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Geometrical characteristics and efficiency of textile fabrics for reinforcing cement composites

Alva Peled*, Arnon Bentur

National Building Research Institute, Faculty of Civil Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel

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Abstract

One of the most efficient ways to obtain a high performance cementitious composite is by reinforcement with continuous fibers. Production of such composites can readily be based on the use of textile fabrics, which are impregnated with cement paste or mortar. The present paper discusses the bulk properties and geometrical characteristics of textile fabrics that should be considered in order to predict the performance of cement composites reinforced with fabrics. Geometrical characteristics are the nature of the basic reinforcing unit in the fabric (yarn) and the various geometries by which these yarns are combined together in the fabric (weft insertion warp knitted, short weft warp knitted, and woven fabrics). It was found that the geometry of a given fabric could enhance the bonding and enable one to obtain strain hardening behavior from low modulus yarn fabrics. On the other hand, variations of the geometry in a fabric could drastically reduce the efficiency, resulting in a reduced strengthening effect of the yarns in the fabric relative to single yarns not in a fabric form. The improved bonding in low modulus yarn was found to be mainly the result of the special shape of the yarn induced by the fabric. Therefore, in cement composites, the fabrics cannot be viewed simply as a means for holding together continuous yarns so that they can be readily placed in the matrix.

Keywords: Cement; Fabric; Fiber reinforcement; Bond strength; Composite

1. Introduction

One of the most efficient ways to obtain a high performance cementitious composite is by reinforcement with continuous fibers. Production of such composites can readily be based on the use of textile fabrics, which are impregnated with cement paste or mortar. This type of technology has been applied to a limited extent in the production of thin sheet cement composites and in in–situ applications such as repair and retrofit. Modern textile technology offers a wide variety of fabrics, with great flexibility in the design of the geometry and the fibers, which make up the fabric. The variables in the fabric can be the geometry and distribution of the fibers in two and three dimensions, as well as combinations of different types of fibers in the same fabric. Fabrics can be produced by different methods, such as weaving, knitting, breading and non-woven. They differ in the way that the yarns (the basic reinforcing unit in the fabric) are connected to each other at the junction points. The interlacing of the yarns to form a fabric affects not only the geometry of the fabric itself but also the geometry of the individual yarns, which make up the fabric.

When polymer matrices are reinforced with fabrics in which the yarns do not maintain a straight geometry, reduction in the reinforcing effectiveness was observed [1]. Therefore, in polymer composites, the reinforcing fabrics should contain as many straight yarns as possible. Prediction of the reinforcement efficiency of the fabric usually takes into account only the longitudinal yarns in the fabric, which are in the loading directions. The perpendicular yarns are treated as "non-structural," whose object is to provide a mechanism to hold the longitudinal yarns in place during the production of the composite.

In cement composites, this concept may not be adequate since the micro-mechanics of the interaction between the cement matrix and the fabric and its individual yarns might be more complex. Indeed, previous work has indicated that fabric geometry and the special geometry of its yarns have a significant effect on bonding [2,3].

* Corresponding author. Center for Advanced Cement Based Materials, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA. Tel.: +1-847-467-3630; fax: +1-847-467-1078.

E-mail address: a-peled@nwu.edu (A. Peled).

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The influence of the bulk properties of continuous fibers (mainly modulus of elasticity and strength) on the strength of the composite can be predicted from available models [4,5]. The bonding in a bundled strand structure has been evaluated mainly in glass fibers [6]. However, very little has been reported on the effectiveness of bonding in polymeric bundles and in particular, the influence of twisting. The latter issue has been recently addressed by Naaman [7], dealing with twisting of single steel fibers. Li et al. [8] assessed the influence of the number of filaments in a strand on the overall bonding, by considering the effective surface area of the filaments which was in direct contact with the matrix. Several studies have evaluated the reinforcing efficiency of woven fabric [2,3,9–11] but much less has been done with respect to knitted fabric.

The object of the present paper is to provide an overview of the characteristics that should be considered in predicting the performance of cement composites reinforced with fabrics. The properties and the geometrical structure of the yarns making up the fabrics, as well as the geometry of the fabrics themselves will be discussed. The geometrical characteristic to be considered are the nature of the basic reinforcing unit in the fabric (yarn) and the various geometries by which these yarns are combined together in the fabric (knitted and woven). The various geometrical parameters of the yarn and the fabric will be presented, based on some of the data in Refs. [9–11] and additional data which were developed recently to enable a comprehensive treatment of fabric reinforcement of cement matrices.

2. Experimental

2.1. Yarn and fabric variables

The following variables were evaluated in the present study:

1. Characteristics of the individual yarns in the textile fabric:
   (i) properties of the polymer yarns—high modulus versus low modulus,
   (ii) nature of the yarn—single continuous filament, an assembly of several hundreds of filaments bundled together or a yarn in the form of a film, and
   (iii) geometrical characteristics—straight, crimped, or twisted filaments.
2. Geometrical characteristics of the individual yarns in the fabric—straight (in weft insertion knit), crimped (in woven), or more complicated shapes (in short weft knit).
3. Geometry of the fabric:
   (i) fabric structure—woven fabric (plain weave, (Fig. 1a)), weft insertion warp knitted fabric (Fig. 1b) and short weft warp knitted fabrics (Fig. 1c); (weft and warp are the terms used for the yarns in the different orientations of the fabrics), and
   (ii) density of the woven and the weft insertion knitted fabrics.

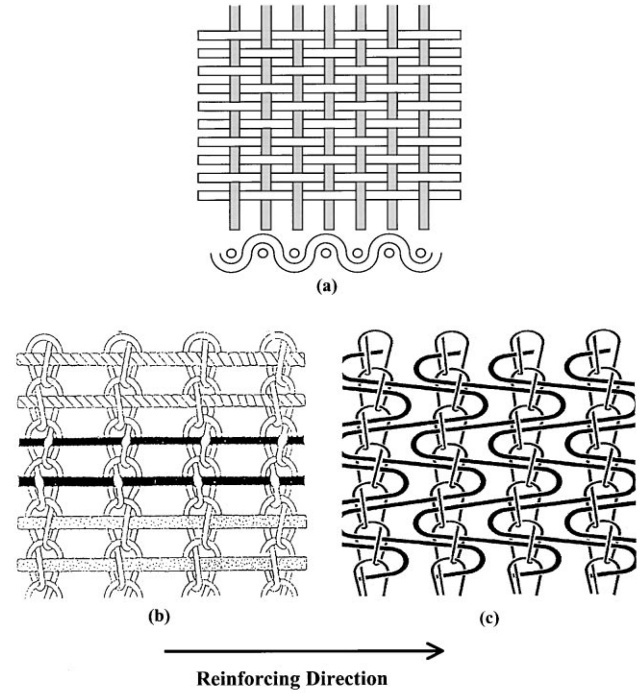

Fig. 1. Structure of fabrics: (a) woven, (b) weft insertion knitted fabric, and (c) short weft knitted fabric.

2.2. Fabric geometry

The fabric structures differ by the way the yarns are combined together.

In the woven fabric, the warp and the fill (weft) yarns pass over and under each other resulting in a crimped shape for the yarns in the fabric (Fig. 1a).

In the weft insertion knitted fabric, the yarns in the warp direction are knitted into stitches to assemble together the straight yarns in the weft (Fig. 1b).

In the short weft knitted fabric, the warp yarns are also knitted into stitches but in this case, they bind together a set of yarns which are laid-in intermittently in both the weft and the warp directions (in a zigzag form in Fig. 1c). In the case of the short weft knit, two different fabric types were prepared: (i) the (short) weft yarns (the reinforcing yarns) were parallel to the applied load, and (ii) the (short) weft yarns were at an angle to the applied load. The short weft yarns were either from monofilament (as of the woven fabrics), or from film (having a dimension of 2×0.02 mm).

The density of the fabrics was varied by changing the density of the yarns perpendicular to the applied load. In the woven fabrics, the fills' density was 5, 7, or 10 fills/cm and the warps' density was kept constant at 22 warps/cm. It

Table 1
Properties and structure of yarns

	Yarn type	Strength (MPa)	Modulus of elasticity (MPa)	Filament size (mm)	Number of filaments in a bundle	Bundle diameter (mm)
Low modulus	PE	260	1760	0.25	1	0.25
	PP (monofilament)	370	3400	0.25	1	0.25
	PP (film)	670	4300	2 × 0.02	1	2 × 0.02
	PP (bundle)	500	6900	0.04	100	0.40
	Nylon	900	8400	0.03	240	0.40
High modulus	Kevlar	2300	44000	0.011	325	0.20
	HDPE	1960	55000	0.008	900	0.25

should be noted that the fabric density affects several characteristics: the crimped structure of the warp yarns in the woven fabric, the number of joints, and the penetrability of the cementitious matrix in the fabric. These can influence the bond capacity with the cement matrix.

In the weft insertion knitted fabrics, the warp density (the stitches) was varied: 0.8, 1.6, 2.4 or 3.2 warps/cm and the wefts' density (straight yarns) was kept constant at 16 weft/cm in all the fabrics. In the short weft knit, the density of the warps (the stitches) was 3 warps/cm for all the fabrics.

2.3. Yarn properties and nature

The polymers evaluated were low modulus (polyethylene (PE), polypropylene (PP), and Nylon) and high modulus (Kevlar and High Density Polyethylene (HDPE)). Their properties are presented in Table 1. The PE was used to produce the woven and short weft knitted fabrics. In the woven fabrics, monofilament PE was used. In the short weft fabric, both monofilament and film were used. The Kevlar, PP, and HDPE were in the form of bundled yarns in a weft insertion knitted fabric.

2.4. Geometries

For better understanding the influences of the yarn itself when it is part of a fabric, the individual yarns (that were applied later to make-up the fabrics) were used to prepare reinforced cement composites to evaluate the efficiency of the yarns in the composite. For this purpose, individual straight yarns (PE and PP in monofilament and multifilament form as well as PP in film geometry) and crimped yarns untied from woven fabric (monofilament PE in a crimped geometry) were used. It should be noted that the crimped monofilament PE untied from the yarn was less crimped than the yarn in the actual fabric. In addition, Nylon yarn was also examined as individual bundles in four different forms:

(i) single bundle in a straight form,
(ii) single bundle in a twisted form,
(iii) twisting together two separate twisted bundles (2× twisted), and
(iv) 2× twisted with a coating of latex.

2.5. Evaluation of reinforcing efficiency

The efficiency of the yarns and the fabrics was determined by evaluating their performance in the composite, by studying the bond behavior as well as the overall properties of the composite in flexure.

2.5.1. Bond

The evaluation of the composite bond characteristics was based on pull-out tests of the original yarn, yarn untied from the fabric, and the fabric itself (Fig. 2). The pull-out tests were carried out in an Instron testing machine at a cross-head rate of 15 mm/min as described in detail in Ref. [3]. Load–slip curves were recorded. In the present paper, only reference to the maximum pull-out load will be made; typical complete pull-out curves for some of the systems are reported in Ref. [3]. The maximum load value was used to calculate the apparent average interfacial bond (obtained by dividing the load by the surface area of the embedded yarn). Although this value has limited physical significance since the bond stress distribution is non-uniform, it can serve as a parameter to compare the bonding efficiency of the different systems.

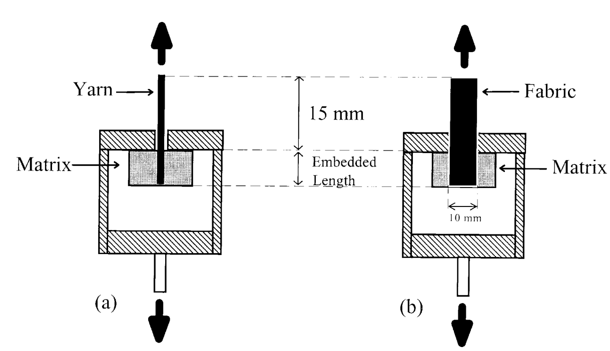

Fig. 2. Schematic presentation of pull-out tests to determine the bonding of (a) yarn and (b) fabric.

Table 2
Effect of yarn structure and content on flexural performance of composites reinforced with individual yarns (not in a fabric form)

Yarn type	Yarn geometry	Reinforcing yarn content in the composite (vol%)	Flexural strength (MPa)	Flexural strength improvement over straight yarn (%)	Yarn efficiency coefficient in the composite
PP	Monofilament	4	9	–	0.61
	Film	4	9	–	0.34
	Bundle	4	10	–	0.50
Nylon (bundle)	Twisted	7.8	16	320	0.22
PE (monofilament)	Straight yarn	5.7	11	–	0.74
	Crimping (5 crimps/cm)	5.7	17	155	1.15
	Crimping (7 crimps/cm)	5.7	20	182	1.35

In the case of yarns consisting of bundled filaments, two average stresses were calculated:

(i) bond per unit of external bundle surface in which only the external surface of the bundle is considered (i.e. the bundle envelope which will be calculated assuming a circular cross-section with the overall bundle diameter), and
(ii) the average bond per single filament, taking into account, in the calculation, the surface area of all the filaments; this can serve as an estimate for the "effective bond", which is much smaller than the previous value, since most of the internal filaments will not be in contact with the matrix.

2.5.2. Flexural properties

Composite specimens were prepared by lay-up of fabrics or yarns in a 0.3 water/cement ratio paste matrix. The specimen dimensions were 15-mm thick with length and width of 110 and 20 mm, respectively. The volume content of the reinforcing yarns (i.e. the yarns in the reinforcing direction) is presented in Tables 2 and 3 for the individual yarns and fabrics, respectively. Note that in the short weft knit, only the part of the yarn that was laid in the reinforcing direction was taken into consideration.

A four-point bending test was carried out in an MTS testing machine at a cross-head rate of 1.5 mm/min, with a span of 90 mm. Load–deflection curves were recorded. Details of specimen preparation and testing are provided in Ref. [11].

3. Results and discussion

3.1. Bonding

3.1.1. Effect of yarn properties

The bond characteristics of a single yarn and yarn in fabric are presented in Table 4. The single yarns in this table are the "raw" yarns from which the fabrics were produced. The value of bond per external bundle surface is of greater physical significance, since it approximates the surface, which is in direct contact with the matrix (the cement particles and the hydration products hardly penetrated into the inner filaments). Although the sur-

Table 3
Effect of fabric structure on flexural performance of the composite

Fabric type	Yarn type	Nature of yarn	Reinforcing yarn content in the composite (vol%)	Flexural strength (MPa)	Yarn efficiency coefficient in the fabric in the composite
Woven					
7 yarns/cm[a]	PE (low modulus)	Monofilament	5.7	18	1.21
5 yarns/cm[a]				15	1.01
Knitted short weft					
3 yarns/cm[a]	PE (low modulus)	Monofilament[b]	2.0	16	3.08
		Monofilament[c]		10	1.92
		film		12	2.31
Knitted weft insertion					
3 yarns/cm[a]	PP (low modulus)	Bundle 100 filaments	3.5	13	0.74
	Kevlar (high modulus)	Bundle 325 filaments		36	0.45
	HDPE (high modulus)	Bundle 900 filaments		19	0.28

[a] Density of yarns perpendicular to reinforcing direction.
[b] Reinforcing yarns are parallel to the applied load.
[c] Reinforcing yarns in the fabric are at a 20° angle to the applied load.

Table 4
Bond characteristics of a single yarn and yarn in the fabric

	Yarn type	Number of filaments in a bundle	Modulus of elasticity (MPa)	Bond per single filament (MPa)		Bond per unit external bundle surface (MPa)	
				Single straight yarn	Fabric	Single straight yarn	Fabric
Low modulus	PE (woven)[a]	1	1760	0.17	1.2	0.17	1.2
	PP (knit)	100	6900	0.30	0.27	3.5	2.8
	Nylon	240	8400	0.22	–	2.8	–
High modulus	Kevlar (knit)	325	44000	1.80	0.35	10.5	5.9
	HDPE (knit)	900	55000	0.40	0.09	11.5	1.8

[a] Woven fabric with density of 7 yarns/cm, perpendicular to the loading direction.
Note that the knit fabrics are weft insertion type.

faces of the filaments in all the single yarns tended to be similar and smooth, there were marked differences in the bond values, by an order of magnitude. It is of interest to note that the differences could be roughly correlated with the modulus of elasticity: bond tended to increase with the increase in the modulus of elasticity of a single yarn (Fig. 3). This is consistent with the analysis and experimental results of Stang [12] who showed that higher bond is expected in higher modulus fibers due to higher clamping stresses which develop around them due to matrix autogenous shrinkage. Also, in the low modulus yarns, there is a detrimental effect on bond strength induced by Poisson effect [4].

On the other hand, in the actual fabric the relation between the bond and the yarn modulus of elasticity is different from that of the single yarn (Table 4). In the fabric, no clear correlation between bond and modulus of elasticity could be established. In the high modulus yarns, the bond in the fabric was significantly lower than the bond of single yarns, whereas in the low modulus yarns,

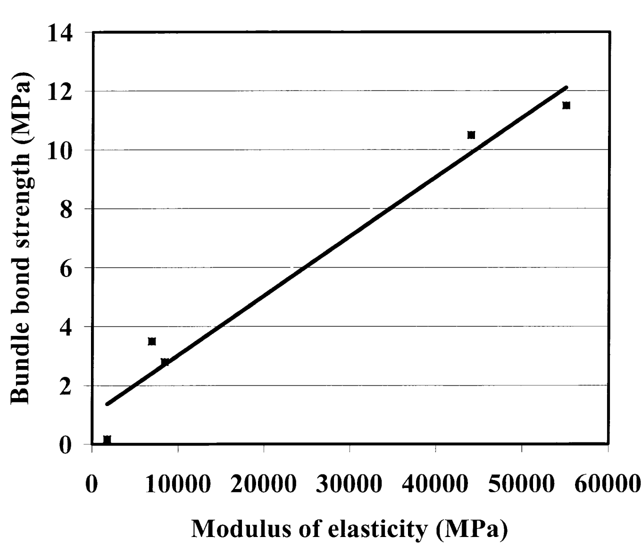

Fig. 3. Relation between the external surface bond strength of yarns of different materials and their modulus of elasticity.

the two were either similar or the bond in the fabric was even higher. This difference in the trends is probably not associated with the modulus of the yarns but rather with other factors such as the geometry of the yarn: the high modulus yarns were in the form of bundles with a large number of filaments (Table 1: 325 and 900 filaments for the high modulus yarns, vs. 1 or 100 filaments for the low modulus yarns) resulting in less efficient consolidation of the matrix around them when the composite was produced from fabrics.

3.1.2. *Effect of bundling*

The last statement in the previous section clearly indicates the potential significance of the number of filaments in the bundle. This issue can be assessed and quantified by considering the "effective bond" calculated as the bond per single filament (Table 4). This bond is quite different from the external bond. This difference, which is particularly high in the high modulus yarns can be attributed to the large number of filaments in these yarns, as discussed previously.

3.1.3. *The effect of the geometrical characteristics of the individual yarn*

In the case of bundled yarns, twisting is often employed (Fig. 4). Fig. 5 compares the external interfacial bonding of bundles (made from Nylon) with various geometries: straight, twisted, double-twisted (×2) and double-twisted (×2) with latex coating. The latex coating which is hydrophilic in nature was applied with the intention of increasing the bonding with the cement matrix.

It is quite clear that twisting of the bundle improved the bonding considerably. This bond improvement was supported by micro-structural characterization using SEM. Fig. 6 shows the grooves of the straight and the twisted yarns in the matrix after the pull-out test. As can be seen, the twisted fibrils remained in the groove after the pull-out (Fig. 6a), which is indicative of an intimate bonding and perhaps, some anchoring effect. With the straight yarns, the fibrils separated completely from the groove and none were seen to

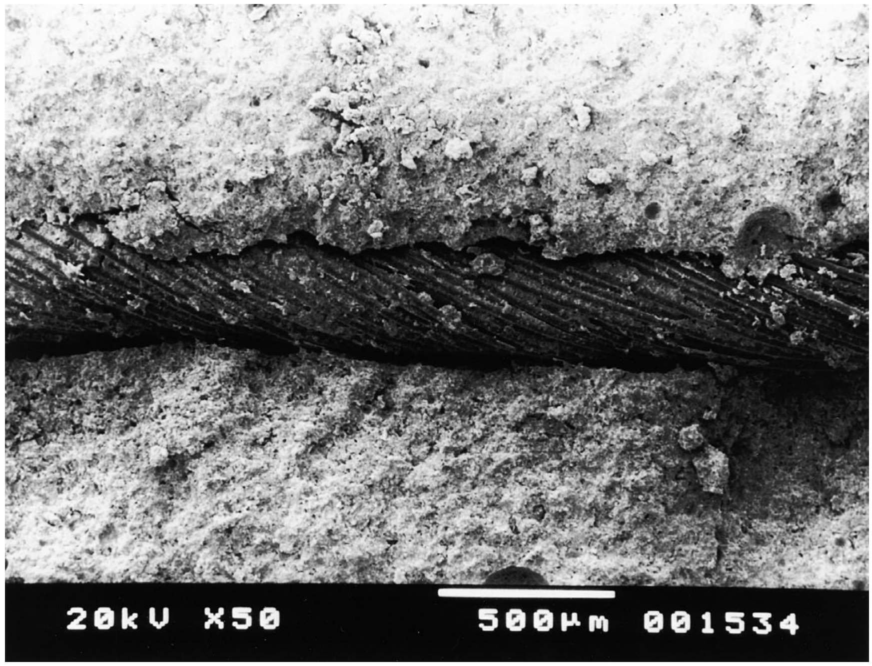

Fig. 4. Structure of twisted yarn bundle.

remain there (Fig. 6b). Twisting together of two separate twisted yarns did not enhance the bonding significantly compared to a single twisted yarn (Fig. 5).

The latex coating decreases the bond properties (Fig. 5). This reduction may be due to the smooth surface created on the bundle by the latex coating, which perhaps acts as a bond breaker rather than a sizing for bond improvement (Fig. 7).

The yarn in the fabric does not always maintain a simple straight geometry. This is the case for the yarn in the woven fabric, which is forced to undulate above and below the perpendicular yarns which it crosses (Fig. 1a). The extent of crimping (i.e. crimp density) is a function of the fabric density. The influences of individual yarn geometry on bond are presented in Table 5, showing the marked improvement in the bond of deformed yarns over that of a straight yarn. This can be attributed to the irregular shape of these yarns, which leads to mechanical anchoring to the cement matrix. The improvement in bond is larger in the crimped yarns (increase by a factor of 3.5 to 4) and is smaller in twisted yarn (increase by a factor of about 1.5).

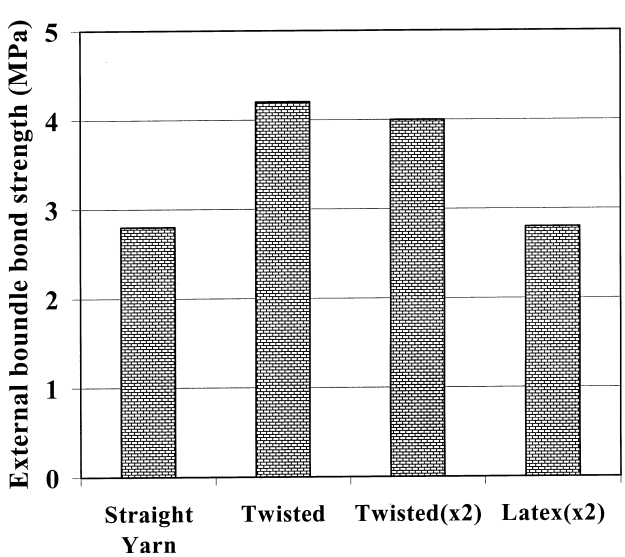

Fig. 5. External bond properties of Nylon bundle with various geometries.

3.1.4. *Effect of fabric structure*

The bonding in the actual fabric is different from that of the individual yarns (Table 6, Fig. 8). For all the weft insertion knitted fabrics, the bond in the fabric is lower than that of the individual yarn. The decrease in the bond is in the range of 20% to 85%, with the higher decrease tending to occur in the bundled yarns with a larger number of filaments. This decrease can readily be explained by limited compaction of the matrix around the bundle, which is interfered with by the stitches. The stitches may also tie the filaments in bundles and drastically reduce the penetrability of the cement matrix between the filaments in the bundle.

In contrast, the bonding in the woven fabric is enhanced relative to the individual straight yarn. This is due to two influences: the crimping which is induced in the woven geometry and perhaps also some anchoring offered by the perpendicular yarn. Other contributing factors may have to do with the monofilament structure and also with the nature of the intersections, which are not as "bulky" as in the knitted fabric.

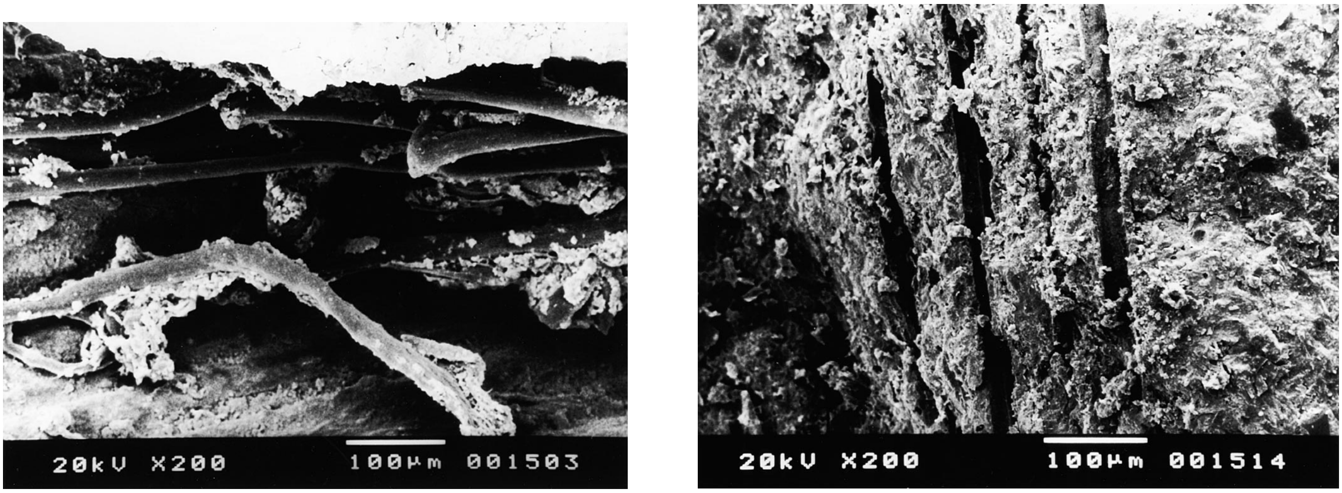

Fig. 6. SEM micrographs of the bundle groove in the cement matrix after pull-out test: (a) twisted yarn and (b) straight yarn.

3.2. Composite properties

The effects of these influences on the bond are reflected in the performance of the composite as evaluated by flexural tests. Two parameters were calculated from the results of these tests: the post-cracking flexural strength and the yarn reinforcing efficiency. The latter is defined as the ratio between the post-cracking flexural strength and the product of the yarn volume and its tensile strength. The efficiency factor can serve as a direct estimate of the fabric efficiency since this value is already normalized for the fiber content in the composite, which was not always the same for all the composites prepared here, due to production constraints. The matrix flexural strength was 9.5 MPa.

3.2.1. Effect of yarn structure

Table 2 presents the flexural performance of composites which are reinforced in the longitudinal direction with individual yarns, with no perpendicular yarns (i.e. these are hand-laid yarns, representing the reinforcing yarns in the fabric). The PP yarns are all in a straight form: single filaments, bundled, and film. The PE and Nylon are in crimped and twisted shapes, respectively.

The nature of the yarns (film, bundle, or single filament) does not significantly affect the flexural strength of the

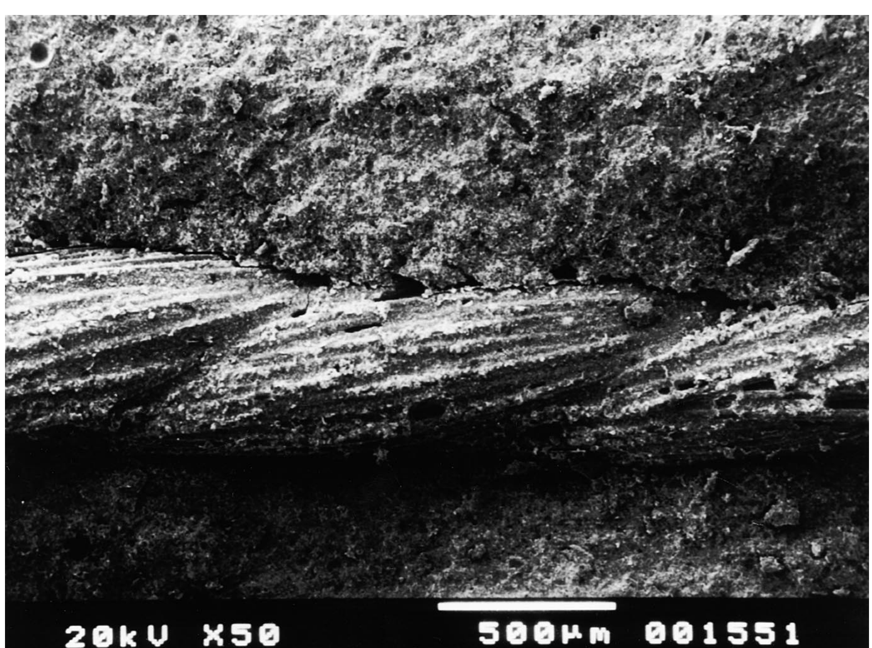

Fig. 7. SEM micrographs of the twisted ×2 bundle with a coating of latex.

Table 5
Effect of yarn structure on bonding

Yarn type	Bond improvement over a straight yarn (%)	Bond per single filament (MPa)
Crimping—5 crimps/cm	260	0.44
Crimping—7 crimps/cm	306	0.52
Twisted bundle	45	0.31

composite. However, the efficiency factor is greatest in the case of the monofilament composite. The low reinforcing efficiency of the bundled yarn can be attributed to limited penetration of the cement matrix between the filaments of the bundle (i.e. low bond).

The crimped and the twisted shape of the individual yarns significantly improved the composite flexural strength compared with the straight yarn; the improvement is between 150% and 300%. The irregular shape of these yarns also led to an enhanced strain hardening response in flexure. The crimped shape resulted in a higher flexural strength (although the fiber volume fraction was lower than that of the twisted yarns) and on extremely high efficiency factor compared with the twisted yarn. This high efficiency factor of the crimped yarn (1.35, compared with only 0.22 of the twisted yarn) reflects its very high bond in the cement matrix, as was observed in the pullout tests (Table 5). Increasing the crimping in the yarn (the crimp density) improves the flexural performance. Efficiency factors greater than 1, as observed here, may indicate that the yarns induce a strengthening effect which is associated with enhanced ductility in tension, resulting in further increase in flexural strengths. A review of such strengthening mechanisms is provided in Ref. [4].

3.2.2. *Effect of fabric structure*

Three different fabric systems were examined in flexure:

(i) woven fabrics in which the reinforcing yarns are in a crimped shape,
(ii) weft insertion knitted fabrics where the reinforcing yarns are in a straight form,
(iii) short weft knitted fabrics having a relatively complicated geometry of the reinforcing yarns.

The flexural performance of composites prepared with these fabrics is presented in Table 3. All the fabric composites, including low modulus yarns, exhibited strain hardening behavior in flexure, and thus, the flexural strength might be considered as representing the load carrying capacity of the reinforcing yarns in the composites.

The short weft knitted fabrics exhibit extremely high efficiency factors, up to 3.08. This is much greater than the efficiency factors of the woven fabric, which is 1.01 to 1.21, and the weft insertion knitted fabrics, in which all the values are lower than 1.0, even for the high modulus yarns. Note that in both woven and short weft knitted fabrics (monofilament), the reinforcing yarns are made from the same low modulus PE monofilament. Moreover, even when the short weft knitted fabric is made from film, the efficiency factor is quite high compared with the woven fabric from PE monofilament. This trend is different from that of the individual single film, which exhibited a low efficiency factor of 0.34 (Table 2). The flexural strength of the short weft knit from monofilament is relatively high (16 MPa), compared to its low yarn content (3 warps/cm).

The better flexural performance of the short weft fabric might be explained on the basis of bonding. In these knitted fabrics, the reinforcing yarns are in a relatively complicated shape, which apparently induces anchoring effects, since they are held tightly by the fabric structure. When the reinforcing yarns in the short weft knitted fabrics are parallel to the applied load, their contribution to the composite performance is higher.

The HDPE fabric shows a poor performance relative to the superior properties of its yarn (it is no better than the low modulus PE). This might be attributed to its low bond (Table 4). The Kevlar fabric seems to provide the best performance in flexure, which reflects the superior properties of the yarn and the small number of filaments in the bundle. The PP does not exhibit any appreciable strain hardening, due to a combination of low modulus and

Table 6
Effect of fabric structure on bonding

Fabric type	Yarn type	Number of filaments in a bundle	Effect of fabric structure on bonding, % of external bond of straight yarn tested individually (%)
Woven			
7 yarns/cm[a]	PE (low modulus)	1	700
5 yarns/cm[a]			430
Knitted weft insertion	PP (low modulus)	100	80
3 yarns/cm[a]	Kevlar (high modulus)	325	55
	HDPE (high modulus)	900	15

[a] Density of yarns perpendicular to reinforcing direction.

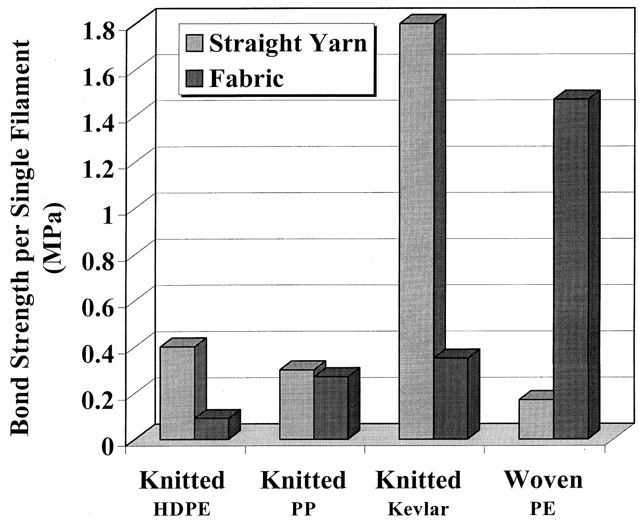

Fig. 8. The effective bond of single yarns and yarns in a fabric for different types of fabrics and yarns.

relatively low bond, which are reflected in its low modulus as well as the geometry of the fabric.

Fig. 9 compares the efficiency factor values of composites made with woven PE and weft insertion HDPE knitted fabrics, to reference composites prepared with straight yarn and crimped yarn untied from the woven fabric. It can be seen that the efficiency factor values of the woven fabrics is greater than that of the straight yarns, but lower than the value of the crimped yarn (untied from the fabric). This suggests that the geometry of woven fabric improves the bonding with the cement matrix, and that this improvement is mainly due to the crimped shape of the reinforcing yarns in the fabric. On the other hand, opposite trend was observed for the weft insertion knitted fabric: in this case, the value of the efficiency factor was lower than the value for the straight yarn. This correlates with the poor bond of the knitted fabric (Table 6).

These characteristics are also demonstrated in Fig. 10 in which the effect of the density of the perpendicular yarns on the flexural strength of woven and weft insertion knitted fabrics is plotted. The positive effect of increasing density is clearly seen for the woven fabric, demonstrating that increased density enhances the positive influence of the crimping, especially in the low density range. At higher densities, the trend is reversed since the poor compaction is apparently too great to be compensated for by the increased crimping. The situation is quite different for the weft insertion knitted fabric, where an increase in density is associated with an immediate marked reduction in flexural properties. Here, the interference with compaction is not compensated for by any other counteracting mechanism (such as the improved bonding due to crimping in the woven fabric).

It is interesting to note the differences between these two fabrics at 0 density: this point represents reference composites which are reinforced in the longitudinal direction with straight yarns, with no perpendicular yarns (i.e. these are hand-laid yarns, representing the reinforcing yarns in the fabric). The improved performance of the HDPE yarn at this point reflects the better properties of the yarn (modulus and strength greater by about an order of magnitude relative to the PE—Table 1) and its effective bond which is higher by almost a factor of 3 (Table 4). However, in the fabric, the trend is reversed, and the effective bond of the HDPE is smaller by more than an order of magnitude than that of the PE (Table 4—bond per single filament in the bundle). This may be due to the fact that the reinforcing yarns in the weft insertion knitted fabrics are straight, made from bundles and connected at the joint points by stitches. The efficiency of

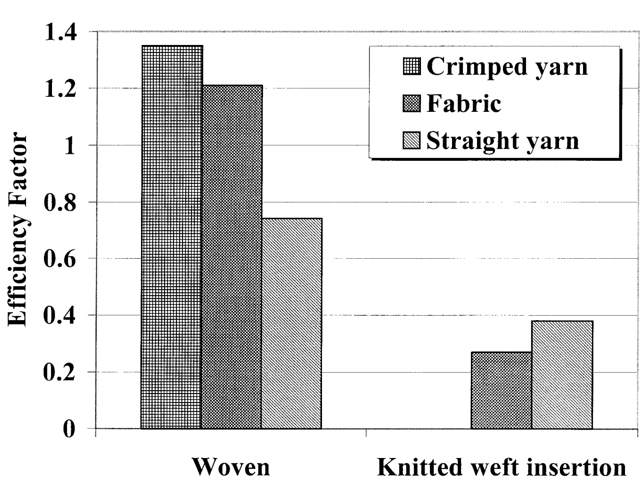

Fig. 9. Comparison between the efficiency factor of individual yarns and fabrics for two systems: woven PE and knitted weft insertion HDPE.

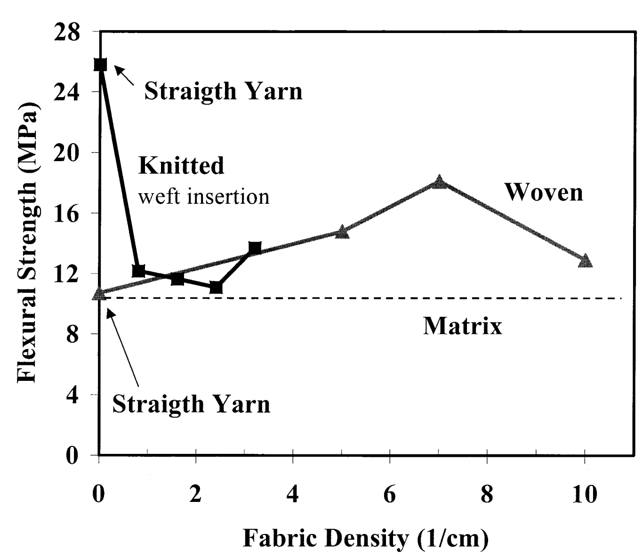

Fig. 10. The influence of the density of yarns perpendicular to the main reinforcement on the flexural strength.

bundles as reinforcement for the cement composite was found to be quite low (Table 2), due to poor penetration of the matrix between the filaments. When these bundles are kept in a straight form but as part of a knitted fabric structure, the penetrability of the matrix is even lower, due to the presence of the bulky stitches themselves, as well as the tightening effect of the stitches which strongly hold the filaments in the bundle and prevent spaces from being opened between them.

4. Conclusions

(1) Predictions of the performance of cement composites reinforced with fabrics should take into account the bulk properties and geometrical characteristics of the yarns making up the fabric as well as the structure of the fabric itself. Such geometry can be a straight form in weft insertion knitted fabrics, a crimped form in woven fabrics, or a more complicated shape in short weft knitted fabrics. Also, the bundled nature of the yarn should be taken into consideration, whether it is as a film, monofilament, or multifilament (the number of filaments in the bundle) as well as the bundle twisting.

(2) Fabrics for cement reinforcement cannot be viewed simply as a means for holding together continuous yarns to enable them to be readily placed in the cement matrix. The geometry of the fabric may have a marked effect on the properties of the composites; it may enhance bonding and result in a strain hardening behavior of low modulus yarn composites, or drastically reduce the efficiency of a high performance bundled yarn that is very effective for reinforcement when it is not part of a fabric.

(3) The enhanced bonding of the fabric structure was found to be mainly dependent on the special geometry induced to individual yarns by the fabric structure. This special geometry may provide mechanical anchoring of the reinforcing yarns in the cement matrix. Thus, fabrics having relatively complicated yarn shapes, such as short weft knit, enhance the bonding and improve the composite performance.

(4) The simplistic predictions of the reinforcement by fabrics usually take into consideration only the longitudinal yarns in the fabric, which are in the loading directions. The perpendicular yarns are treated as "non-structural," whose object is to provide a mechanism to hold the longitudinal yarns in place during the production of the composite. However, the results of the present study indicate that these apparently "secondary" yarns may have significant and opposing influences: in woven fabric structures, they enhance bonding and therefore an increase in their density (up to an optimum value) is beneficial. On the other hand, in weft insertion knitted fabric, this "secondary" reinforcement is detrimental to bond, and its density should be kept to the minimum required to obtain a stable fabric that can be handled in the production of the composite.

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