusion) does not increase paste penetration between the filaments (Fig. 7a and b). Thus, pultrusion has no advantage over casting for glass fabric (Fig. 4a).

The above discussion also explains why single PP yarn and PP knit fabric exhibited different bond strengths when casted but similar ones when pultruded (Table 3). When the yarn is not in a fabric, the filaments are not strongly held by the stitches, and spaces between filaments are more easily filled (Fig. 9c). Thus, the bond developed during casting is greater with a stand-alone PP bundle yarn than one in a fabric form. With a single bundle an impregnation process to fill up the bundle filaments is unnecessary, and therefore the pultrusion process does not affect the bonding properties of individual single yarns (Table 3).

The vacuum procedure applied to the cement paste leads to a denser (Fig. 10a) and stiffer matrix. This benefits the fabric–matrix interfacial zone, but reduce paste penetration (Fig. 8e and f) between the bundle filaments and decreases the bond strength of the PP fabric (Fig. 5b), thus reducing the overall advantages of such systems. When a single yarn is used, however, the bundle is opened and the penetration of a strong, stiff matrix between the filaments can improve the bond (Table 3, Fig. 5b). The glass fabric (with coated yarns) has limited potential for cement paste penetration between the yarns, and the bond is mainly developed between the bundle perimeter and the cement matrix. As such, a stiffer and stronger matrix can lead to improved bond strength (Fig. 5b).

Results obtained with different embedded lengths (Fig. 6a and b) suggest that the nature of shear stresses developed at the yarn–matrix interface are not the same for pultruded and cast systems. Bond strength values in pultruded fabric systems were dependent on the fabric embedded length, suggesting that shear stresses are not constant along the fabric–cement interface. However, in cast systems no significant difference in bond strength values was observed for the short and long embedded lengths, suggesting constant shear stresses governed mainly by friction along the fabric–cement interface.

From the above discussion it can be concluded that the pultrusion process is highly valuable for improving the bonding characteristics of a multifilament structure, as the intensity of the process impregnates interstitial filament spaces. The composite action between the matrix and individual fine filaments is activated, leading to a higher efficiency of fibers when compared to other systems.

6. Conclusions

1. The results of this study indicate that the production processes for fabric–cement composites should be coordinated with the fabric structure and its yarn to optimize bond efficiency.
2. When using multifilament bundles connected in a weft insertion warp knitted fabric or woven fabric as studied here, an intensive processing technique is needed to open up the spaces between the filaments for impregnation. The pultrusion process is effective in doing so, resulting in a stronger bond and better utilization of the filaments to maximize their efficiency.
3. For fabrics composed of bundles of coated yarns, the pultrusion process offers no advantage from a mechanical point of view because no fiber interstitial spaces are available for impregnation. Thus, casting and pultrusion result in similar pullout behavior.
4. For a single multifilament bundle in which the filaments are kept open with no tightening effect induced by the fabric structure, the pultrusion process offers no advantage in filling the bundle filaments, as these filaments can be efficiently filled without intensive processing.
5. Vacuum procedure leads to a denser and stiffer matrix and therefore benefits the fabric–matrix interfacial zone improving the bond with single or coated bundle. Penetration of such stiff matrix between bundle filaments of a fabric, however, is reduced, decreasing the overall advantages of such systems with fabric reinforcement.

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