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Effects of Woven Fabric Geometry on the Bonding Performance of Cementitious Composites

Mechanical Performance

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The effect of the geometry of woven fabrics on the bond between monofilament polyethylene yarns and cement matrix was studied in the present work. The fabrics were all plain weave, with varied fills density: 5, 7, or 10 fills per cm; the warps' density was kept constant at 22 warps per cm. The interfacial bond was evaluated by pullout tests. To characterize the influence of the fabric's geometry on bond performance, the influence of different parameters of the fabric's geometry that may affect bond were separated: (1) pullout of a single crimped yarn untied from the fabric to characterize the influence of the shape of the individual crimped yarn; (2) pullout of a single yarn from free fabric (not embedded in the cement matrix); and (3) pullout of a yarn from a fabric embedded in the cement matrix. Straight yarns were also tested for comparison. It was found that the woven fabric provided a considerably better bond to the cementitious matrix than the bond of a single straight yarn. The crimped geometry of the yarn in the fabric was found to have a significant influence on increasing the bond between the woven fabric and the cementitious matrix. ADVANCED CEMENT BASED MATERIALS 1998, 7, 20–27. *© 1998 Elsevier Science Ltd.*

KEY WORDS: Bond, Cement, Composite, Crimped yarn pullout, Monofilament, Polyethylene, Woven fabric, Yarn

The use of textile fabrics as reinforcement in cementitious composites is potentially quite attractive. A major advantage is the possibility for flexibility in the design of the composite by controlled incorporation of yarns (fibers) to enhance its quality [1]. The use of fabric forms as reinforcement for cement composites has been developed only in recent years. With fabric structures one may achieve rather easily a high volume content of reinforcement and maintain control of its properties by governing its orientation and content. These advantages are essential in the design of thin cementitious elements where primary reinforcement is required. Fabric meshes may generate enhanced bonding performance by providing mechanical anchoring to compensate for the poor interaction between hydrophobic reinforcing yarns (fibers) and the cementitious matrix. Several studies were carried out in an attempt to better understand the flexural behavior of cementitious composites reinforced with woven fabrics [2–4]. It was found that the flexural strength and toughness of the composite increased significantly with woven fabric reinforcement even if the fabric was made of low modulus hydrophobic yarns.

Woven fabrics are commonly made of orthogonal interlacing yarns, warp, and fill. The warp and the fill yarns pass over and under each other, with each yarn having a crimped shape (Figure 1). The density of the fills and warps can be fully controlled independently for each direction. The warp and fill densities affect the crimped structure of each yarn in the fabric and will also have an influence on the penetrability of the cementitious matrix into the fabric. The crimped geometry of the individual yarn is expected to reduce its reinforcement efficiency in comparison to a straight yarn and may lead to stress concentration in the matrix. However, in cement composites the crimped geometry of the individual yarn may be advantageous, since it may provide mechanical anchoring. Improved flexural performance of cementitious composites reinforced with woven fabrics was attributed to improved bonding, induced by the penetration of cementitious matrix through the fabric openings, and to the crimped geometry of the individual yarns in the woven fabric [4]. However, such studies did not deal with the role of the fabric bond characteristics that may have a crucial influence on the composites performance.

To resolve the effects of the woven fabric structure geometrical parameters on bond performance, a systematic study was carried out. Two major effects were studied: (1) the influences of the crimped shape of a

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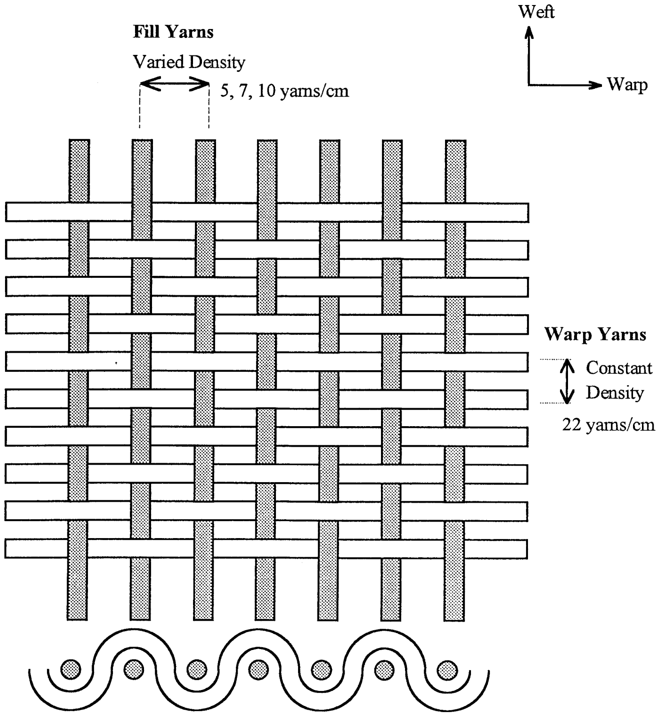

FIGURE 1. Schematic description of fabric structure.

single yarn, and (2) the influences of the warp and fill yarn densities.

The wavy structure of the yarn was evaluated by untying the yarn from the fabric and referring to its geometrical characteristics: its wave length and wave amplitude. The pullout mechanisms involved were reported previously [5], where the bonding capacity was correlated with the wave amplitude of each individual wave, and the wave length determined the number of waves per unit length. It was found that the density of the woven fabric influenced both the wave length and the wave amplitude of the individual yarn.

This article deals with the whole fabric, not just one element of it. The results of pullout tests are reported to evaluate the effects of the fabric geometry on bond capacity. In a subsequent paper, microscopic observations will be reported and discussed to resolve additional characteristics of the micromechanical processes.

Experimental

Fabric Geometry and Properties

The fabrics used in this study were all plain weave, with each warp and fill yarn passing over and under each other, as shown in Figure 1. In this configuration the yarn curvature is larger than in other weave structures. The fabrics were especially produced for this research and their geometry was controlled. They were made with varied fills density: 5, 7, or 10 fills per cm; and the warps' density was kept constant at 22 warps per cm. The yarns were all polyethylene monofilament, 0.25 mm in diameter, to better resolve the interfacial interaction. The mechanical properties of the different fabrics are presented in Table 1 and of the straight yarn, from which the fabrics were produced, in ref. 5.

TABLE 1. Mechanical properties of fabrics

Fill Yarns Density (1/cm)	Tensile Strength (MPa)	Modulus of Elasiticity (MPa)
5	293	1025
7	286	861
10	290.6	672

For simplicity the fabrics will be denoted by their fills density: fabric 5, fabric 7, and fabric 10.

To characterize the influences of the crimped geometry of the individual yarn in the fabric on bond performance, the warp yarns were untied from the different fabrics and were examined separately. Three different crimped yarns were obtained, with 5, 7, and 10 crimps per cm. The crimps' density of the untied yarns will be referred to by the original density of the fill yarns in the fabric, i.e., yarn 5, yarn 7, and yarn 10.

The wavy structure of the individual yarn can be characterized by two main parameters: wave length and wave amplitude. Table 2 presents the measured wave amplitude and wave length of the untied yarns. The data in Table 2 indicate that the woven fabric's density influences both the yarn's wave length and wave amplitude.

The mechanical properties of the individual crimped yarns were presented previously [5].

Test Program

The interfacial bond was evaluated by pullout tests. To characterize and to understand the influences of the fabric's geometry on bond performance, it was necessary to separate the influence of different parameters of the fabric's geometry that may affect bond: the influence of the shape of the individual crimped yarn, the influence of the resistance offered by the interaction

TABLE 2. Amplitude and wave length of fill yarns in embedded fabric at initial tensile load of 0.1 N

Fill Yarns Density (1/cm)	Wave Amplitude (mm)		Wave Length (mm)	
	Yarn	Fabric	Yarn	Fabric
5	0.13	0.19	4.00	3.70
7	0.14	0.18	2.86	2.70
10	0.11	0.24	2.20	2.20

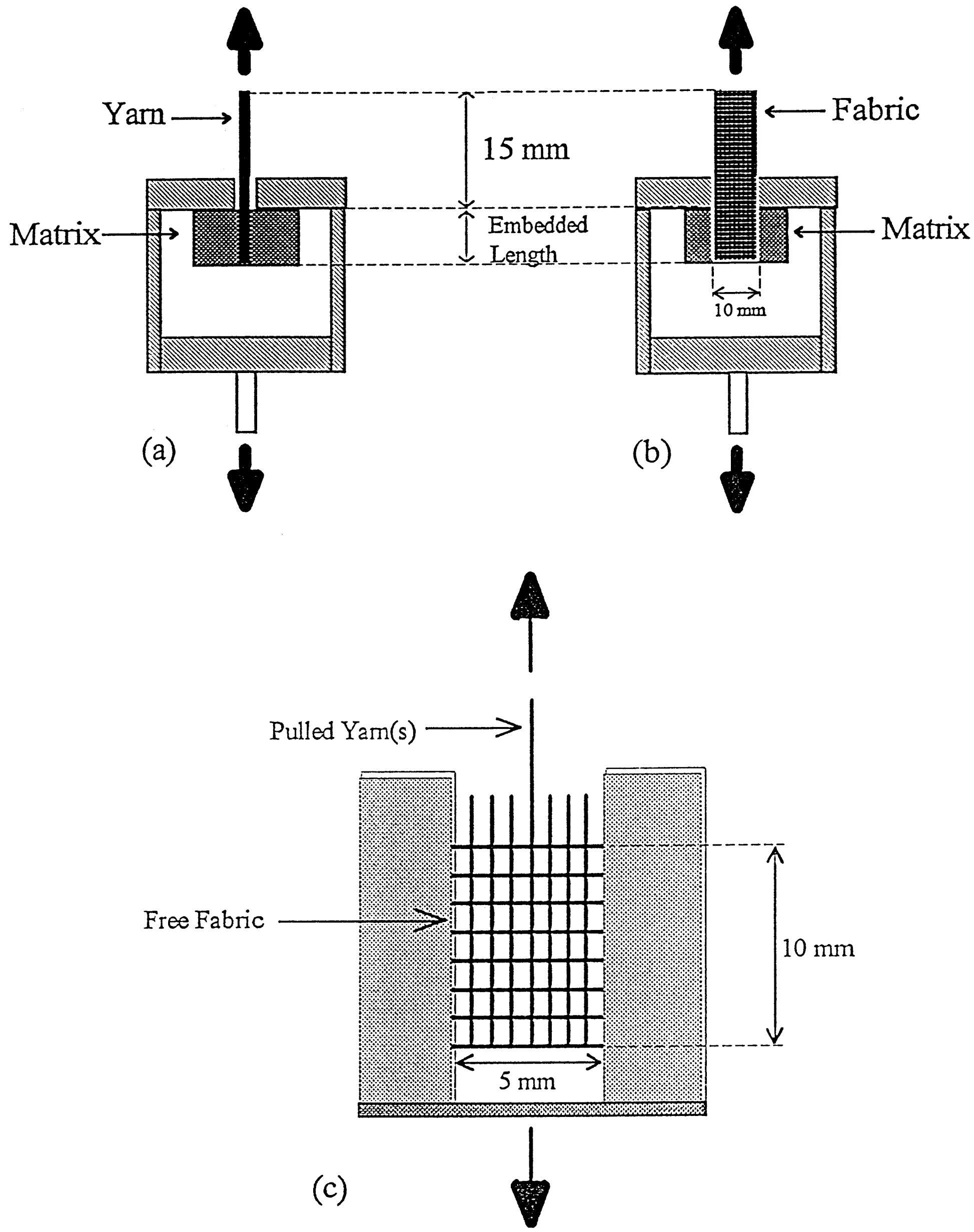

FIGURE 2. Schematic description of the pullout testing arrangement. (a) Yarn from matrix; (b) yarn from embedded fabric; (c) yarn from free fabric.

between the fill and warp yarns at their junction point, and the combined influence of all these parameters in the embedded fabric in the composite. For that purpose three different pullout tests were performed:

(1) Crimped yarns: pullout of a single crimped yarn, which was untied from the different fabrics and embedded in the cement matrix (Figure 2a).
(2) Embedded fabrics: pullout of a single central yarn from a fabric that was embedded in the cement matrix (Figure 2b).
(3) Free fabrics: pullout of a single central yarn from a free fabric that was not embedded in a cement matrix (Figure 2c).

Straight yarns from which the fabrics were produced, having similar cross-section and mechanical properties, were also embedded in a cement matrix and tested for pullout for comparison.

The pullout test of a free fabric and of an embedded fabric was carried out in two directions:

(1) Warp direction: In this case the density of the yarns parallel to the load direction was constant

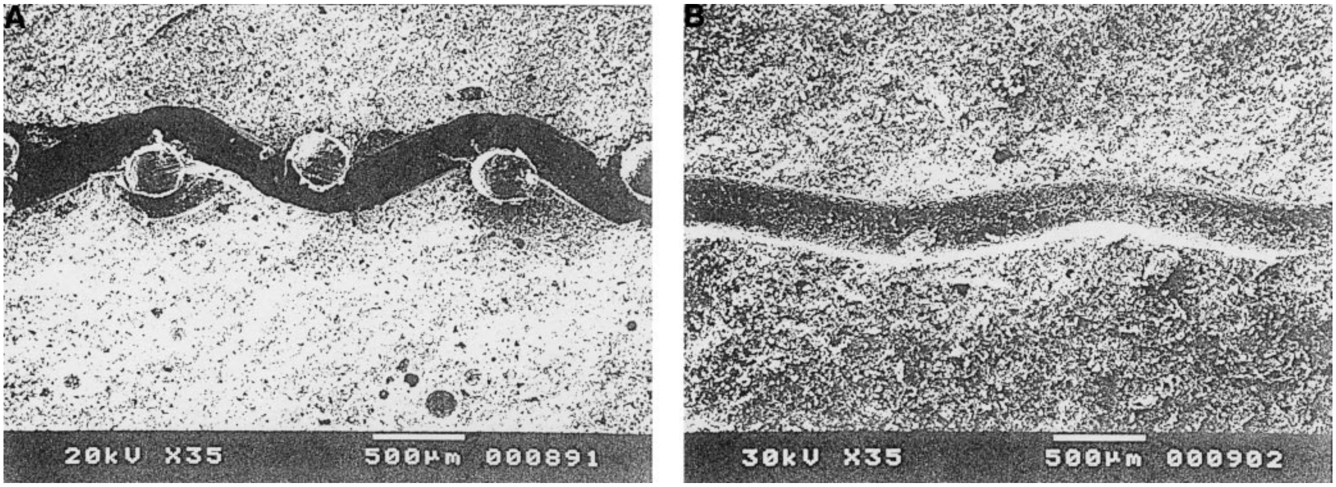

FIGURE 3. Geometry of the groove in the matrix around the crimped yarn. (A) Yarn in embedded fabric; (B) untied yarn in the cement matrix.

(22 yarns per cm). The density of the yarns perpendicular to the load direction was 5, 7, and 10 yarns per cm for the different fabrics. Therefore, increasing the fabric density increased the number of junction points parallel to the pullout load direction, and the shape of the pulledout yarn was more crimped.

(2) Weft (fills) direction: In this case the density of the yarns that were placed parallel to the load direction varied: 5, 7 and 10, yarns per cm. The density of the perpendicular yarns was kept constant (22 yarns per cm). Therefore, the crimps density of the pulled yarn was the same for all fabrics in this group, whereas the distance between the yarns parallel to the load direction varied.

In the case of an embedded fabric, another series of tests was carried out, in which all the yarns parallel to the load direction were pulled out together. This test was intended to examine whether the overall resistance is a simple superposition of a single yarn's resistance. In this series of tests, the density of the embedded fabrics parallel to the load direction was 5, 7, and 10 yarns per cm for the different fabrics tested. The yarns' density perpendicular to the load direction was kept constant (22 yarns per cm).

Test Method

The pullout tests were carried out in an Instron testing machine at a crosshead rate of 15 mm/minute. Load displacement curves were recorded. The pullout testing arrangement is shown schematically in Figure 2. The same arrangement was used for the different test series (untied yarn, free fabric, and embedded fabric). The embedded length was 10 mm. The bond between the embedded fabric and the cement matrix was so high that yarn failure rather than bond failure occurred at longer embedded lengths.

Specimen Preparation

The specimens were prepared by hand lay up technique. The matrix was a paste of type I Portland cement with a water/cement ratio of 0.30. The specimen dimensions were 16 mm thick, 20 mm wide, and 10 mm long. The individual yarns or the fabric layer were embedded at the center of the specimen. The specimens were water cured for a period of 7 days, after which they were tested in saturated surface dry conditions. During the production process of the composite specimens (embedded yarn or embedded fabric) it was necessary to keep the yarns or the fabrics in place throughout the process. This was achieved by applying a small tensile load (pretension) of 0.1 N per single yarn, which was released after hardening of the matrix. The pretensioning load produced a tensile stress of about 2 MPa in each yarn, which is about 0.75% of the yarns' strength. Pretension was not applied to the free fabrics.

Results and Discussion

Geometrical Characteristics of the Individual Yarn

In the systems studied there are some differences in the wavy geometry of the embedded fabric (Figure 3a) and the individual (untied) yarn (Figure 3b). In the embedded fabric the wave amplitude of the yarn is larger and the wave length is smaller than in the untied crimped yarn.

The measured wave length and wave amplitude of the yarn for these two cases are shown in Figure 4 as a function of the fills density of the fabrics (i.e., crimps

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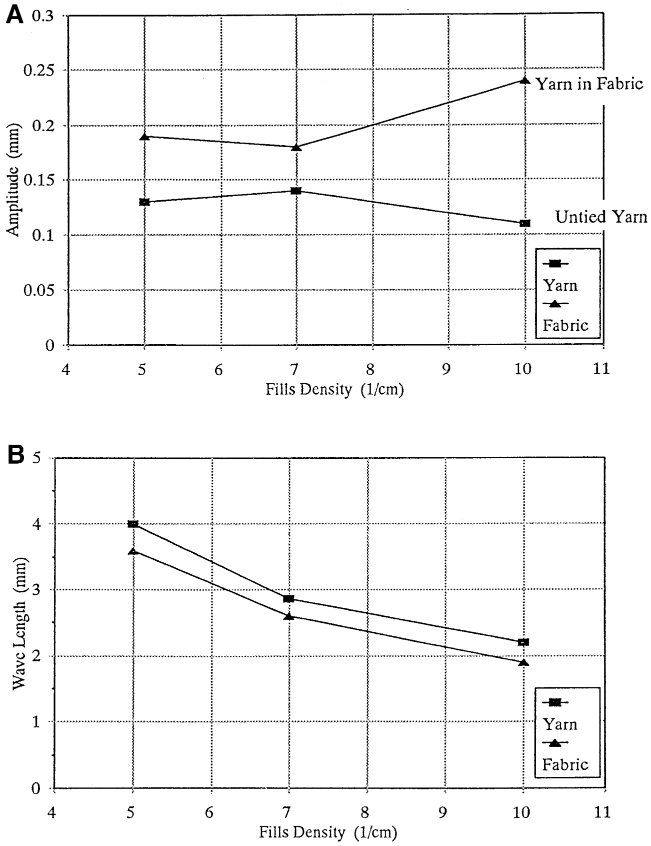

FIGURE 4. Crimped yarn geometry vs. fills density, compared to untied yarn, at initial tension of 0.1 N. (A) Wave amplitude; (B) wave length.

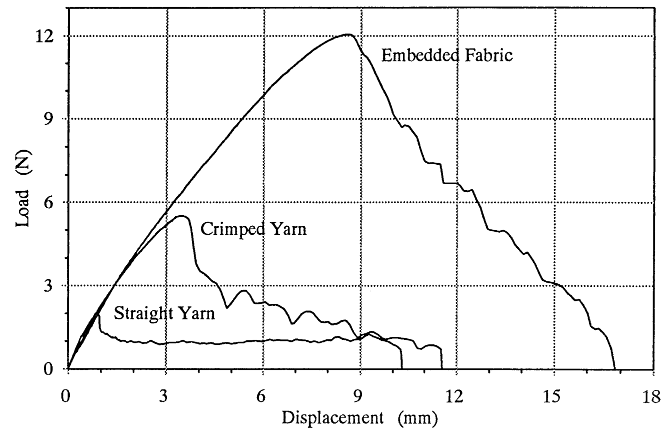

FIGURE 5. Pullout load-displacement curve of a straight yarn from the matrix, crimped yarn 10 from the matrix, and a single yarn from fabric 10 embedded in the matrix (initial tension 0.1 N, embedded length of 10 mm).

density of the untied crimped yarn). In both cases the yarns were pretensioned to a level of 0.1 N per yarn. It can be seen that the wave length decreases with increasing fills density, whereas the wave amplitude is approximately the same for the 5 and 7 fills density but decreases in the untied crimped yarns for higher densities (from 7 to 10 fills per cm) and increases in the case of an embedded fabric. For the same nominal density, the wave length is higher and the wave amplitude is lower for the untied crimped yarns compared to the yarn in the fabric. During the fabric production the straight yarn is being bent, thus inducing initial internal stresses, which are released upon untying. This may account for the observation that untying the yarn from the fabric yields a reduced wave amplitude and an increased wave length. The fills and warps form a restrained structure and the changes in geometry due to initial tension of the fabric (which is applied to the fabric while producing the specimen) is smaller in comparison to those in the untied yarn.

In the case of a free fabric, tensile stresses were not applied prior to the pullout test. This may result in slight differences between the crimped geometry of the yarn in the free fabric compared to the embedded fabric.

Effects of Fabric Density on Bonding Characteristics

FILLS DENSITY VARIES PERPENDICULAR TO THE PULLOUT LOAD DIRECTION. Increasing the fabric density (the fills) increases the number of junction points in the loading direction. This is expected to enhance the resistance to pullout. The distance between the yarns parallel to the load direction is kept constant.

The effect of the geometry of the pulled out yarn (yarn in a fabric, untied yarn [crimped] and straight yarn) on the pullout performance is shown in Figure 5. In this figure pullout load vs. displacement curves are presented for embedded fabric with 10 fills per cm and for crimped yarns that were untied of the fabric. It can be observed that the pullout performance of the fabric is the best, the straight yarn pullout is the lowest, and the untied (crimped) yarn is in-between.

Figure 6 presents the pullout load vs. displacement curves of a yarn in an embedded fabric, a free fabric, and an untied (crimped) yarn (untied from the fabric). It can be seen that both the wavy structure of the yarn and the interlacing of the warp and fill in the fabric itself provide a similar pullout resistance. The influence of the wavy structure of the yarn is due to the mechanical anchoring, which was discussed previously [5]. The resistance to pullout due to the interlacing of the warp and the fill in the free fabric is probably the result of the friction developed at the junction points between the fill and warp yarns.

The average maximum pullout load as function of the fills density is shown in Figure 7a, for three systems: free fabrics, untied crimped yarns, and yarn from a

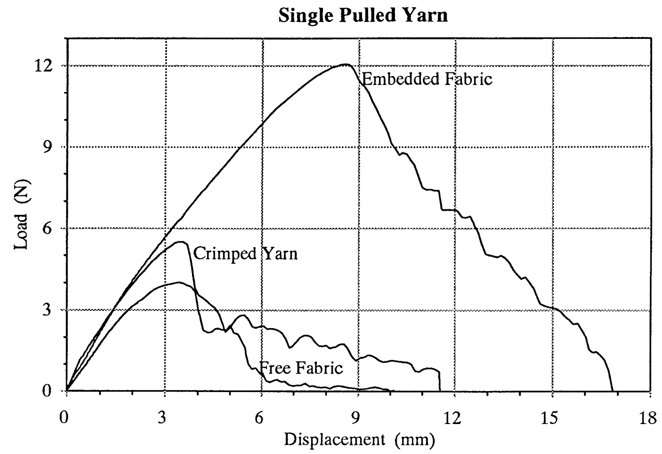

FIGURE 6. Pullout load-displacement curve of crimped yarn 10 from the matrix, single yarn from free fabric (fabric 10) and single yarn from fabric 10 embedded in the matrix (initial tension 0.1 N, embedded length of 10 mm).

fabric embedded in a cement matrix. The zero fills density represents the straight yarn. It may be concluded that the pullout resistance is enhanced with increasing fills density for all the three systems. This tendency may be attributed to the increase in the number of junction points of the pulled yarn in the fabric itself and in the cement matrix, as well as to the crimped structure of the yarn in the untied yarn and the fabric, which may lead to enhanced anchoring.

Examination of Figures 6 and 7a indicates that the magnitude of the maximum pullout load of a yarn from an embedded fabric is larger than the sum of the maximum pullout load of a yarn from the free fabric and the pullout load of a single yarn from the matrix. This is demonstrated in Figure 7b. It may be observed that the difference is considerably larger for the higher densities (7 and 10 fills per cm). This observation implies that a synergetic effect is involved, which may be attributed either to the differences in the wavy structure of the yarn in the fabric compared to the untied yarn (as shown in Figure 4) or to the matrix contribution to the restraint of the perpendicular yarns compared to limited restraint in the case of a free fabric.

In an attempt to quantitatively determine the influence of the yarns' geometrical characteristics on its pullout resistance, an empirical expression was developed [5], which correlates the maximum pullout load with the wave amplitude and wave length parameters for untied crimped yarn. The following empirical relation was developed [5]:

$$P_{\max} = (8 \cdot Amp + 0.18)*\frac{l}{\lambda} \quad (1)$$

where P_{max} = maximum pullout resistance (in N), amp = wave amplitude (in mm), l = embedded length (in mm), and λ = wave length (in mm).

The first term in eq 1, in the brackets, represents the pullout resistance of an individual wave (crimp), which was found to be a function of its amplitude. The second term represents the number of waves along the embedded length.

In Figure 8 the calculated pullout resistance according to eq 1 is presented and compared with the experimental maximum pullout load for the yarn from the embedded fabrics.

The fact that the calculated curve for the individual untied (crimped) yarn shows a similar trend and is only slightly lower than the curve of the yarn pulled out from the embedded fabric suggests that most of the pullout resistance in the fabric can be attributed to the individual yarn. The fact that the calculated curve in Figure 8 leads to higher pullout resistance values than the experimental curve of the untied yarn in Figure 7b

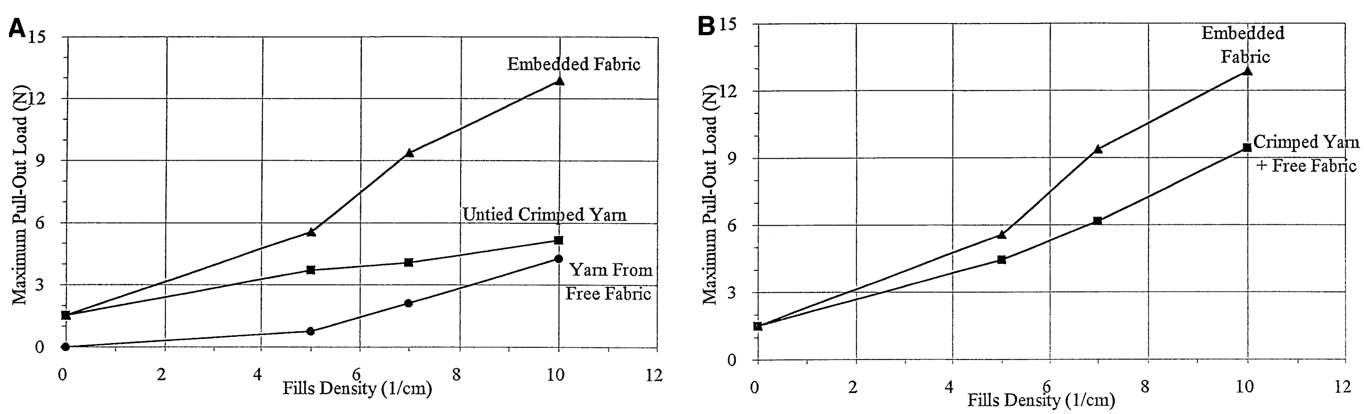

FIGURE 7. Effect of fills density on the maximum pullout load. Fills density varies perpendicular to load direction: (A) Experimental data; (B) sum of maximum pullout load of untied crimped yarn from matrix and yarn from free fabric compared to the pullout results of embedded fabric.

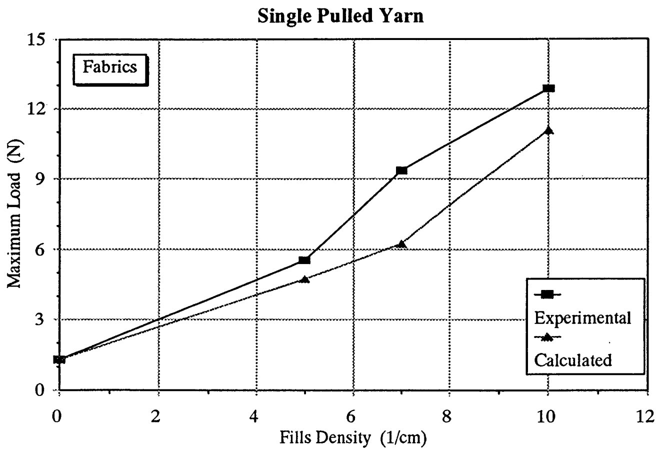

FIGURE 8. Maximum calculated pullout load of crimped yarn vs. fills density compared to the maximum experimental load of the embedded fabric.

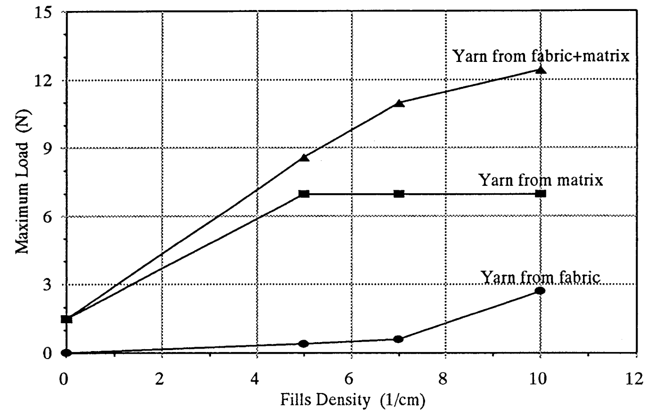

FIGURE 9. Maximum pullout load vs. fills density for a single crimped yarn from the matrix, a single yarn from a free fabric, and a single yarn from fabrics embedded in the matrix (initial tension 0.1 N, embedded length of 10 mm). Fills/crimps density varies parallel to load direction.

may be the result of the difference in the amplitude, which is higher in the yarn in the fabric (Figure 4a). This interpretation suggests that part of the difference noted in Figure 7b may not necessarily be due to a synergistic effect, but rather the consequence of a more simple mechanism: the fabric structure enables it to maintain and conserve a more favorable geometry of the crimped yarn when embedded in the matrix. This implies that the contribution of the junction points and fill yarn perpendicular to the pullout direction is relatively small.

FILLS DENSITY VARIES PARALLEL TO THE PULLOUT LOAD DIRECTION. In this case, increasing the fabric density (the fills) varies the distance between the yarns parallel to load direction, while the number of junction points along the pulled yarn and its crimped structure are kept constant.

The effect of the distance between the pulled out yarns on the pullout resistance is shown in Figure 9. It may be observed that although the individual yarn that is pulled out is identical for all the densities, the increase in density, i.e., closer distance to a neighboring yarn, enhances the pullout resistance. Figure 10 presents a schematic description that may explain the influence of the decreasing distance between the parallel yarns on the increase in resistance to pullout. The junction points in the fabric that are not crossing with the pulled yarn itself may enhance the resistance of the perpendicular yarns to the pullout load by restraining the perpendicular yarns. Increasing the yarns density parallel to the load direction therefore increases the pulled yarns' stiffness and decreases its displacement, as well as the lateral displacements of the perpendicular yarns. This restraining effect enhances the effectiveness of the anchoring of the pulled yarn in the fabric.

Pullout of Several Yarns Together

In this case, the fills density varies parallel to the load direction and a group of yarns is being pulled out together from the embedded fabric. In this series of tests, 5, 7, or 10 fills were pulled together from the different fabrics. Observations after complete pullout indicated that the yarns perpendicular to the load direction (22 yarns in all the cases) remained in the cement matrix.

Figure 11 presents the maximum pullout resistance per single yarn vs. the fills density. The results are compared with the pullout of a single yarn from an embedded fabric. It may be concluded that a marginal difference exists, and the pullout resistance of a group

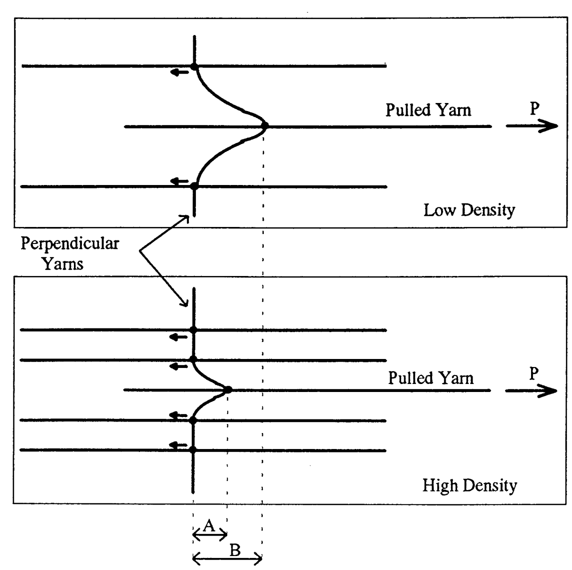

FIGURE 10. Schematic description of the anchoring mechanism of the pulled yarn.

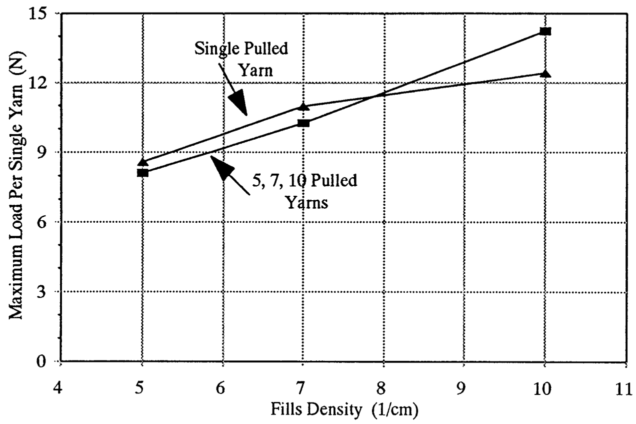

FIGURE 11. Maximum pullout load per single pulled yarn for systems where all the yarns are pulled simultaneously, compared to a system where a single yarn is pulled out.

of yarns may be predicted on the basis of a single yarn's resistance. Therefore, the results obtained for a single yarn may represent the bonding characteristics of the whole fabric.

Conclusions

A series of tests were carried out in an attempt to study the pullout resistance of woven fabrics. The results may lead to the following conclusions:

(1) The woven fabric provides a considerably better bond to a cementitious matrix than the bond of a single straight yarn. The anchoring mechanisms that may be involved are:
   (a) The crimped geometry of the yarn in the fabric may provide mechanical anchoring.
   (b) The interlacing between the warps and the fills in the fabric may develop a frictional resistance at their contact points.
   (c) The yarns perpendicular to the load direction contribute to the bond between the fabric and the cement matrix, due to restraining of the perpendicular yarns by the cement matrix, which might increase the frictional component between the pulled yarn and the perpendicular yarns at their contact points.

(2) Increasing the density of the fills in the fabric enhances the pullout resistance, due to a possible combination of different mechanisms:
   (a) The increase in the number of crimps per unit length and the corresponding influence on the anchoring effect.
   (b) The increase of junction points in the fabric, which increase the resistance to the pullout in the free fabric.
   (c) The increase in number of anchoring points in the cement matrix at the junction of the warps and the fills and the corresponding increase to pullout.

(3) Increasing the density of the yarns parallel to the load direction increases the pullout resistance, although the number of junction points and the crimps density in the yarn are kept constant. This influence may be explained on the basis of the increase in the density of the yarn parallel to the load direction, which may decrease the lateral displacement of the yarns being perpendicular to the load direction.

(4) The bonding capacity between the woven fabrics and the cementitious matrix is practically independent of the number of pulled out yarns. Therefore, the bond performance of a single pulled yarn may characterize the bond performance of the whole fabric.

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