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Pre-tensioning of fabrics in cement-based composites

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Abstract

This paper studies the effects induced by applying a pre-tension load during the production of fabric–cement composites. The flexural behavior as well as the bonding between the different fabrics and the cement matrix was examined, as a means for characterizing the processing parameters. Microstructure characteristics of the fabric–matrix interface as well as the viscous elasticity properties of the fabrics were also explored and correlated with the mechanical properties of the composite. It was found that pre-tensioning of fabrics and the time at which the tension is removed can significantly influence the performance of the composite depending on yarn properties, mainly the viscous–elastic properties, and fabric geometry.

Keywords: Bending strength; Pull-out strength; Cement; Composites; Textile

1. Introduction

Unreinforced cement-based products are brittle, having high compressive strength but low tensile strength and low toughness. The main method to improve the tensile strength, flexural strength, and toughness of thin cement-based elements is by adding fiber reinforcement [1,2]. A wide range of fiber types can be used for reinforcement in cement-based materials. Fibers with high modulus of elasticity, such as Glass and Kevlar, improve the tensile strength and the toughness of the cement composite, leading to strain hardening behavior. Fibers with low modulus of elasticity such as polypropylene (PP) and polyethylene (PE) are also used, mainly to control cracking and to improve the ductility of the composite product. The reinforcements can be either in the form of short fibers, continuous reinforcements (yarns, filaments), or fabrics. There are several methods to produce fabrics, resulting in different geometries: weaving, knitting, breading and non-woven. The wide variety of production methods allow extensive flexibility in fabric design which enables control of the fabric geometry, yarn geometry, and orientation of yarns in the fabric in various directions. This enables the design and engineering of a large range of cement and concrete products.

The use of textile fabrics as reinforcement for cement and concrete elements is gaining increase interest in recent years for various applications such as thin elements, lightweight products, repair, strengthening, and prestressed concrete components [3–8]. It was reported that fabrics of adequate geometry could improve the mechanical performance of cement composites to a greater extent than that obtained with straight yarns not in a fabric form. Enhancement of mechanical properties could be obtained even with low modulus yarns, due to increased fabric–cement bonding through mechanical anchoring [9].

Several studies reported that the processing characteristics of cement-based composite could have a substantial impact on the properties of the final product [10–14]. The manufacturing process could affect the properties of the composite even when the same matrix and fibers were used.

When continuous reinforcements such as fabrics are used there is, in most cases, a need to apply tensile load during the composite production in order to keep the yarn and fabric parallel to the reinforcing axis. The properties and geometry of the reinforcement, as well as the level of tension applied during the composite production and the time at which the tension is removed, can significantly influence the overall behavior of the cement composite components. Peled et al [15] reported differences in the bond strength between a polyethylene yarn and a cement matrix when the level of pre-tension loads was

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changed. In addition, several researchers reported that concretes which were prestressed with fabrics exhibited very promising results [7,8,16]. Concrete prestressed with fabrics can increase the load bearing capacity of the element as well as the cracking force, providing a better utilization of the fabrics.

This paper studies the influence of pre-tension loads applied during composite production, as well as that of the time of removal of those loads on the flexural behavior and on the bonding between different textile fabrics and the cement matrix, as a means for characterizing the processing parameters. The bond was studied by pullout tests. The influences of the pre-tensioning on the microstructure characteristics of the fabric–matrix interface were examined and correlated with the mechanical properties of the composites. The viscous elasticity properties of the various fabrics were also evaluated and related to the flexural and pullout behavior of the composites. A variety of fabric geometries, such as woven and warp knitted, as well as fabrics made with low and high modulus yarns, were examined. Individual yarn which made up the fabrics were also studied for comparison.

2. Experimental procedure

2.1. Fabrics and yarns

Three different fabric structures were studied: (i) weft insertion warp knitted fabric (Fig. 1a), (ii) woven fabric (plain weave, Fig. 1b, and (iii) warp knitted short weft fabric (Fig. 1c). The various fabric structures result differences in reinforcing yarns geometry: (a) straight geometry of the yarns in the weft insertion knitted fabric; (b) "zigzag" shape of the yarns in the warp knitted short weft fabric, these yarns are tightly held by the perpendicular yarns; and (c) crimped shape of the woven fabric yarns.

The weft insertion knit fabrics were made from high modulus Kevlar yarns and low modulus polypropylene (PP) yarns, both in a bundle form. The woven and short weft knitted fabrics were made from low modulus polyethylene (PE) in a monofilament form. The properties and geometry of the yarns making up the fabrics are presented in Table 1. More details on fabric structures and densities are provided in Ref. [3].

Table 1
Properties and geometry of yarns

Yarn type	Yarn nature	Tensile strength (MPa)	Modulus of elasticity (MPa)	Filament size (mm)	Number of filaments in a bundle	Bundle diameter (mm)
PE	Monofilament	260	1760	0.25	1	0.25
PP	Bundle	500	6900	0.04	100	0.40
Kevlar	Bundle	2300	44,000	0.008	900	0.25

2.2. Preparation of fabric–cement composite for flexural tests

During the preparation of the fabric–cement elements, tensile loads must be applied in order to keep the yarn or fabric parallel to the reinforcing axis. This initial loading can affect the mechanical properties of the composite. The pre-tensioned (prestressed) component may exhibit improved cracking behavior and good overall performance. Composite specimens with 4 layers of fabric were prepared from the different fabrics. These composites were made by hand lay-up of the fabrics in 0.4 water/cement ratio paste matrix (water + cement only), giving a laminated specimen with ∼2 mm cement paste between the fabric layers. The reinforcing yarns were placed along the length of the bending specimens. All the fabrics were pre-tensioned by a load value of 1 kg/cm width of fabric (∼7 MPa) during composite production. Two sets of specimens were prepared for each fabric type: in one set the pre-tension was released immediately after casting, and in the second set the pre-tension was removed 24 h (1 day) after casting. For the high modulus Kevlar fabric another set of specimens was prepared; in this set the pre-tension was released 7 days after casting (168 h).

All specimens were 10 mm thick, with lengths and widths of 110 and 20 mm, respectively. Six specimens were prepared for each fabric type and for each pre-tension load release time. 24 h after casting, the composites were demolded and cured in 100%

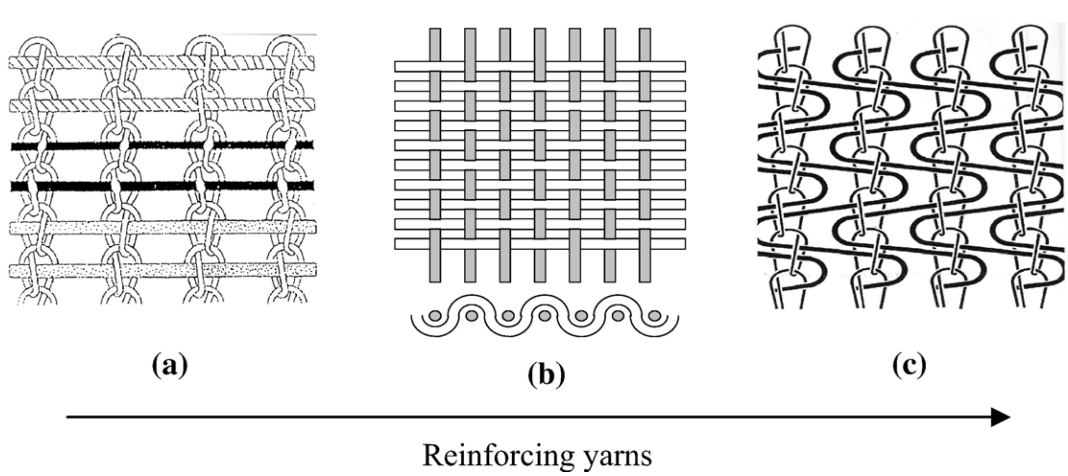

Fig. 1. Geometry of the different fabrics: (a) weft insertion knitted fabrics, (b) woven fabric, and (c) short weft knitted fabric.

RH (Relative Humidity) and 20 °C for up to 21 days, and the flexural properties were then evaluated.

2.3. Preparation of specimens for pullout tests

The influence of the pre-tension on the bond between the fabric and the cement matrix was studied in pullout as well. The specimens for pullout were prepared by hand lay up of a single layer of fabric in the center of a cement paste with 0.4 water/cement ratio (same as the bending specimens). The width of the fabric in the specimen was 10 mm. All fabrics were pre-tensioned by a load of 1 kg/cm during specimen production, the same as the bending specimens. Two sets of specimens were prepared, similar to the flexure specimens, for each fabric type: in one set the pre-tension was released immediately after casting and in the second set the pre-tension was released 24 h after casting. For comparison, similar two sets of specimens were prepared with a single yarn used to make the fabrics. In these specimens a single yarn was placed in the center of the cement paste with the same tension level as that for the fabrics. Also with the single yarn specimens, the pre-tension was released immediately after casting and 24 h after casting. In the case of the yarns only, another set of specimens was prepared; in this set the pre-tension load was removed 7 days after casting (168 h).

For the pullout tests, specimens with PE, PP and Kevlar were prepared, fabrics and yarns. In the case of the PE, only woven fabric was tested in pullout, as it was impossible to pullout the short weft knit fabric due to its complex geometry (Fig. 1c).

The specimens were removed from the mold 24 h after casting, and cured in 100% RH and 20 °C for 21 days similar to the bending specimens and then tested in pullout. Each specimen for pullout was 10 mm thick and 20 mm wide with a length equal to the embedded length of the fabric or single yarn (10 mm long).

3. Testing

3.1. Flexural tests

The flexural properties of the fabric–cement composites were determined by four-point loading at a span of 90 mm. The test was carried out in an MTS testing machine at a crosshead rate of 1.5 mm/min. Load-deflection curves were recorded and the flexural strength as well as the area under the curve (toughness) of the composite was calculated. The test was discontinued when the central deflection approached 8 mm. The test results are the average of at least 5 specimens. Typical curves from each test set were chosen for comparison.

3.2. Pullout tests

Pullout tests were carried out with a crosshead rate of 1 mm/min. The test was continued until the embedded fabric or yarn was completely pulled out. The test setup is presented in Fig. 2.

During the pullout test it was not possible to constantly hold the fabric or single yarn in the grip exactly at the exit point of the fabric/yarn from the cement matrix. The grips were attached in such a fashion as to leave a free length of fabric/yarn between the edge of the sample and the machine grip, as presented in Fig. 2. This free fabric length affected the slip deformation recorded during the pullout tests. The deformation of the free fabric is inconsequential to the interface properties and should be accounted for as pointed out by Shao et al. [17]. In the present study only the maximum pullout loads were considered and the bond strengths were calculated for each set of fabric and time of pre-tension release.

3.3. Viscous–elastic tests of fabrics

The behavior of the different fabrics themselves (without the cement) under continuous loading was studied, in order to estimate the influence of tensioning on the behavior of the fabric when it is part of the composite. Two main parameters can influence the behavior of fabrics under continuous loading: the raw material of which the yarn making up the fabric is composed of, and the fabric geometry. The different fabrics (low modulus knitted PP and woven PE, and high modulus knitted Kevlar) were loaded for 168 h (7 days) with a pre-tension of 1 kg/cm width of fabric. The change in fabric length over time – i.e., the creep behavior of these fabrics – was measured. The measurements were taken every 12 min for the first hour and then at 2, 5, 20, 24, 50, 100 and 168 h, for all fabrics. The change in fabric length vs. time, relative to the length of the original fabric before applying the load, was plotted for each fabric. After 168 h the load was released and the level of fabric retraction – i.e., the ability of the fabric to shift back after creeping – was measured 10 min after removing the tension. The strain of the fabrics after retraction was calculated (the remains deformation of the fabric relative to its original length before creeping). The results are an average for at least 3 specimens for each fabric type.

3.4. Microstructure characteristics

Fragments of specimens obtained prior to and after pullout tests were dried at 60 °C and gold-coated for observation

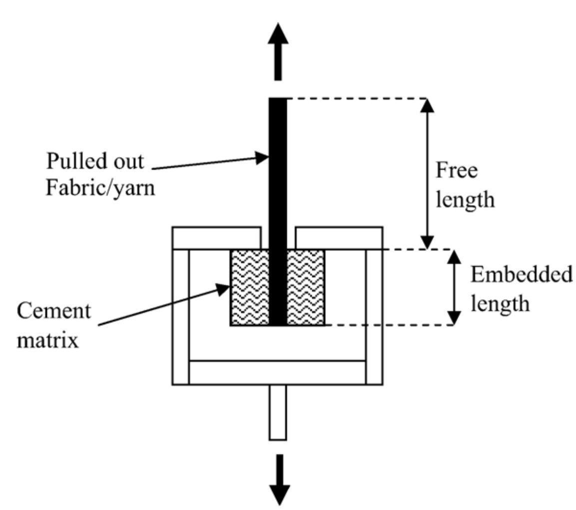

Fig. 2. Pullout tests set up.

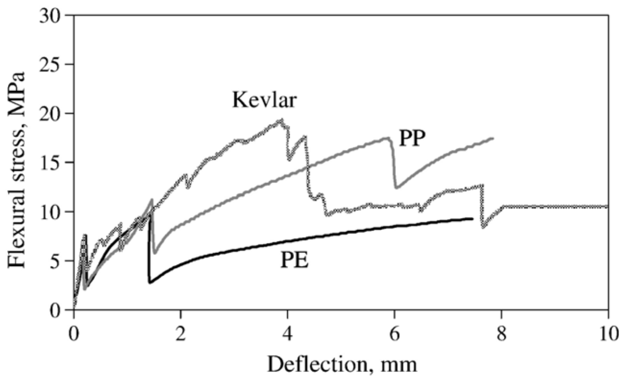

Fig. 3. Flexural behavior of fabric–cement composites with the different fabrics, pre-tension was removed immediately after casting.

under SEM to characterize the microstructure of the fabric–cement interface. The microstructure of the fabric–cement interface was characterized for the low modulus PP and the high modulus Kevlar. Observations were carried out for specimens where the initial load was released immediately after casting, 1 day after casting, and 7 days after casting. Attention was given to the microstructure of the matrix groove around the reinforcing yarn (tensioned yarn), i.e., the foot prints of the reinforcing yarns in the matrix. These microstructure features were correlated with the pullout and bending properties.

4. Results

4.1. Flexural performance of the composite

Fig. 3 compares the flexural behavior of the composites with the different fabrics. The fabrics in these specimens were subjected to a pre-tension of 1 kg/cm and the pre-tension load was removed immediately after casting. The Kevlar system exhibits strain-hardening behavior, while the PE system tends to show an elastic–plastic behavior. The PP system is in-between, showing moderate strain hardening.

The effects of pre-tensioning and the time of removal of this tension on the flexural performance of the different composites are presented in Table 2 and Figs. 4, 5, and 6. Several types of tendencies can be observed:

(a) For both; the short weft knitted PE (Fig. 4a) and the weft insertion knitted PP (Fig. 4b), the time of pre-tension release does not affect the flexural performance. Note that in knitted PP fabric the reinforcing yarns are straight.

Table 2
Flexural properties of the composites with the different fabrics and time of pre-tension released

Material type	Fabric geometry	V_f, %	$\sigma_{ultimate}$, MPa			Toughness, N*mm		
Initial load release, days			0	1	7	0	1	7
PE	Woven	5.7	10.2	4.2	–	1046	994	–
PE	Knit [a]	2.0	6.0	6.8	–	547	684	–
PP	Knit [b]	3.5	17.7	16.7	–	1856	1937	–
Kevlar	Knit [b]	3.5	19.5	10.8	27.2	2286	1001	32

[a] Warp knitted short weft.
[b] Warp knitted weft insertion.

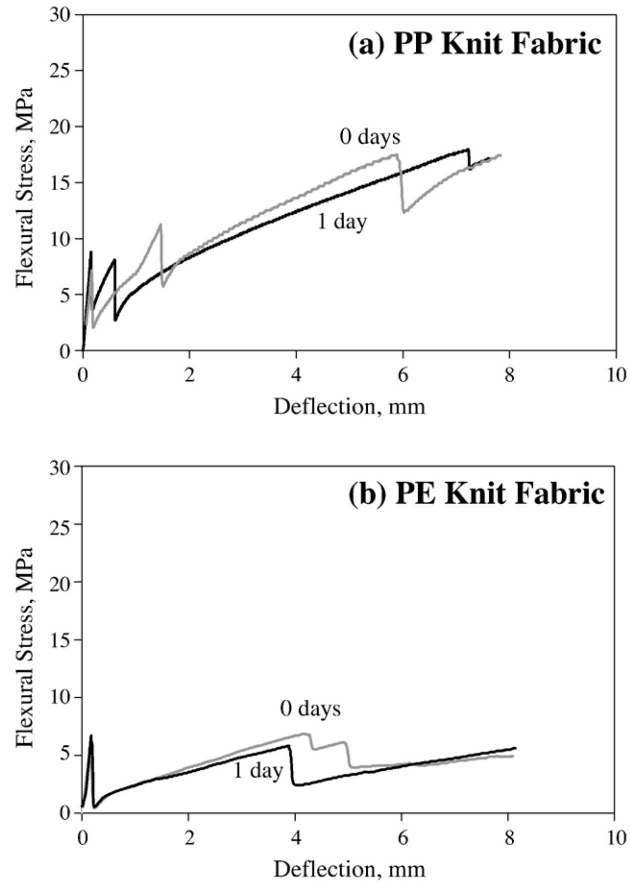

Fig. 4. Effects of time of release of the pre-tension on flexural behavior of low modulus fabric composites: (a) weft insertion PP knitted fabric and (b) short weft PE knitted fabric.

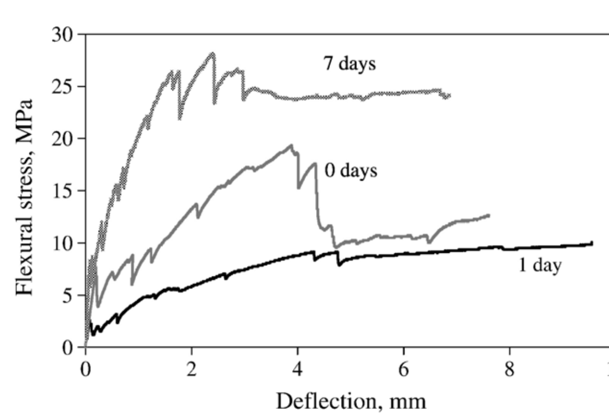

Fig. 5. Effects of time of release of the pre-tension on flexural behavior of high modulus Kevlar knitted fabric composite.

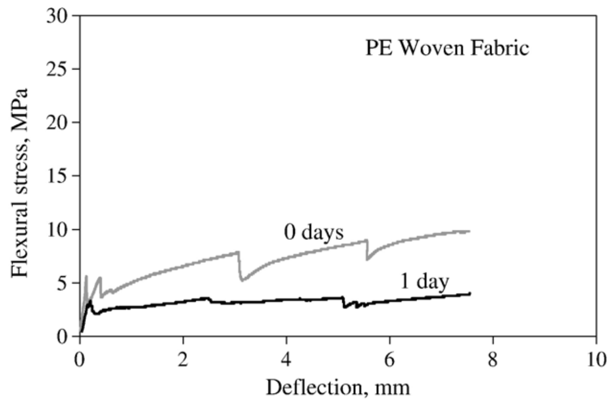

Fig. 6. Effects of time of release of the pre-tension on flexural behavior of the low modulus PE woven fabric composite.

With the knitted PE fabric the reinforcing yarns are in a "zigzag" geometry but are held strongly and tightly to the fabric, resulting in a stiff structure.

(b) For the high modulus knitted Kevlar (Fig. 5), releasing the pre-tension after 1 day results in a weakening of the composite. Both strength and toughness are reduced (Table 2). A reduction of about 50% in strength and toughness is observed compared to a composite where the pre-tension was released immediately after casting. A reduction in composite performance is also observed with the low modulus woven PE fabric (Fig. 6, Table 2). The differences in the behavior of the PE woven and PE knitted fabrics indicating that the effects related to the time of release of the initial load are dependent not only on yarn properties but also on fabric geometry as in both fabrics the same PE yarn was used.

(c) For the high modulus-high properties Kevlar fabric (Fig. 5), releasing the pre-tension load after 7 days results in a significant strengthening of the composite. Excellent flexural behavior with strengthening and toughening of about 30% is observed when comparing the 7 days and immediate-release composites. Greater stresses and a much stiffer response at early loading stages (low deflections) of the 7-days-to-release composite are seen, compared to the other two time released systems. This is beneficial with cement-based products.

In view of the above, it can be summarized that the pre-tension release time can have a significant influence on the flexural performance of fabric–cement composites, depending on yarn material, yarn modulus of elasticity, and fabric geometry.

4.2. Pullout properties

The bond between the different fabrics and their yarns (single yarns) and the cement matrix was studied by pullout tests for systems with different release times: immediate and 1 day after casting. For the yarns only, a set of specimens with a tension release time of 7 days after casting was also studied. The pullout test was performed for the low modulus woven PE and knitted PP systems, and the high modulus knitted Kevlar system. Note that the PP and Kevlar knitted fabrics are with the same geometry. The average bond strengths are presented in Table 3 and Figs. 7 and 8 for the different yarns and fabrics, the yarns results are presented along with the standard deviation values.

The trends of pullout results are quite different for the high Kevlar and low modulus PP and PE systems described as follows (for 1 day and immediate release):

(a) The releasing of the pre-tension after 1 day results in a weakening of the bond between the high modulus Kevlar and the cement matrix. In the case of the yarn the Kevlar exhibits bond strength of 2.73 MPa when the pre-tension load was removed immediately after casting (Fig. 7 and Table 3). Significantly lower bond strength of 0.87 MPa was observed for the Kevlar yarn when the load was released 1 day after casting, i.e., reduction of about 70%. A similar trend was also seen for the Kevlar fabrics when comparing the systems with differing release times (immediate and 1 day), but was not as significant (Fig. 8).

(b) The pre-tension release time (1 day and immediate) does not significantly affect the bond strength between the low modulus PP and PE yarns and the cement matrix (Fig. 7). No reduction in bond strength is observed with the PP and PE fabrics either (Fig. 8).

The release time barely affected the bond strength of the low modulus yarns, PP and PE, also when the pre-tension was released 7 days after casting (Fig. 7). However, the situation is quite different for the high modulus Kevlar yarn. In the case where the pre-tension load was removed 7 days after casting a substantial improvement in bond strength was observed compared to the 1 day release system; but more than that, the 7 days release system exhibits even greater bond strength than that observed in the system where the pre-tension load was released immediately after casting. The bond strength value in the 7 days release system is as high as 3.55 MPa, providing an improvement of more than 20% in bond strength over that in the immediate release system. A similar improvement of 30% was also reported in flexural strength for the Kevlar system (Table 2).

The above results indicate: (i) the bond between the Kevlar and the cement matrix is significantly influenced by the time at which the pre-tension load is released, (ii) when the initial load is released after a short time (1 day after casting) the bond

Table 3
Bond strengths of fabrics and yarns

Material type	Bond strength, MPa				
	Fabric		Yarn		
Initial load released, days	0	1	0	1	7
PE	0.31	0.30	0.28	0.22	0.25
PP	1.00	1.33	0.97	0.84	0.85
Kevlar	1.67	1.10	2.73	0.87	3.55

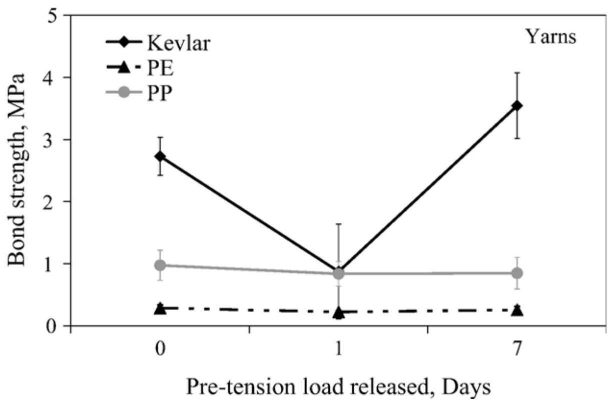

Fig. 7. Bond strength of the different yarns vs. time at which the pre-tension loads were released.

strength is diminished, (iii) late release of the pre-tension load (after 7 days) with the high modulus Kevlar yarn improves the bond with the cement matrix, and (iv) these effects are not observed with low modulus yarns (PP and PE). These trends are similar to the flexural behavior of the low modulus systems, PP and PE (Fig. 4) as well as the high modulus Kevlar system (Fig. 5).

4.3. Viscous elasticity behavior of fabrics

In order to better understand the influences induced by pre-tensioning of the fabrics when they are part of the composite, it is important to examine the behavior of the fabrics under continuous loading when they are not in a cement matrix. Therefore, the change in fabric length (out of cement) under a continuous tensile loading of 1 kg/cm and its retraction level after removing the load were studied. Fig. 9a presents the creeping results. The low modulus woven fabric exhibits the highest creep behavior, followed by the knitted low modulus PP fabric. The high modulus knitted Kevlar fabric is less affected by continuous loading. The PP and PE are both low modulus fabrics and therefore exhibit high creep, the modulus of the PE is lower (1.8 GPa, and 6.9 GPa for the PE and PP respectively, Table 1) leading to its increased creeping. Note that the PE is in a woven structure where the yarns are in a crimp shape (Fig. 1b). This crimping may result some of fabric lengthening, due to straightening of the crimps, especially at early loading.

After 7 days (168 h) the tensile load was removed from all fabrics. When the tension was removed, the yarn tended to shift back, shortening its length. Fig. 9b shows the strain values of the different fabrics prior removal of the pre-tension load and 10 min after the load was removed. The differences between these two values can indicate the ability of the fabric to retract against the cement matrix (when it is part of the composite) after continuous loading. Similar retraction trend of the elastic deformation after 1 day and 7 days of loading are assumed. Fig. 9b clearly shows that the shortening of the knitted Kevlar fabric is the greatest, while the retraction of the knitted PP is the smallest; i.e., the low modulus PP fabric does not retract as far towards its original length as the high modulus Kevlar fabric. The retraction level of the Kevlar is 0.55% in strain values, where as of the PP is less than 1% strain, i.e., retraction of more than 80% of the Kevlar and only 9% of the PP system (relative to the length of the fabric after 7 days of creeping). The low modulus PE exhibits lower retraction level, of 0.24% strain, than the Kevlar but higher than that of the PP, giving shortening of 16% (relative to the length of the fabric after 7 days of creeping).

The above results indicate that the creeping and retraction levels of the different fabrics are dependent on the properties of

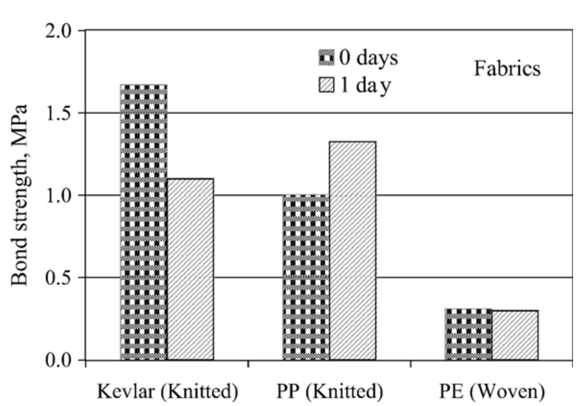

Fig. 8. Bond strengths of fabrics with different initial load released time.

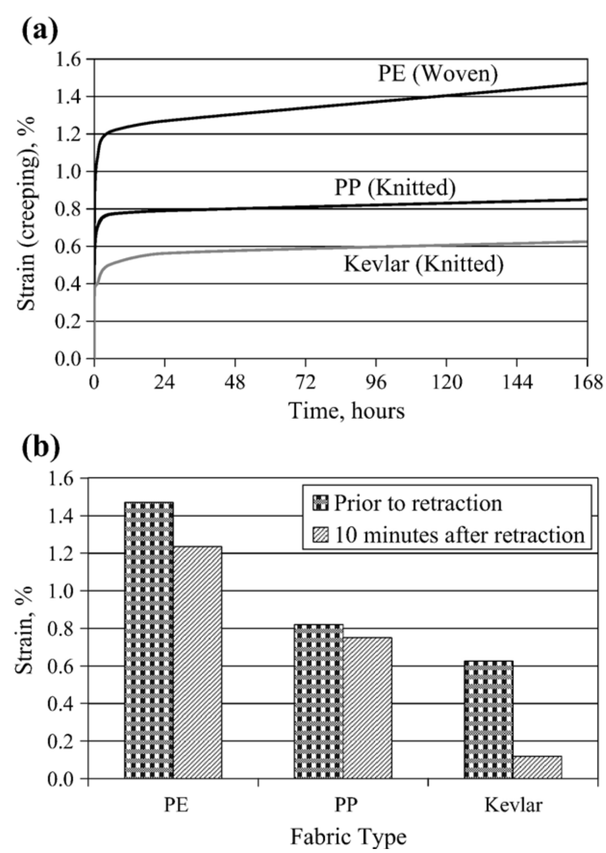

Fig. 9. Viscous–elastic behavior of the different fabrics: (a) creeping, and (b) retraction.

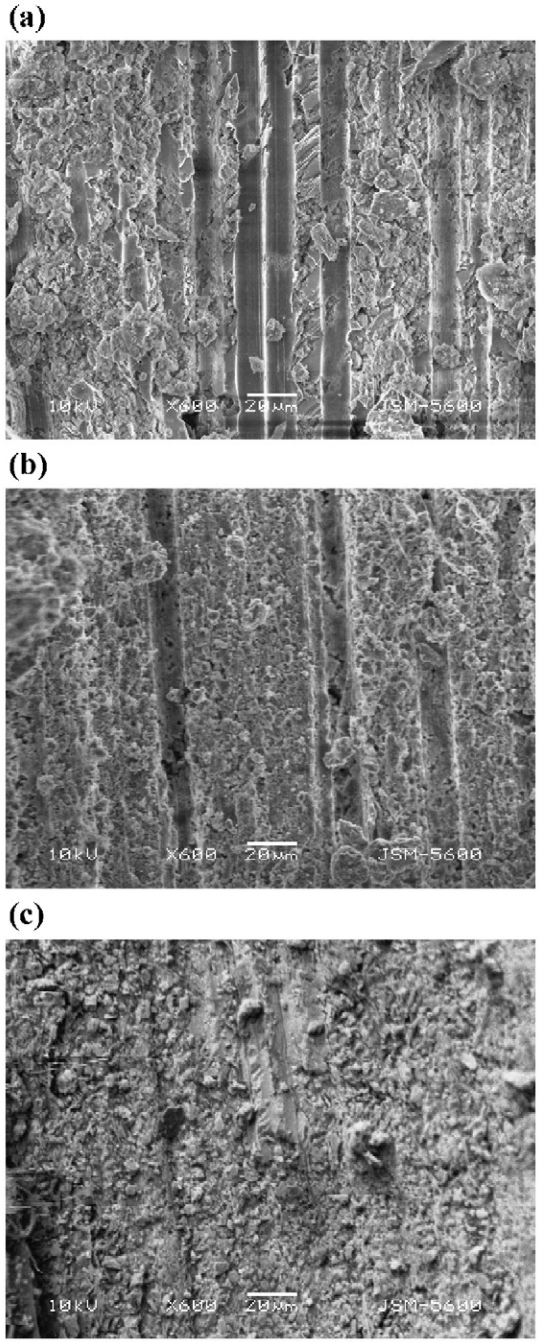

Fig. 10. Grooves in the matrix of Kevlar bundle prior to pullout: (a) the pre-tension was removed immediately after casting, (b) the pre-tension was removed 7 days after casting, and (c) the pre-tension was removed 1 day after casting.

the yarns made up the fabric as well as fabric geometry. The Kevlar and PP systems are having the same knitted fabric structure (Fig. 1a) and in both the loaded yarns are in a straight geometry, suggesting that in these cases the differences in their retraction levels are mainly due to yarn properties (Table 1). The PE is a woven fabric where the loaded yarns are in a crimp shape which may also influence the retraction level. The following described these influences: (i) For the high modulus Kevlar fabric which exhibit low creeping, the yarns shift back significantly when the load is released; (ii) For the low modulus fabrics, PP and PE the level of yarn retraction is small — these are viscous–elastic yarns which exhibit large creep, and the stresses within the yarn are relaxed during tensioning. The woven PE fabric retracts less than the high modulus fabric, but it does shorten by about 16%, as the yarns can "coil" back to their crimped shape when the load is released, at least to some extent. The level of yarn retraction when the load is released can affect the bonding with the cement matrix, as we will discuss later.

4.4. Microstructure characteristics

Fig. 10 presents SEM micrographs of the cement matrix at the groove around the Kevlar yarn prior to pullout tests for systems where the pre-tension load was released immediately, 1 day and 7 days after casting. For the immediate release system, clear matrix grooves of the bundle filaments are observed (Fig. 10a), due to penetration of the cement matrix in between the filaments of the yarns at the bundle perimeter. The clear print of the bundle yarn on the cement matrix can also observe for the 7 days release system (Fig. 10b). In addition, fibrils are seen on top of the cement groove for the 7 days release system, as observed in Fig. 11. Similar observations of fibrils were also seen for the immediate release system, indicating strong bonding, as it was difficult to peel off the bundle yarn from the cement matrix for the SEM observations.

On the other hand, a relatively smooth surface of the cement matrix with substantial damage of the filament grooves is observed for the Kevlar system where the initial load was released 1 day after casting (Fig. 10c). In this case no clear grooves of the bundle filaments are observed. Such damage might be due to development of relatively strong compression and friction forces at the yarn–cement interface during the removal of the pre-tension load as we will discuss in the next chapter. Damaged of the 1-day-release interface can reduce the bond with the cement matrix and results the low flexural properties compared to the immediate-release and 7-days-to-release systems.

Fig. 12 presents the filament grooves in the matrix of the PP bundle yarn prior to pullout, for the system where the

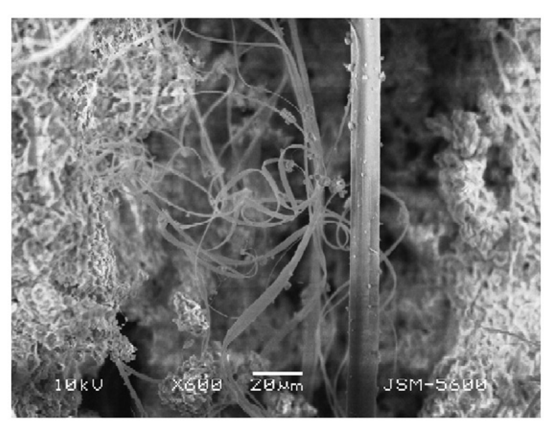

Fig. 11. Fibrils of the bundle on the matrix groove, the pre-tension was released 7 days after casting.

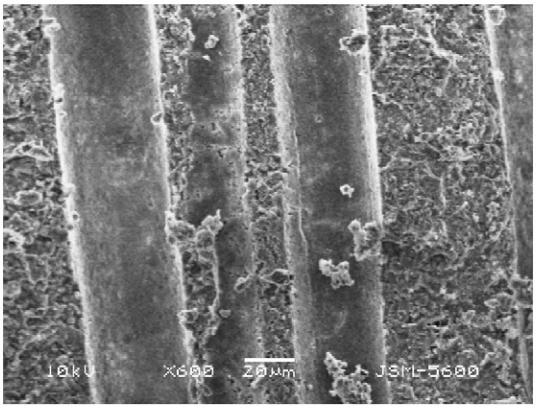

Fig. 12. The grooves in the matrix of PP bundle prior to pullout, the pre-tension was removed 1 day after casting.

initial load was released 1 day after casting. In this case no severe damage is observed at the yarn–matrix interface. Similar effects were also observed in the immediate-release system. This correlates with the bonding and flexural properties of the PP system, where no significant effects were reported for the systems with the different pre-tension release times.

5. Discussion

The results obtained in this study indicated that pre-tensioning of fabrics and the time at which the tension is removed can significantly affect the performance of fabric–cement systems, depending on yarn properties and fabric geometry. Two opposing effects were found:

(i) When high modulus fabric was pre-tensioned (Kevlar), the flexural properties and bond strength were significantly reduced when the initial load was released 1 day after casting, compared to the immediately-released system (Fig. 5 and Table 2). However, when the initial load was removed at a later stage, 7 days from casting, the composite properties are significantly improved. Improved properties were also observed for the PE woven composite with the immediately-released system as compared with the 1-day-to-release system.

(ii) For low modulus fabrics (knitted, PE and PP), the time at which the pre-tension load is released does not significantly affect the flexure and bonding properties of the composite (Fig. 4 and Table 2).

Several mechanisms can be suggested to account for these differences in behavior:

(a) In the high modulus low creep fabric (where the geometry of the reinforcing yarn is straight), when continuous tension is applied and then released, compression and friction forces can develop during the release stage, while the tensioned (reinforcing) yarn is shifted back (Fig. 9b), and laterally expands against the surrounding matrix. When such retraction of the yarn takes place at an early time, after 1 day of curing, the cement matrix is relatively weak and such forces can cause damage at the yarn–cement interface (Fig. 10c). This damaging of the interface can reduce the pullout resistance of the yarn/fabric as indicated in Figs. 7 and 8, leading to the low flexural performance of the composite (Fig. 5). However, if the pre-tension is released 7 days after casting, the matrix is relatively strong and can therefore sustain the compression and friction forces which develop during the retraction and expansion of the released yarn. Thus, no severe damage of the matrix at the interface occurs (Fig. 10b) and the lateral expansion of the yarn can lead to improve bonding (Figs. 7 and 8). The prestressed component with the increased bonding can lead to the excellent flexural properties with stiff behavior and high cracking forces of the composite (Fig. 5). When the initial load is released immediately after casting the matrix is still fresh and can overcome any changes in the bundle yarn position. These may account for the behavior of the Kevlar system.

(b) In the low modulus fabrics the yarns are creeping when continuous tension is applied, the stresses within the yarn can be relaxed during tensioning and there is no

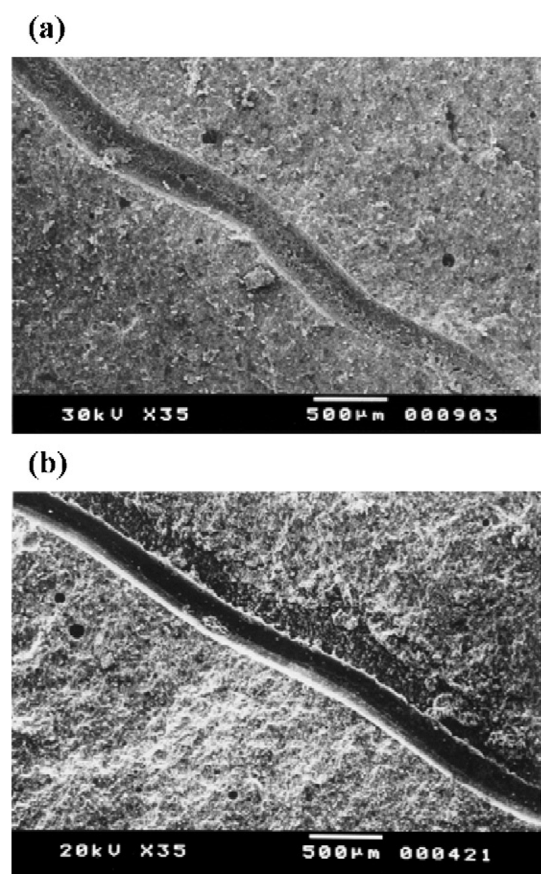

Fig. 13. Influences of pre-tension loading on matrix groove of PE crimped yarn untied from woven fabric (a) low pre-tension load (0.1 N) and (b) high pre-tension load (0.6 N).

significant retraction of the yarn at the release stage (Fig. 9b). No significant lateral expansion of the yarn is expected and compressive stresses are barely developed against the surrounding matrix. Therefore, the matrix is not damaged (Fig. 12) and the bond is similar whether the pre-tension is released after 1 or 7 days from casting (Figs. 7 and 8), resulting no significant differences in flexural performances (Fig. 4). This may account for the behavior of the knitted PP and knitted PE fabrics.

(c) In the case of PE woven fabric, the tensioning results in “straightening” of the crimped yarns. If the pre-tension is released immediately after casting, the yarns are “coiled” back to their original crimped shape. At that stage the matrix is still fresh and can overcome any changes in the crimped yarn location, thus leading to greater mechanical anchoring of the reinforcing yarns with the cement matrix and better flexural performance of the immediate-release system compared to the 1-day-to-release system (Fig. 6). This explanation is supported by microscopical observations (Fig. 13).

6. Summary and conclusions

It was found that pre-tensioning of fabrics and the time of removing the tension can significantly influence the performance of fabric–cement composites depending on yarn properties, modulus of elasticity and viscous–elastic behavior, as well as fabric geometry.

For the low creep Kevlar fabric (with high modulus), the pre-tension can significantly improve the bonding and flexural behavior of the composite, if the tension is released immediately after casting or at late stage. The greatest improvement is at late release where the matrix around the reinforcing yarn is strong enough to sustain the compression and friction forces developed during the removal of the tension. In such case, the prestressed composite exhibits increase in the load bearing capacity of the element as well as the cracking force, providing a better utilization of the fabrics. If the pre-tension is removed at early age, when the matrix is still weak, the transition zone is damaged, resulting in reduction of the bond and the flexural performance.

For the high creep PP and PE fabrics (with low modulus) the time when the pre-tension is removed does not significantly influence the properties of the composite. In this case, no significant compression forces and lateral expansion of the yarn are expected during tension release, due to the viscous–elastic behavior of these fabrics.

The geometry of the fabric should also be considered in cases where pre-tension of fabrics is applied during composite production, as reported in this study for the PE knitted and woven fabrics. With woven fabric, the tensioning results in “straightening” of the crimped yarns. If pre-tension is released immediately after casting, the yarns can retract to their crimped shape to a great degree, thus leading to better mechanical anchoring and improved flexural performance of the immediate-release system compared to the 1 day release system — this is not the case with the knitted fabric where the reinforcing yarn are strongly held by the fabric structure.

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