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ENHANCED BONDING OF LOW MODULUS POLYMER FIBERS-CEMENT MATRIX BY MEANS OF CRIMPED GEOMETRY

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ABSTRACT

Low modulus polymeric yarns (fibers) can be used as primary reinforcement in thin sheet cement products if their bonding to the matrix can be made sufficiently high. Straight yarns usually have a low bond due to the hydrophilic nature of the yarn and its low modulus which does not allow for sufficient clamping stresses to develop and enable effective frictional bond. In the present paper the potential of modifying the shape of the yarn to achieve a crimped geometry was studied to enhance its bond resistance. Such geometry can be achieved in the production of individual yarns and it is the geometry which exists in woven fabrics. The crimped yarns investigated here were obtained by untying yarns from woven fabrics. The fabrics were produced especially for this work to achieve controlled geometry of the yarn, which was characterized in terms of the wave length and amplitude of the crimped shape. The bonding performance was characterized by pull-out tests of the crimped yarns. The crimped shape enhanced the bonding considerably, and the pull out resistance was found to be a linear function of the product of the wave amplitude of each crimp and the number of waves (i.e., yarn length/wave length) along the yarn. The dominant bonding mechanism was mechanical anchoring. © *1997 Elsevier Science Ltd*

Introduction

Low modulus polymer yarns (fibers) are being increasingly used as cement reinforcement, and they are particularly attractive because of their durability in the cementitious matrix (1-5). However their reinforcement efficiency is limited because of their low modulus, low bond, and the difficulty of incorporation in the matrice sufficiently large yarn content (1). The low bond is the result of the hydrophobic nature of the fiber as well as the low modulus. The latter has an indirect influence as it does not allow for sufficient clamping stresses to develop when the matrix shrinks around the yarn; such lateral stresses are needed to generate frictional bonding (6). These deficiencies can be overcome when using woven fabrics as reinforcement. The hand lay up production methods can provide a means for obtaining a composite with sufficiently large volume of reinforcement and the geometry of the fabric can provide improved bonding, which is associated with the crimped nature of the yarn in the fabric (Fig. 1) as well as the additional anchoring effect of the yarns perpendicular to the reinforcing yarns.

The majority of reinforcing textile fabrics used in commercial reinforced plastics are woven. Woven fabrics consist of interlacing x,y (fill and warp) coordinate systems. The warp and the fill yarns pass under and over each other and therefore an individual yarn in the fabric has a crimped geometry (Fig. 1). This crimped geometry may reduce the efficiency of

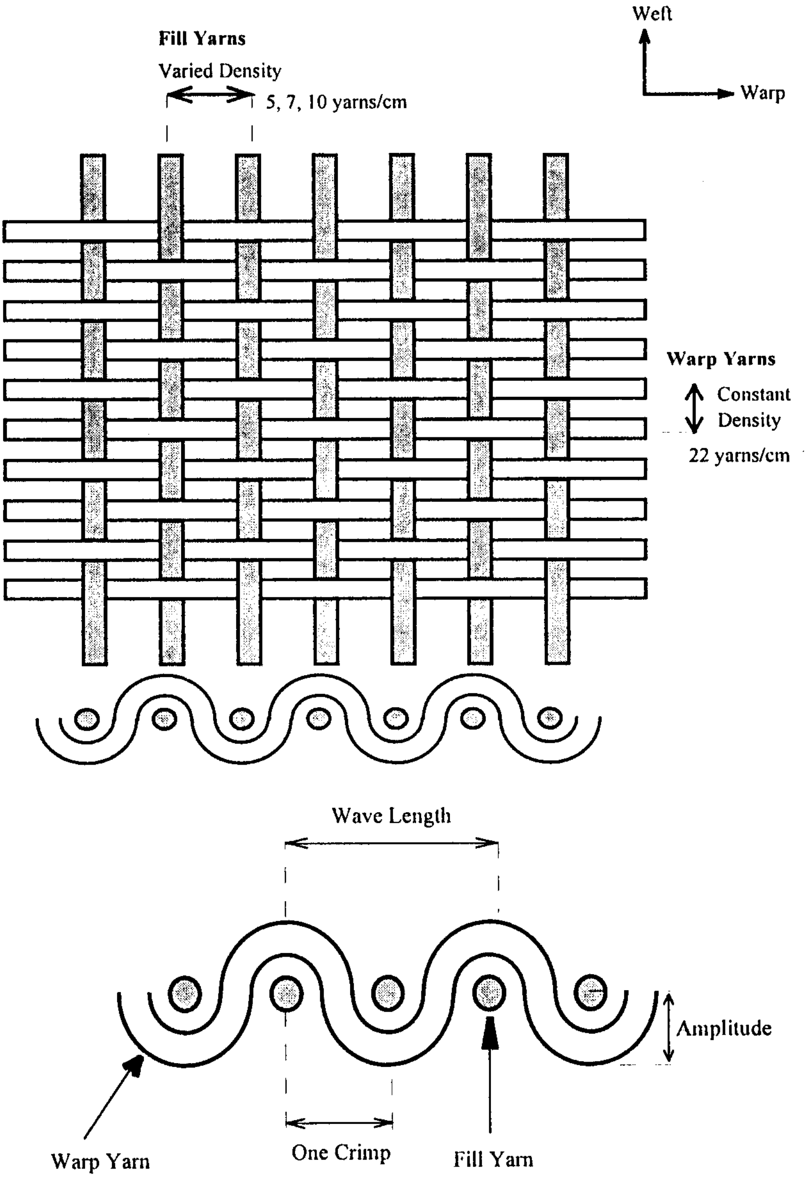


FIG. 1
Schematic presentation of the structure of the fabric and the crimped yarn.

TABLE 1

Mechanical Properties of the Untied Yarns

Modulus of Elasticity MPa	Tensile Strength MPa	Yarn Type
1032.0	233.2	5
948.7	224.2	7
972.3	248.6	10
1728.0	337.7	22
1765.0	260.0	Straight Yarn

the reinforcement, because the stresses developed in the composite are not parallel to the yarn direction, and due to stress concentration that may be generated in the matrix (7). To overcome these limitations different fabric forms have been developed to be used in plastic composites.

The advantages of fabric forms for composite materials are based on the possibility of designing the composite characteristic and reducing cost while increasing the quality of the composite. In the field of cementitious composites, the use of fabric form as reinforcement can possess several advantages. Woven fabric might provide a mechanical anchoring with the cement matrix due to it special geometry, which is induced as the cement penetrates in between the openings in the fabric (when it is in an open net form) and by the curved geometry of the individual yarns. This advantage is important when synthetic fibers are incorporated in the cement matrix. The potential of such reinforcement has been demonstrated in several publications (8-10).

The issue of improved bonding has been studied mainly with respect to straight yarns with different surface treatments (2-6). In order to better optimize the use of woven yarns there is a need to address more systematically the parameters which control the bonding in this type of reinforcement, in particular those related to its geometry. The objective of the present paper is to resolve the significance of one parameter of the geometrical structure which is the crimped shape of the yarn. The study of this parameter is of significance not only with regard to fabric reinforcement but also in relation with reinforcement by discrete dispersed short yarns which can also be produced in a crimped geometry.

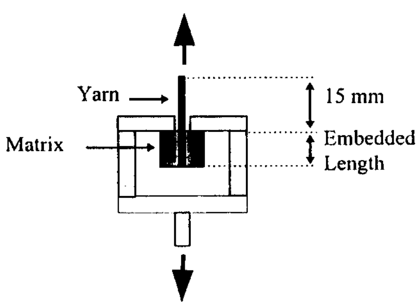


FIG. 2.

Schematic presentation of the pull-out specimen and testing arrangement.

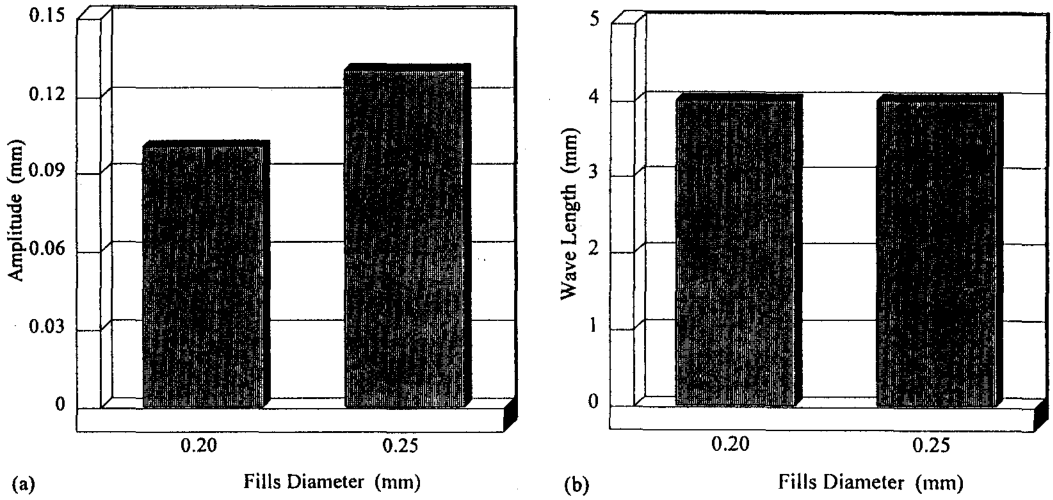


FIG. 3.
Effect of fill yarn diameter on the structure of the weft yarn (a) weft yarn amplitude, and (b) weft yarn wave length.

The yarns investigated in the present work were obtained by untying from fabrics of controlled geometry which were produced especially for this study. Thus controlled crimped geometry was obtained and its influence on the nature of bond was evaluated by means of pull-out tests of the individual crimped yarns.

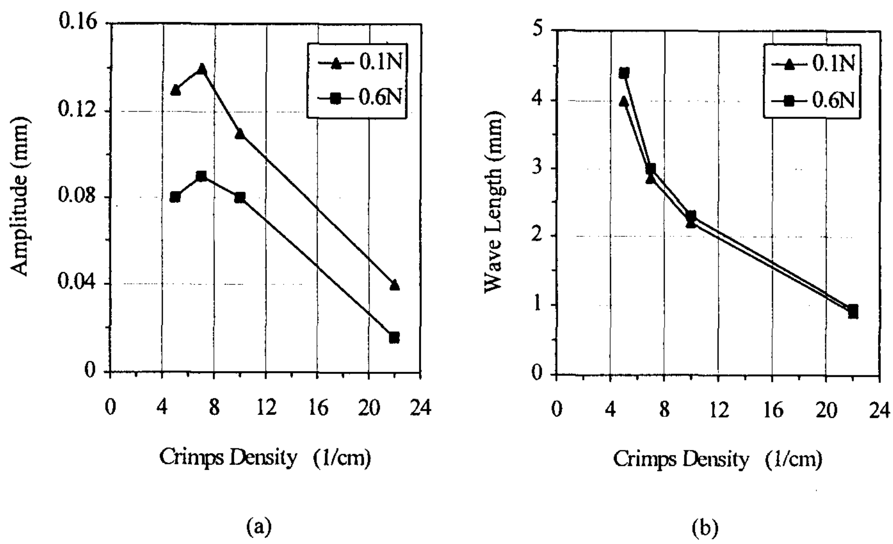


FIG. 4.
Effect of initial tension and yarn density (i.e. number of crimps per cm) on the structure of the crimped yarn (a) amplitude, and (b) wave length.

Experimental

Yarn Geometry. The crimped yarns were obtained by untying the yarns from plain weave fabrics. In plain weave fabrics the fills (lateral direction) and the warps (longitudinal direction) pass over and under each other, on and off, resulting in the crimped wavy structure. The yarn curvature in plain weave fabric depends on the spacing between the yarns (number of yarns per unit length) and the yarns diameter.

The fabrics were produced specially for this study so that their geometry would be controlled and thereby control the curvature geometry of the individual untied yarn. This was achieved by changing two parameters of the fabric, the fills density and the fills diameter, one parameter at a time: In all of the fabrics the warps' density was the same, 22 yarns per cm, and the fills density varied: 5, 7 and 10 yarns per cm. Therefore the warp yarns which were untied from the fabrics had crimp densities of: 5, 7 and 10. The untied fills had a crimp density of 22 crimps per cm. For fabric with density of 5 fills per cm two different diameters of the fills were used: 0.20 and 0.25 mm. This resulted in changes in the wavy structure of the warp yarns.

The crimped yarns will be refered here by their crimp density: yarn 5, yarn 7, yarn 10 and yarn 22. For comparison straight yarns were also evaluated.

The straight and crimped yarns both had a diameter of 0.25 mm. The mechanical properties of the different yarns are presented in Table 1.

Yarn 22 (the fill yarn in the fabric) was produced separately from the warp yarns and therefore its mechanical properties are different (Table 1). In spite of this, yarn 22 was studied here for pull-out because it provided useful additional data for a highly crimped geometry.

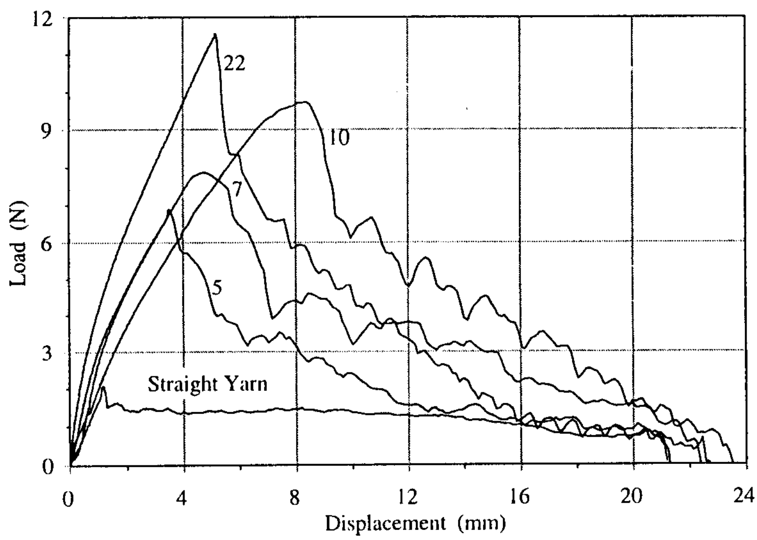


FIG. 5.
Typical load-displacement curves of crimped yarns of different shapes.

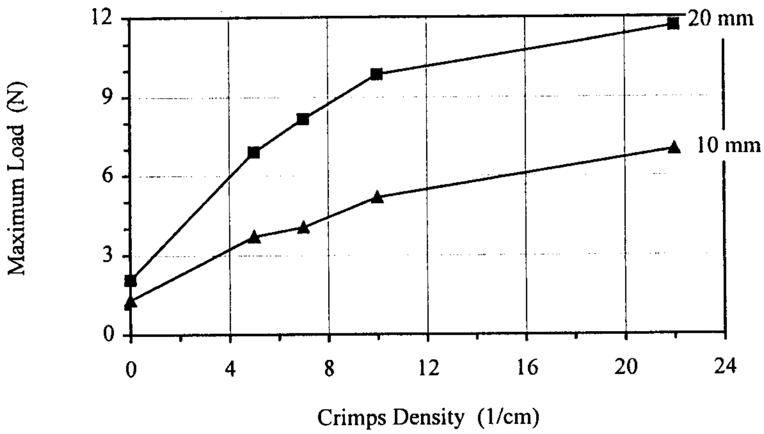


FIG. 6.
Effect of crimp density in the crimped yarn on the pull-out resistance determined in tests with 10mm and 20mm embedded lengths.

Pull-out Testing. The bond performance was characterized by pull-out testing. Special specimens were prepared in which the yarn was embedded in the center of the cement block. The specimen and testing arrangement are shown schematically in Fig. 2. The cross section of the block was 8 by 20mm. The length was 10 or 20mm, equal to the yarn embedded length. The specimen was prepared in longer dimensions with the yarn extending from both sides. After hardening it was cut to the required length. The matrix was a paste of 0.3 water/cement ratio.

During the production process of the pull-out specimen it was necessary to position the yarn in place using some initial tensile load which was applied along its longitudinal direction. Two levels of load were used, 0.1 and 0.6N. These loads are equivalent to stresses of about 2 and 12 MPa, which are only a small fraction of the tensile strength (0.8% and 4.6%, respectively). The initial stress was released after 24 hours, at which time the matrix had already hardened. Thus, although the stress is small it had some effect on the geometry of the crimped yarn which was "frozen" in the hardened matrix. The shape of the yarn when under tension was measured and characterized by the wave length and amplitude. Thus, in the evaluation of the pull-out tests reference could be made to the actual shape of the crimped yarn in the matrix.

All the specimens were water cured for 7 days and tested at this time. At this age the matrix strength reached 80% of its 28 days strength.

The pull-out test was carried out in an Instron testing machine at a cross-head rate of 15mm/min.

The surface of the yarns before and after the pull out process and the yarn-matrix interface were observed by scanning electron microscopy (SEM). The specimens for that purpose were dried at 60°C prior to being gold-coated.

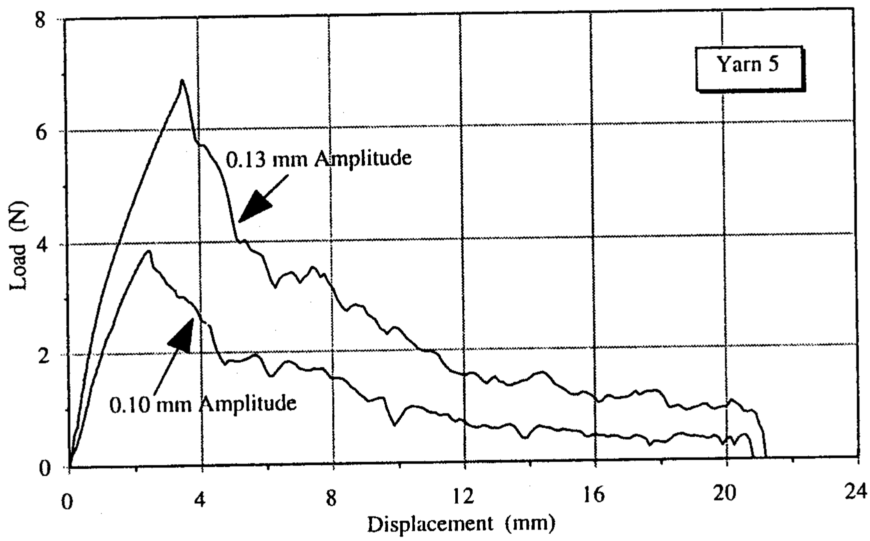


FIG. 7.
Effect of the amplitude of the yarn on the pull-out curve. The two yarns are of the same wave length, and they were obtained from yarn 5 with weft yarns of two different diameters.

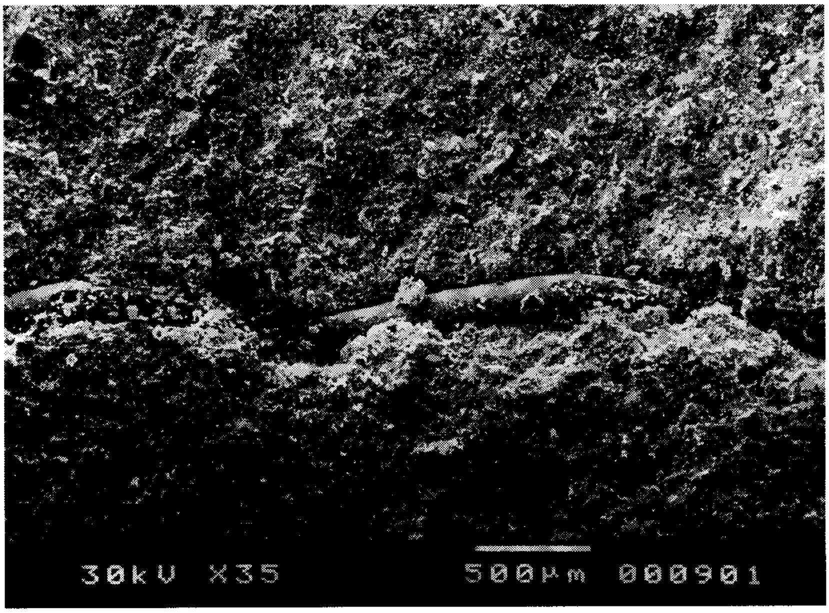
Results

Geometrical Characteristics of the Yarns. The geometry of the crimped yarns was quantified in terms of the wave length and wave amplitude (Fig. 1). The data are presented in Table 2. It can be seen that the geometry was influenced by three parameters: (1) The fills diameter of the woven fabric; (2) The density of the fills and warps in the woven fabrics: 5,7,10, and 22 yarns per cm; (3) The initial tension applied during the production of the specimens.

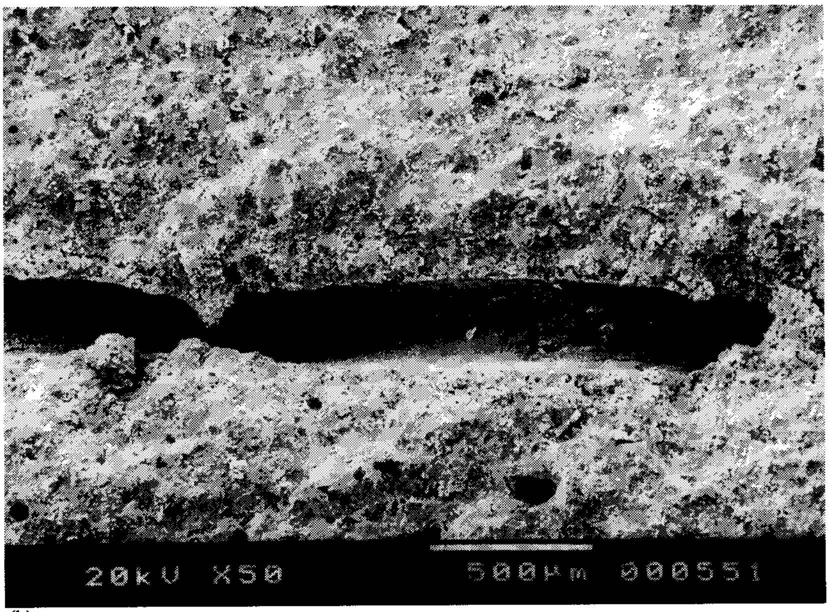
The influence of these parameters is presented graphically in Figs. 3 and 4. Several observations can be made:

1) Changing the fills diameter from 0.20 to 0.25mm did not affect the wave length but increased the wave amplitude (Fig. 3)
2) The wave amplitude decreased with increase in the crimp density and the initial tension (Fig. 4a).
3) The wave length decreased with increase in the crimps density but was unaffected by the initial tension (Fig. 4b).

Pull-out Performance. Typical pull-out curves for the different geometries are shown in Fig. 5 demonstrating the marked enhancement in bond achieved with the crimped geometry. Maximum pull-out loads obtained as the average of at least 5 samples are shown in Fig. 6. Again, the positive influence of the crimped structure is evident providing an enhancement in pull-out resistance which exceeds by a factor of about 5 that of the straight yarns (point 0 on the crimp density axis). When comparing the 10 and 20mm embedded length curves in Fig. 6, one can clearly see that there is similarity between the two.



(a)



(b)

FIG. 8.
The structure of the crimped yarn in the matrix: (a) the yarn prior to pull-out, and (b) the groove after pull-out.

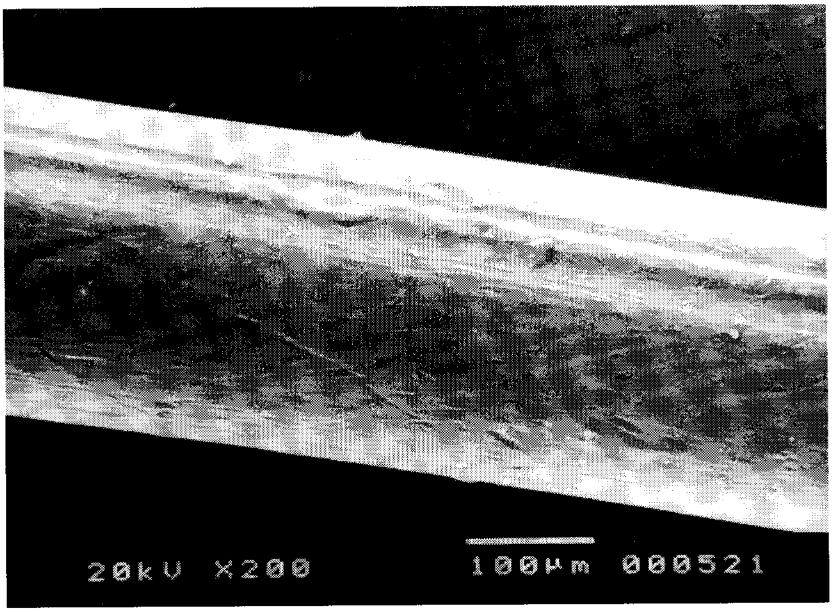


FIG. 9.
The surface of straight yarn after pull-out.

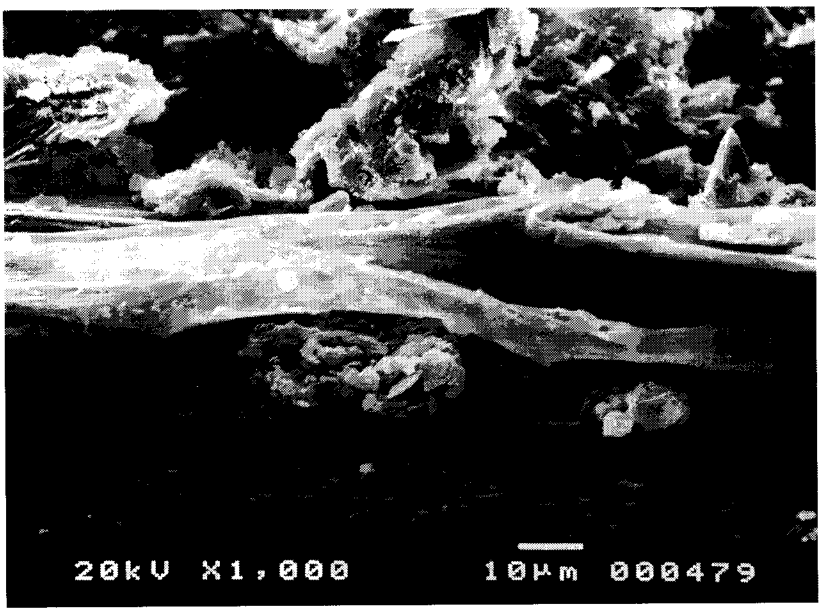


FIG. 10.
The surface of a crimped yarn after pull-out.

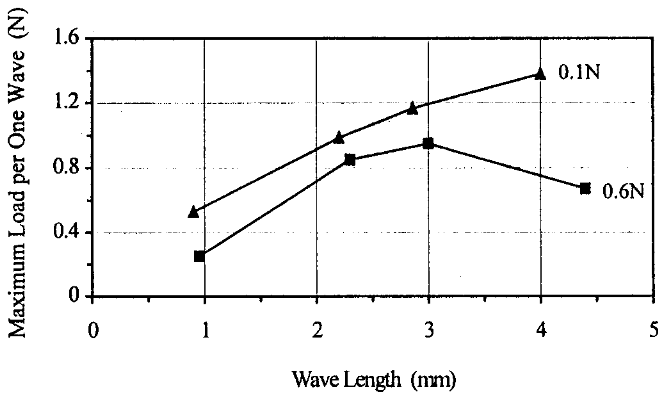


FIG. 11.
The effect of wave length and initial tension on the pull-out load per one wave (i.e. pull-out load divided by the number of waves along the embedded length).

The influence of the wave amplitude for crimped yarns having the same wave length is shown in Fig. 7. Increase in the amplitude by 30% resulted in about doubling of the pull-out resistance.

Microstructural Characterization. The overall wavy nature of the yarn in the matrix can be seen in Fig. 8. The matrix around the yarns is quite compact which is an indication that the specimens were properly produced.

The SEM results suggested that the major microstructural differences could be observed at the yarns surface. Prior to pull-out the surface of the yarn, whether straight or crimped was smooth. After pull-out the surface of the straight yarn remained smooth (Fig. 9) while that of the crimped yarn was heavily abraded and hydrated cement particles could be seen interlocked into the abraded surface (Fig. 10).

TABLE 2

Crimped Yarns' Amplitude and the Wave Length for Different Initial Tensile Load

Initial Tension (N)						Yarn Type
0.6	0.1	0.0	0.6	0.1	0.0	
Wave Amplitude (mm)			Wave Length (mm)			
0.08	0.13	0.14	4.40	4.00	4.00	5(0.25)
----	0.10	----	----	4.00	----	5(0.20)
0.09	0.14	0.18	3.00	2.86	2.86	7
0.08	0.11	0.20	2.30	2.20	2.00	10
0.016	0.04	0.06	0.95	0.90	0.90	22

Note: the number in brackets indicates the diameter of the fills in the woven fabrics, which the yarn untied of.

Discussion

The microstructural characterization (Figs. 9 and 10) provide some qualitative indications to the processes involved in the enhancement of the bonding performance in the crimped yarns: the crimped geometry apparently forces the yarn to abrade itself against the surrounding matrix as it is being pulled out. This is perhaps a manifestation of an anchoring mechanism that is responsible to the enhanced bond.

Attempts were made to establish empirical correlations between the pull-out resistance and the geometrical parameters of the crimped yarns. In order to isolate the effect of individual waves, the pull-out resistance per individual wave was calculated and plotted as a function of the wave length and wave amplitude. No clear cut relations could be established with wave length (Fig. 11), but a significant single linear relation could be established with the wave amplitude (Fig. 12). Linear regression resulted in the following relation:

$$p = 8 \cdot \mathrm{Amp} + 0.18 \tag{1}$$

Where: p = the pull-out resistance per one wave (N), Amp = the crimped yarn amplitude (mm), 0.18 = constant which reflects the contribution of the straight yarn per unit length.

The linear correlation coefficient of this relation is 0.88.

This correlation is in agreement with the observation in Fig. 7, which shows that in a controlled experiment where only the amplitude was changed considerable enhancement in the pull-out resistance was obtained. One would expect that the anchoring effect would be sensitive to the deviation of the shape from the longitudinal axis, and the amplitude quantifies such "bulges."

The empirical relation (Eq. 1) implies also that the contribution of each of the waves along the pulled out yarn is the same, regardless of its position along the pulled out yarn. This suggests that the overall pull-out resistance would be the product of the pull-out resistance of the individual wave (expressed by Eq. 1) multiplied by the number of waves along the embedded length, which is the length divided by the wave length. Thus the overall pull-out resistance can be expressed as follows:

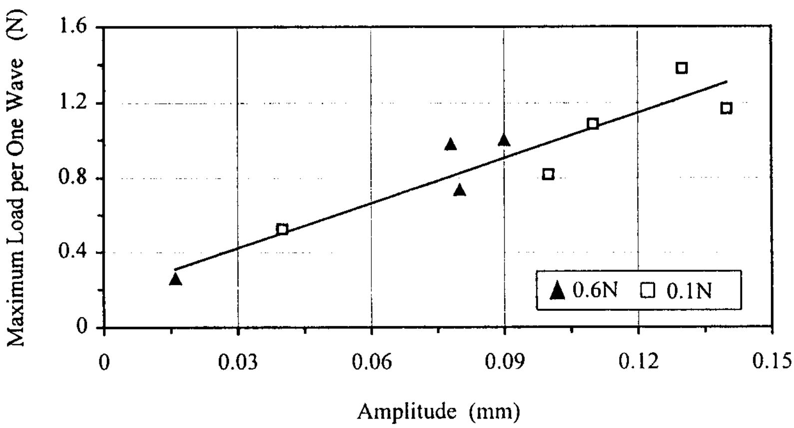


FIG. 12.

The effect of wave amplitude and initial tension on the pull-out load per one wave (i.e., pull-out load divided by the number of waves along the embedded length).

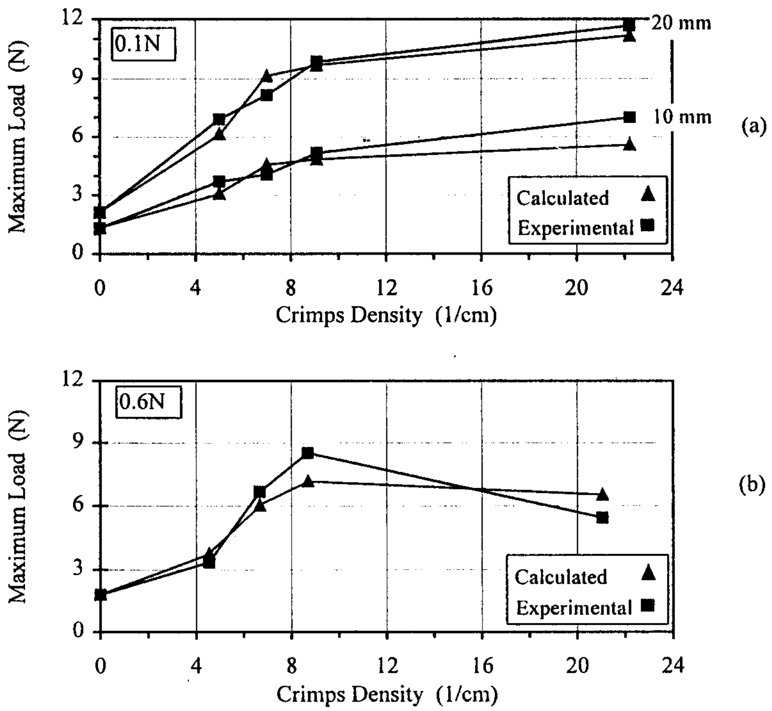


FIG. 13.

Calculated and experimental values of pull-out resistance for systems with initial tension of 0.1N (a) and 0.6N (b).

$$P_{max} = p\left(\frac{l}{\lambda}\right) = (8 \cdot Amp + 0.18)\left(\frac{l}{\lambda}\right) \quad (2)$$

Where: P_{max} = the total pull-out resistance (N), p = pull-out resistance of an individual wave (N) l = embedded length (mm), Amp = amplitude (mm), λ = wave length (mm)

Inserting into equation 2 the geometrical values of Table 2 enables one to calculate the total pull-out resistance of all the systems tested in this work. Comparison between the experimental and calculated values is given in Fig. 13, showing an excellent agreement.

Conclusions

1) The crimped geometry of the yarn improved the bond performance between polyethylene monofilament yarn and cements matrix compared to straight yarn. The mechanism involved is probably mechanical anchoring which is dependent on the wave amplitude of the crimped yarn.
2) The pull out resistance of the crimped yarn depends significantly on the wavy yarn structure which is characterized by two main parameters, the wave amplitude and the wave length. Empirical relation was developed based upon the following concepts:
   a) The wave amplitude of the crimped yarn determines the resistance to pull-out of each wave, due to mechanical anchoring. Increasing the wave amplitude causes an

increase in the bond capacity of each wave and increases in the mechanical anchoring accordingly.

b) The wave length of the crimped yarn controls the number of waves per unit length, which influences the overall anchoring effect. Decreasing the wave length increases the crimp density along the yarn, and results in increase in the number of waves per unit length.

3) Based on the wave amplitude and wave length of the crimped yarn it is possible to predict the total resistance to pull-out of crimped yarn of monofilament polyethylene.
4) The fabric density affects not only the wave length but also the wave amplitude of the fills and the warps. In view of the significance of the wave amplitude in controlling bonding this effect should be considered when optimizing the fabric's structure.
5) The enhanced bonding achieved by the crimped structure suggests that crimping should also be considered as an important potential means for improvement of the efficiency of reinforcement by individual dispersed short yarns.

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