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Influences of textile characteristics on the tensile properties of warp knitted cement based composites

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Abstract

This study explored the influences, of different textile characteristics of warp knitted fabrics made from multifilament yarns, on the tensile properties of textile reinforced cement elements and on the bonding quality between the fabrics and the cement matrix. Several parameters such as loop size, bundle size (number of filaments), and fiber type (high density polyethylene, polypropylene, AR-glass and aramid) were examined. In addition, the influence of a hybrid fabric made from polypropylene and aramid was examined and compared to single fabrics made of aramid and polypropylene separately. All the composite elements were produced by the pultrusion technique. It was found that fabric made of combination of a small bundle diameter and a large loop size exhibited the greatest efficiency factor and developed the best bond strengths with the cement matrix, based on improved cement penetrability between the filaments of the bundle. The hybrid composite system showed better mechanical properties and a higher efficiency factor compared to the non-hybrid systems.

Keywords: Cement composites; Textile; Multifilament yarn; Tensile behavior; Knitted fabric

1. Introduction

Recently, there has been increased interest in the use of textile fabrics as reinforcements for cement based composite materials, defined as textile reinforced cement (TRC) [1–6]. Reinforcement by textiles improves the tensile and flexural performances of the cement composite. Several researchers reported that fabrics could significantly improve the mechanical behavior of cement composites. In addition to the improved strength, these fabric reinforced cement composites exhibited strain-hardening behavior even when the reinforcing yarns had low modulus of elasticity. This was explained by the enhancement in bonding due to the mechanical anchoring provided by the non-linear geometry of the individual yarns within the fabric as induced by fabric structure [7–9].

Textile fabric reinforcements can be in knitted, woven, non-woven, glued, or plaited structures, which differ by the manufacturing process and several other parameters such as yarn density, the fineness and the number of filaments in the bundle that construct the fabric. These characteristics can influence the stability and the mechanical properties of the whole fabric, ultimately affecting the penetrability of the particulate cement matrix. For example, fabric comprising multifilament yarns (bundles) reduces the potential penetrability of the cement particles between the bundle spaces since the junction points of the fabric induce tightening effects that hold the bundle filaments firmly in place and prevent them from opening [9,12]. Therefore, matrix penetrability into the fabric, especially between the filaments, depends heavily on the nature of the fabric junctions and the resultant tightening effects,

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the structure of the fabric, the number of filaments in the bundle, and the production process of the composite.

The process of preparing cement composites with textile fabrics must ensure good penetrability of the cement particles between the spaces within both the fabric and the bundle filaments that compose the fabric. Pultrusion, a composite production technique that promotes high cement matrix penetrability, generates composite elements with mechanical properties superior to those achieved with ordinary casting [4,10].

In this paper, weft insertion warp knitted fabrics made from multifilament yarns and applied as reinforcements for cement composites are studied. Parameters related to these fabrics, such as loop size/stitch density, bundle size (number of filaments in a single yarn), and fiber types [AR-glass, aramid, high density polyethylene (HDPE) and polypropylene (PP)] are investigated for their corresponding influences on the tensile performances and reinforcement efficiencies of cement based composites. A correlation between the mechanical performances of the fabrics themselves (not in a matrix) and the fabric–cement composites is examined. The mechanical properties of the composites are also correlated with microstructure characteristics. All composites in this study were prepared by the pultrusion process, and their bond strengths and adherence values were evaluated using the ACK model [11].

2. Experimental program

2.1. Fabrics and yarns

The weft insertion warp knitted fabrics studied in this research were designed and produced specifically for this work (Fig. 1). Straight yarns in the warp direction (lengthwise) were inserted into stitches (loops) and assembled together with straight yarns in the weft direction (crosswise). The stitches were tightly connected with the two sets of perpendicular yarns, which were very difficult to separate, thereby producing a single, strong unit of fabric. All yarns, warp and weft, were in a multifilament, non-twisted form. The stitches in all the fabrics were arranged at a density of 2.5 stitches per cm and were made from 16.7 tex PP, tex being a measurement of yarn or bundle weight per length ratio, in grams per 1000 m of yarn. The weft yarns were inserted into every second loop (stitch), giving the fabric a "one loop in one loop out" structure, so that between every two weft yarns was an empty loop. This design gave a relatively open net structure that enhanced cement penetrability (Fig. 1b). The weft yarns in all the fabrics were composed from aramid with 167 tex fibers. Oriented in the warp direction, the reinforcing yarns comprised different raw materials: HDPE, aramid, AR-glass and PP.

Four different HDPE fabrics having different loop sizes and bundle sizes (tex values) were prepared and studied: (i) fabric made from 140 tex HDPE yarns (the reinforcing yarns) with 2 mm loops (stitches); (ii) similar to (i), but with loops of 4 mm; (iii) fabric made from 90 tex HDPE yarns and 2 mm loops; and (iv) 90 tex HDPE fabric with 4 mm loops. Higher tex values and bundle diameters translate into a larger number of filaments per bundle (Table 1). The different loop sizes produced fabrics of varying spacing, 4 and 8 mm for 2 and 4 mm loops, respectively, between the weft and the warp yarns. Alternating the spacing between the yarns can influence cement penetrability between the bundle filaments and the fabric openings, thereby providing mechanical anchoring of the fabric within the cement matrix.

Hybrid fabric, comprising both aramid and PP yarns and employing 2 mm loops, was also prepared. The general concept of the hybrid fabric was to combine ductile, low cost yarns with more expensive, stiff yarns. The hybrid fabric in this study was constructed from an equal number of PP and aramid yarns, arranged in an alternating fashion. However, the PP yarn had a larger bundle diameter than did the aramid yarn (Table 1), and therefore, it accounted

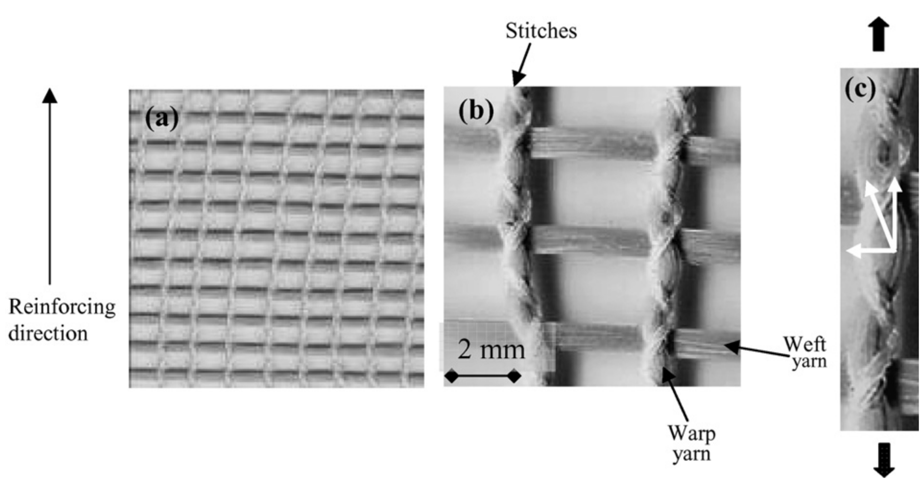

Fig. 1. Warp knitted weft insertion fabric (made from aramid): (a) general view; (b) enlarged view of fabric; (c) components of tensile force in warp yarn.

Table 1
Properties and geometries of the different fabrics and yarns that made up the fabrics in the reinforcing direction

Fabric #	Yarn type	Fabric loop length (mm)	Yarn tex (gr/km)	Yarn diameter[b] (mm)	Filament diameter (mm)	Number of filaments per yarn	Fabric tensile strength (MPa)	Yarn modulus of elasticity (GPa)
1	Aramid	2	167	0.38	0.012	1106	2367 (114)[a]	55
2	AR-glass	2	168	0.28	0.010	815	1591 (153)[a]	78
3	HDPE	2	140	0.43	0.024	310	1388 (121)[a]	45
4	(dyneema)	4					1460 (96)[a]	
5	HDPE	2	90	0.34	0.024	200	1349 (200)[a]	45
6	(dyneema)	4					1631 (186)[a]	
7	PP	2	334	0.69	0.039	315	223 (12)[a]	7
8	Hybrid–	2	167	0.38	0.012	1106	2367 (114)[a]	55
	aramid PP		168	0.48	0.039	315	223(12)[a]	7

[a] Numbers in parentheses are the standard deviations.
[b] Bundle diameter was calculated based on tex number.

Table 2
Composite tensile strengths, efficiency factors, and bond strengths for several strain levels

Fabric – specimen #	Yarn type	V_f(%)	Bond strength (MPa)	At 1% strain		At 2% strain		At max stress	
				Efficiency factor	$\sigma_{1\%}$ (MPa)	Efficiency factor	$\sigma_{2\%}$ (MPa)	Efficiency factor	σ_{max} (MPa)
1	Aramid	1.9	5.29	0.19	8.35 (0.53)[a]	0.31	13.87 (1.35)[a]	0.58	26.2 (8.83)[a]
2	AR-glass	1.1	5.13	0.74	13.03 (1.17)[a]	–	–	1.04	18.11 (0.93)[a]
3	HDPE	2.7	4.54	0.17	6.43 (0.38)[a]	0.31	11.49 (1.28)[a]	0.77	28.75 (2.82)[a]
4	HDPE	1.5	8.83	0.36	7.88 (0.88)[a]	0.50	10.92 (1.14)[a]	1.60	35.11 (3.62)[a]
5	HDPE	1.6	5.69	0.26	5.55 (0.52)[a]	0.44	9.59 (0.87)[a]	1.14	24.61 (1.54)[a]
6	HDPE	0.9	13.66	0.50	7.33 (1.07)[a]	0.63	9.31 (1.58)[a]	1.42	20.81 (3.88)[a]
7	PP	6.2	2.34	0.27	3.66 (0.64)[a]	0.33	4.60 (0.83)[a]	0.67	9.25 (0.72)[a]
8	Hybrid– aramid PP	1.0 1.6	3.24	0.37	10.16 (1.95)[a]	0.56	15.38 (2.22)[a]	0.94	25.75 (4.98)[a]

[a] Numbers in parentheses are the standard deviations.

for a correspondingly greater volume within the hybrid composite (Table 2, specimen 8).

2.2. Composite preparation

All composites in this study were prepared by the pultrusion process (Fig. 2), in which the fabric passed through a slurry infiltration chamber (cement paste), and was then pulled through a set of rollers that squeeze the paste between the fabric openings and into the filaments of the bundle while simultaneously removing excess paste from the fabric. The fabric–cement composite laminate sheets are then formed on a plate-shaped mandrel, resulting in samples 200 mm wide × 300 mm long × 8 mm thick. Each specimen comprised three layers of fabric. The matrix in all cases was cement paste made with a 0.4 water/cement ratio.

After forming the samples, a constant pressure of 50 N was applied to the fabric cement laminate to improve matrix penetration between bundle and fabric openings. The pressure was maintained for up to 24 h, after which each of the laminated sheets was cut into 250 mm × 34 mm sections and then cured at 100% relative humidity (RH) at room temperature for 25 days. At the end of the curing period, the specimens were kept at room temperature for another three days until tested in tension.

2.3. Tensile tests

2.3.1. Fabrics

Tensile properties of the different fabrics were studied with a closed loop control direct tensile testing machine with a 10 kN capacity. The rate of cross-head displacement

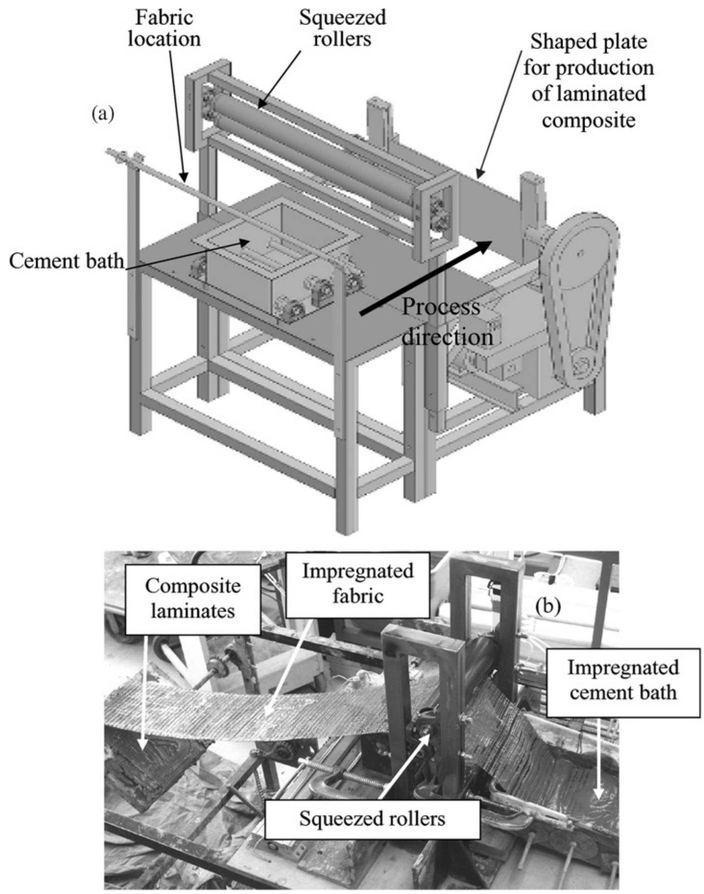

Fig. 2. (a) Schematic description, and (b) a picture of the pultrusion process, in which fabric passes through the cement bath, through the rollers, and onto the shaped plate.

was set at 10 mm/min. The tested fabrics were cut along each warp yarn to produce strips of fabric, each comprising a single warp yarn lined with the evenly spaced junctions of the weft yarns held in place by the stitches [6]. Tensile strengths and modulus of elasticity were calculated for all fabrics.

2.3.2. Composites

The mechanical performances of the pultruded composite laminates were studied using closed loop control direct tensile tests performed on a 10 kN capacity testing machine. The rate of cross-head displacement was set at 0.5 mm/min. Metal plates were glued onto the gripping edges of the specimens to minimize localized damage and to provide better load transfer from the grips to the specimens. At least six replicate samples were tested from each fabric and yarn category; the reported results reflect the average and standard deviation values. Typical stress–strain curves representing the tensile behavior of individual composites were compared. All tests were ended at failure or at the maximum strain of 8%, whichever occurred first. Posts cracking tensile stresses were calculated for all systems at three different levels, including maximum stress ($\sigma_{\max}$), 2% strain ($\sigma_{2\%}$), and 1% strain ($\sigma_{1\%}$). To compare the different fabric systems with the various yarn properties and volume contents, composite reinforcing efficiency factors were calculated. The efficiency factor was defined as the ratio between the post cracking tensile strength of the composite and the yarn volume in the composite multiplied by its tensile strength.

$$\text{Efficiency factor} = \frac{\sigma_c}{V_f \cdot \sigma_f} \tag{1}$$

where σ_c, σ_f-the composite and fabric strengths, respectively, V_f-fiber volume fraction.

The bond strength between the fabric and the matrix was calculated based on the mean spacing between the cracks that developed during tensile loading using the ACK model [11]. Note that the results of this calculation were used for comparison purposes only between the different systems, as all fabrics were made from the same aramid weft yarns and same PP stitches, with the same tex value. Calculation of the bond strength, τ, is presented in Eq. (2).

$$\tau = \left(\frac{V_m}{V_f}\right)\frac{\sigma_{mu} r}{2X'} \tag{2}$$

where X' – mean spacing between the cracks (mm); V_m, V_f – volume fraction of matrix and reinforcing yarns, respectively; r – radius of the reinforcing yarn in the fabric (mm);

σ_{mu} – yield/ultimate strength of the matrix without reinforcing (4 MPa).

3. Results

3.1. Fabric properties

Table 1 presents the tensile properties of all the tested fabrics. The aramid fabric was the strongest followed by the AR-glass and HDPE. The PP fabric had the lowest strength and the highest elongation value, as expected. The HDPE with the 90 tex yarn performed better than a similar, 140 tex fabric containing 4 mm loops. Note that a greater tex value means a larger bundle diameter. Improvement in fabric strength was also observed when the loop size was increased from 2 to 4 mm, for both 90 and 140 tex HDPE fabrics. Enhancements in fabric strength of 20% and 5% were observed for the 90 and 140 tex fabrics, respectively. The change in tensile strength may be a result of the non-linear shape (crimped) of the reinforcing yarn (warp) in the fabric (Fig. 1). The wavy shape of the yarn was influenced by the density of the stitches (loops) and the number of filaments in a single yarn, i.e., a smaller loop size/higher tex number (denser stitches) conferred greater crimping on the yarn. Yarn crimping, in turn, can affect the stresses that develop along the length of the yarn (Fig. 1c), such that reduced crimping of the yarn along tensile loading (i.e., with larger loop size) resulted in better tensile strength of the fabric as observed in this work. Such an influence can also affect the overall properties of the composite.

3.2. Composite properties

Several parameters were compared for all the composites tested: raw materials of reinforcing yarns composing the fabrics, bundle size (yarn fineness, tex), and the size of the loops connecting the weft and warp yarns.

3.3. Single fabric composite

Composites made from aramid and HDPE fabrics, with 2 mm loops and similar yarn tex values of 140 and 167 for HDPE and aramid, respectively, exhibit similar tensile behaviors with relatively high strengths at failure and improved toughness values (Fig. 3 and Table 2, specimens 1 and 3). The lowest tensile strength value of only 9.25 MPa was observed for the PP composite. These results correlated well with the fabric properties (Table 1), which show that the aramid and HDPE fabrics were the strongest while the PP fabric exhibited the lowest strength. Note that above strains of about 2%, no new cracks developed in the HDPE, aramid, or PP systems, suggesting that from this point forward, additional increases in the strain were caused mainly by a widening of the existing cracks.

When comparing the properties of the aramid and HDPE composites with similar bundle tex measurements

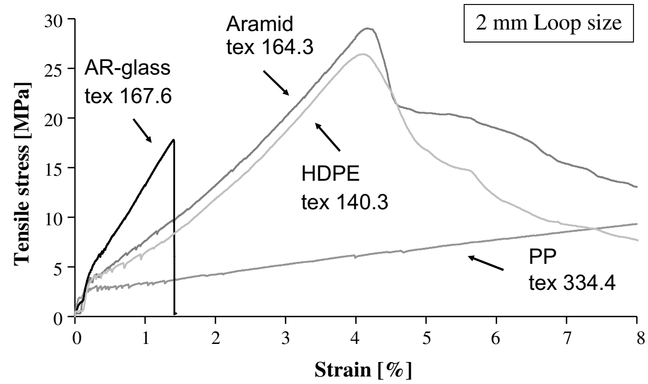

Fig. 3. Stress–strain responses of composites with different fabrics.

at the lower strain values of 1% and 2%, i.e., during the multiple cracking stage, the aramid composite performed better than the HDPE composite (specimens 1 and 3, Table 2). Improvements in composite tensile strength of about 15% and 30% for 2% and 1% strain levels, respectively, were obtained for the aramid over those of HDPE.

Comparison of the reinforcing efficiency factors of the aramid and HDPE composites shows better efficiency factors for the HDPE system at the high (peak) strain levels (Table 2, specimens 1 and 3). At lower strain values of 2% and 1% there was no significant difference between the two systems. Taken together, the results suggest that at high strain levels the HDPE fabric was a more efficient reinforcement for cement based composites.

The glass fabric composite exhibited relatively brittle behavior when compared with the other composite systems. Tensile strength at failure was higher than that of the PP composite but lower than those of the HDPE and aramid composites at their peak values (about 4% strain). At a lower strain of 1%, the tensile stress was greatest for the AR-glass composite, which shows an improvement in the efficiency factor of more than 300% over those of the HDPE and aramid composite systems (Table 2). These results suggest that for low strain applications, the AR-glass composite was the best choice from the different fabrics examined.

The tensile results were correlated with the bond strength values of the different composite systems (Table 2). The strongest bonding was observed for the aramid, followed by AR-glass and HDPE, and the weakest bonding was for the PP composites. The chemical natures of glass and aramid (hydrophilic, as was the cement) and their high modulus of elasticity (Table 1) may explain the strong bonding observed with the cement matrixes. No chemical bonding was expected, however, between the PP fiber and the cement matrix due to the significant differences in their chemical natures (hydrophilic for the cement and hydrophobic for the PP) and the low modulus of elasticity of the PP fabric, thereby resulting in weaker bonding and a relatively low efficiency factor compared with the high performance composites fabrics.

The high bond value of the AR-glass system can lead to the brittle behavior of this composite, as the fabric tended to fail (fracture) rather than pull out during the tensile test. Furthermore, the non-linear shape of the reinforcing glass yarns when they were part of the fabric (Fig. 1c), including their high bonding to the cement paste, may even magnify such brittle behavior. When a tensile load was applied on the brittle crimped glass yarn, its brittleness was evident as it was easily broken. The HDPE and aramid fabrics (yarns), on the other hand, were in general more ductile, and therefore, composite failure occurred only at much higher strain levels.

3.4. Hybrid fabric composite

The tensile behavior of the composite reinforced with the hybrid fabric containing aramid and PP yarns was presented in Fig. 4, along with the tensile responses of single PP and single aramid fabric composites. The hybrid composite performed similar to that of the single aramid fabric composite in terms of strength, although half of the aramid yarns were replaced with PP. Moreover, the hybrid composite exhibited much better tensile behavior than that of the PP composite. It should be noted that the total volume content of the reinforcement yarns in the hybrid fabric composite was 2.6%, which was slightly above that of the single aramid fabric composite (1.9%) but significantly lower than that of the single PP fabric composite (6.2%). In addition, in the hybrid composite, the aramid content was only 1.0% and that of the PP was 1.6% (Table 2).

The superiority of the hybrid composite was obvious when comparing the efficiency factors of the hybrid composite with those of the single aramid and single PP composites (Table 2, specimens 8, 1, and 7 for the hybrid, aramid, and PP, respectively). An improvement of as much as 90% was observed for the hybrid composite when compared with the efficiency factor of the single aramid composite. These improved properties were observed not only at maximum strengths, but also at strain levels of 1% and 2%. The relatively low aramid yarn content and the higher PP yarn content of the hybrid composite led to its relatively low bond strength value compared with the single aramid composite system (Table 2). The aramid yarns are about thirty times more expensive than PP yarns, therefore the hybrid composite is a cost effective system with energy properties similar to those of the single aramid composite.

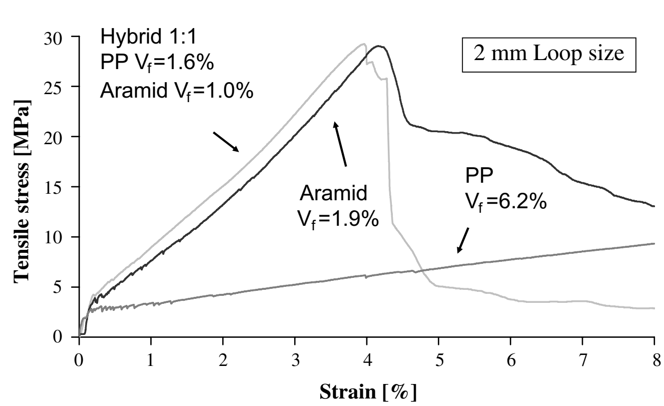

Fig. 4. Tensile behavior of composite reinforced with hybrid fabric made from PP and aramid yarns.

3.5. Influences of loop size

The influences of the knitted fabric loop size on composite tensile properties were studied with HDPE for the 140 and 90 tex bundle sizes (Fig. 5). The 140 tex systems showed that the strength of the 4 mm loop size fabric was markedly higher (20%) than that of the composite with 2 mm loops (samples 3 and 4, Table 2). This improvement was observed mainly at large strains. Tensile strength of the 4 mm loop size fabric itself (without cement) was almost identical (about a 5% difference) to that of the 2 mm loop size fabric (Table 1), indicating that the differences between the two loop size composites was not based on fabric properties alone. Moreover, the volume content of reinforcement of the small loop size composite was 2.7% (sample 3 in Table 2), greater than that of the large loop size composite with a V_f of only 1.5% (sample 4 in Table 2). Despite the higher volume content of the 2 mm loop size composite, the composite with the lower fiber content (4 mm loop size) performed much better. Also, during tensile loading, the composite with the 4 mm loop size fabric showed multiple

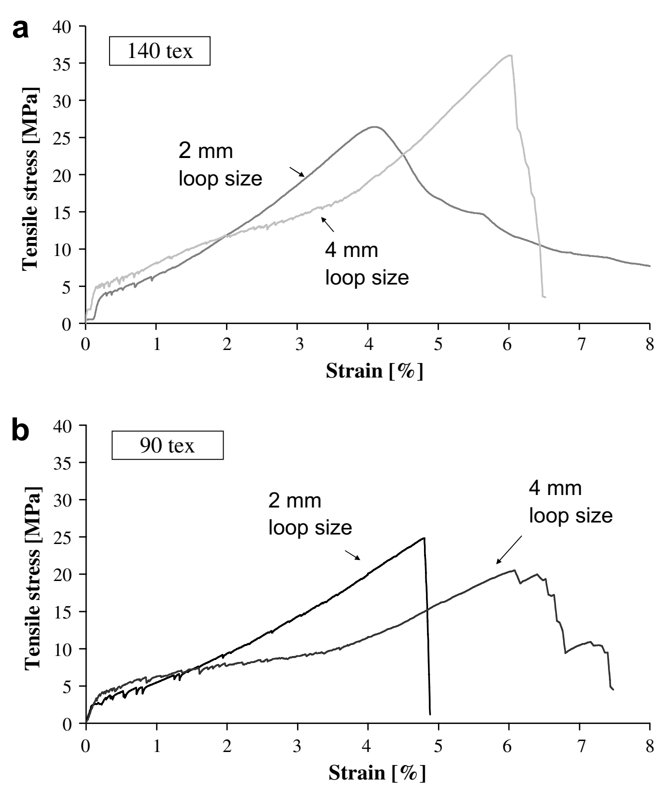

Fig. 5. Comparison of composite tensile behavior of fabrics reinforced with HDPE and made with different loop sizes for bundle sizes of: (a) 140 tex, and (b) 90 tex.

cracking behavior up to strain level of 3.5%, whereas the 2 mm loop size system exhibited such cracking behavior until strain of 2%. Based on the above discussion, in terms of the 140 tex bundle, the larger loop size fabric was clearly preferable as reinforcement for cement composites.

The trend cited above was not as significant when comparing the composite tensile properties of 140 tex bundle fabrics with those of the 90 tex bundle fabrics. The small loop size system performed well in terms of tensile stresses (Fig. 5) and under relatively high strains (Table 2, specimens 5 and 6). The improved tensile behavior of the small loop size composite may be caused by its greater reinforcement content. However, because the large loop size fabric alone (without cement) was about 20% stronger than that of the small loop size fabric (Table 1), the two loop size systems were compared based on their respective efficiency factors, which were calculated taking into account fabric strengths and the volume contents of reinforcement.

Based on the efficiency factors of the two loop size systems, clearly the 4 mm loop size systems were better than the 2 mm loop size systems for both the 90 and 140 tex bundle sizes (Table 2). The benefit of the 4 mm loop size systems was evident at high and low strain levels. In general, the improvement in the efficiency factor of the 4 mm loop size composite over that of the 2 mm loop size was greater for the 140 tex systems, above 50%, than for the 90 tex systems, which exhibited less than 50% improvement. At a low, 1% strain level, the efficiency of the 4 mm loop size fabric was twice that of the 2 mm loop size fabric. This trend was observed for both the 140 and 90 tex bundle size systems. For the large bundle size system, at the maximum stress level, improvements in efficiency of about 100% were observed for the 4 mm loop size composite compared to the 2 mm loop size fabric.

Based on crack patterns, the bond strengths were also greater for the large loop size systems than they were for the small loop size systems, for both the 140 and 90 tex bundle size systems (Table 2, Fig. 6). The 4 mm loop size fabric exhibited a bonding strength with the cement matrix about twice that of the 2 mm loop size fabric. Such an improved bonding strength indicated that the 4 mm loop size fabric was more efficient as reinforcement for cement composites.

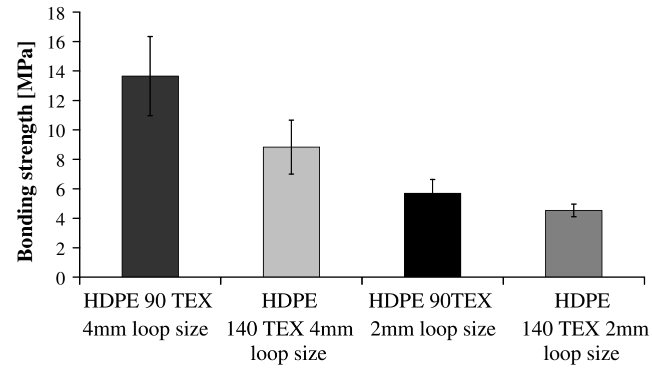

Fig. 6. Bonding strengths of HDPE composite systems having different bundle and loop sizes.

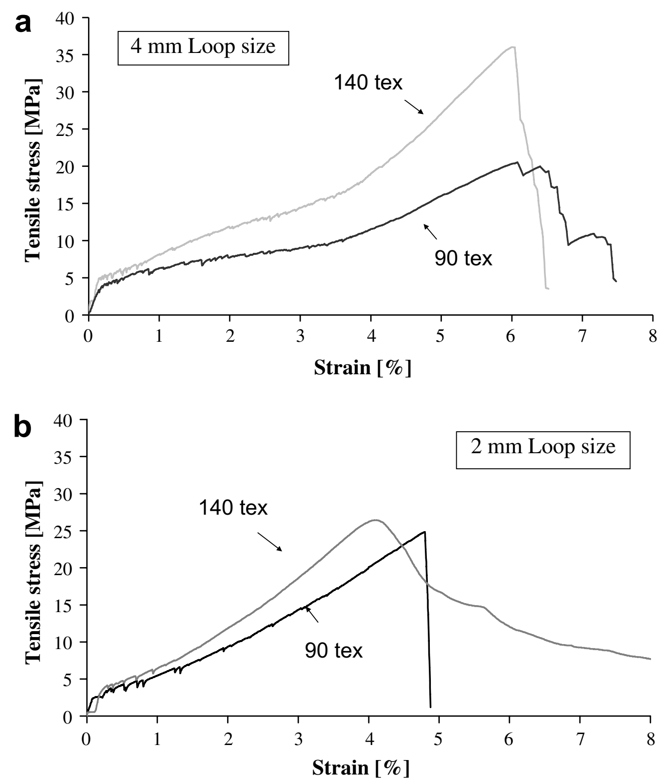

Fig. 7. Comparison of composite tensile behavior of fabrics reinforced with HDPE and made with different bundle sizes utilizing loop sizes of: (a) with 4 mm loop size, and (b) with 2 mm loop size.

3.6. Influences of bundle size (tex)

The influences of the bundle size (140 and 90 tex yarns) on composite performance are presented in Fig. 7 and Table 2, for 4 and 2 mm loop size fabrics (specimens 4 with 6 and 3 with 5 in Table 2). In terms of strength, for both loop sizes the larger (140 tex) bundle size composite outperformed that of the smaller size bundle due to the higher reinforcement content in the 140 tex composite. For the 4 mm loop size system, the advantage of the large bundle size was more significant. Fabric strength also depended on bundle size as reported in Table 1 and discussed above. Comparing the efficiency factors of the two bundle systems, however, shows that the values for the small (90 tex) bundle size system exceeded those of the large bundle system for both loop sizes (Table 2). This trend was observed both at low and at peak strain levels for the small loop system. These results may indicate that the small bundle size with fewer filaments was more efficient than the large bundle size in reinforcing the knitted fabric cement based composite. This trend was also reported by Jesse et al. [12].

An examination of the bond strengths of thin bundle composites (Fig. 6) revealed that bonding was stronger for the fabrics with the 4 mm loop size (Table 2, specimens 6 with 4, and 3 with 5). The greater bond strengths of

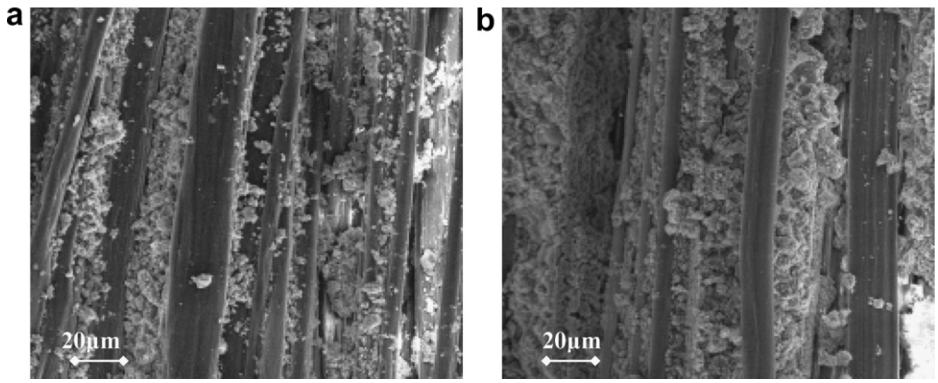

Fig. 8. Influence of loop size on cement penetrability between the filaments of the reinforcing yarns (warp): (a) 2 mm loop size, and (b) 4 mm loop size.

composites with 4 mm loops may be the result of the greater reinforcement efficiency of the 90 tex bundle fabric.

3.7. Microstructure characteristics

The microstructure of the HDPE systems may help with understanding the trends observed in the previous chapters. The penetrability of the cement matrix between the reinforcing filaments of the bundle for the fabrics with both 4 and 2 mm loop sizes was examined at high magnification (Fig. 8). Fabrics with the 4 mm loops exhibited deeper and better cement penetrability (Fig. 8b); thereby improving overall fabric–cement matrix bonding because of the relatively high bundle surface area was in contact with the cement matrix. Accordingly, for fabrics with small loop size of 2 mm, the stitches are relatively dens and small, therefore strongly tightened the filaments in the bundle and the cement matrix cannot penetrate as deeply into the bundle between the filaments (relative to the 4 mm loop, Fig. 8a and Fig. 9), resulting in lower bond strengths obtained with these composites (Table 2, Fig. 6). Such reduction in cement penetrability in 140 tex fabric would lead to a significant reduction in the performance of the 2 mm loop size composites relative to the 4 mm loop composites, even at high strain levels (Table 2, specimens 3 and 4, and Fig. 5a). However, for the smaller bundles (90 tex), due to their small sizes, the tightening effects by the stitches were less dominant, and the difference in tensile performances between the large and small loop size fabric systems was not as significant (Table 2, specimens 5 and 6, and Fig. 5b).

The above discussion can also explain the improved bonding of the small diameter bundle as compared with the large diameter bundle (Fig. 6). A thinner bundle with fewer filaments can be more easily penetrated by the cement matrix than can a larger diameter bundle with many filaments. For the smaller bundles greater penetration with respect to the cross-sectional area was taking place, i.e., the smaller bundles exhibited better penetration in a greater percentage of the cross-sectional area. Therefore, a relatively larger number of filaments were in contact with the cement paste, providing the thinner bundle systems with stronger bonding. Bundle size had a more prominent effect on bond strength in cases of fabrics with the large loop size, where the bundle was more open, i.e., less tightened, thus enabling the improved bonding conferred by the deeper penetration of the cement into the bundle.

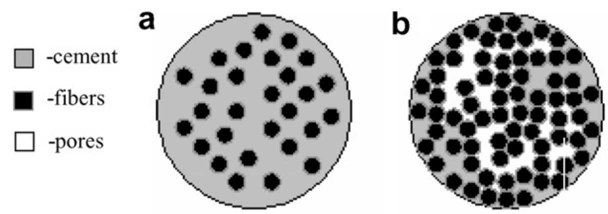

Fig. 9. Illustration of the influence of filament density in the bundle on cement penetration: (a) low density, (b) high density.

Loop size also influenced the bond with the cement matrix as the matrix penetrated between the loop itself (Fig. 10a). Such penetration provides mechanical anchoring of the loop within the cement matrix, creating a strong bond. Note that with the fabrics studied here, the loops and the warp yarns were strongly connected and difficult to separate, i.e., the filling of loops by the cement matrix was an important factor. Therefore, an increase in loop density, i.e., a decrease in loop size, led to stronger mechanical anchoring. However, the smaller loops strongly tightened the filaments of the reinforcing bundle, and as such reduced the depth of cement penetrability between these filaments and decreased bonding. Mechanical anchoring was also improved by cement penetration into the spaces created by the weft yarns that are perpendicular to the load direction (Fig. 10b). Such anchoring restrained the warp yarn movement in the composite material during loading, producing a better bond between the fabric (warp yarns) and the cement matrix. The effects of weft yarn anchoring and bond improvement were reported in Refs. [7,8]. The contribution to anchoring by the weft yarns was also influenced by loop size and bundle size in a manner similar to that for warp yarns.

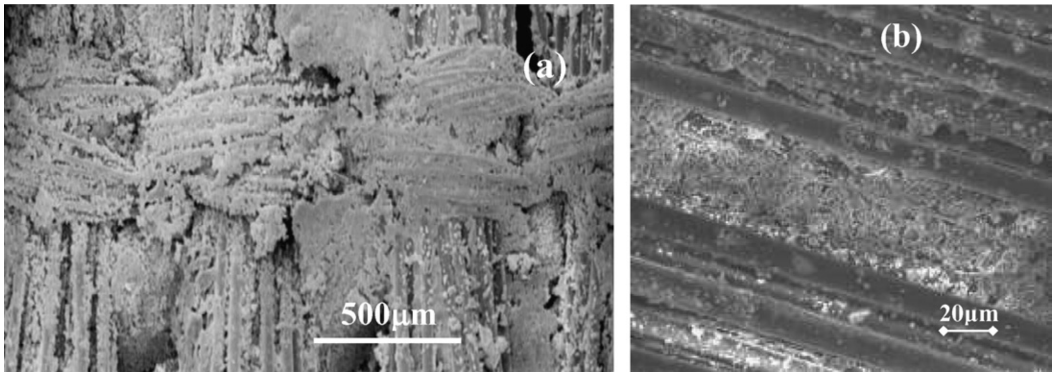

Fig. 10. Penetration of cement between (a) the loops and (b) weft yarns, perpendicular to load direction.

4. Discussion

In warp knitted fabrics the yarns are interconnected by stitches (loops). In this work, the fabrics were specifically developed to provide strong contact (bonding) between warp yarns, weft yarns, and stitches. In general, a larger loop size improved bonding and composite tensile properties such as efficiency factors. In addition, fabric composed from relatively thin bundles developed superior bonding with the cement matrix, leading to improved composite performance.

Several competing factors determined how the loop size of the knit fabric affected the composite properties:

(I) Increasing the number of loops consequently increased the number of anchoring points, and thus provides stronger anchorage of the fabric with the hardened cement paste, which penetrated between the loops before hardening (Fig. 10a).

(II) On the other hand, increasing the number of stitches tightened the filaments of the reinforcing bundle, which reduced the spaces between the filaments and decreased cement matrix penetrability (Fig. 8). As the number of stitches increased, their sizes decreased, which further reduced matrix penetrability and potentially degraded overall composite performance.

(III) The tensile strength of the fabric itself increased as the number of loops per unit length decreased and the loop size increased, i.e., fabrics with 4 mm loops were stronger than fabrics with 2 mm loops (Table 1). Composite performance can be increased in this manner.

(IV) The number of stitches, i.e., the size of loop, affected the shape of the reinforcing yarn (bundle). Dense stitches resulted in a crimped yarn shape, which, in turn, can lead to stress dispersions, as the stresses are not necessarily developed in the loading direction (Fig. 1c).

(V) The yarns perpendicular to load direction, the weft yarns, also functioned to anchor the fabric in the cement matrix due to matrix penetrability (Fig. 10b) and strong connections with both the warps and loops. The fabric may be anchored more strongly within the cement matrix by reducing bundle size and by increasing loop size, both of which can increase the size of the open spaces between the yarns.

In this study, between the two loop sizes investigated, the 4 mm loop size performed better than the 2 mm loop size.

The crimping shape of the reinforcing yarns with the 2 mm loop size can also explain the brittle behavior of the composite made with the AR-glass fabric. Due to the brittle nature of the glass filaments, such a crimped shape can cause the filaments to fracture during tensile loading, leading to the brittleness of the AR-glass composite (Fig. 3). Increasing the size of the loop, i.e., reducing bundle crimping, can minimize this effect. This behavior should be further investigated. Due to the more ductile behavior of the HDPE and aramid fabrics, they were less sensitive to yarn crimping, and therefore, exhibited the best tensile properties among the investigated composites.

Another important composite parameter was the size of the reinforcing bundle. Increasing the bundle diameter and the number of filaments reduced the ability of the cement to penetrate between the filaments of the bundle, thus reducing bond strength (Fig. 6) and composite tensile properties (efficiency factor). Although cement penetrability was affected by bundle diameter, it was also affected by the knitted fabric loop size: for wide bundle diameters, the larger loop size was more efficient. When a thinner bundle was used to produce the knit fabric, however, cement penetrability was much easier, and therefore, the influence of the loop size was less important.

5. Conclusions

The correlation between fabric strength and cement composite properties is not necessarily straightforward. The properties of the composite are influenced by the geometry of the fabric and the bond that develops between the fabric and the cement matrix and less by fabric strength.

In this work it was found that the geometry of warp knitted fabric strongly influenced the performance of cement based composites, and therefore, fabric geometry must be carefully considered when fabric is used to reinforce such composites. Two main parameters were studied: the size of the loops composing the knit fabric, and the size of the reinforcing yarns in the fabrics (bundles, their tex number). Increasing loop size and reducing bundle size improve composite performance. The influence of loop size was more pronounced with larger bundle sizes, due to their improved cement penetrability between the reinforcing filaments.

Composites made from aramid and HDPE fabric exhibited the best tensile performance in terms of strength and toughness. Glass fabric composites showed improved performance at low strain values but with brittle behavior. These fabrics bonded well with the cement matrix. The PP fabric did not bond strongly with the cement matrix, resulting in relatively low composite performance. The aramid-PP yarn combination in a hybrid fabric should be considered as reinforcement for cement composites. It exhibited behavior similar to that of the single aramid composite, when half of the aramid yarns were replaced with the inferior, low cost PP yarns. Although its volume content of reinforcement, 2.6%, was much lower, the hybrid composite also performed much better than the single PP fabric composite, which had a V_f of 6.2%.

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