ELSEVIER

PII:S0958-9465(98)00007-9

Cement and Concrete Composites 20 (1998) 319–327
0958-9465/98/$ — see front matter

The Nature of Bonding Between Monofilament Polyethylene Yarns and Cement Matrices

A. Peled, A. Bentur* & D. Z. Yankelevsky

National Building Research Institute, Technion — Israel Institute of Technology, Haifa, 32000 Israel

(Received 31 October 1997; accepted 22 December 1997)

Abstract

The bond performance of monofilament polyethylene yarns embedded in a cement matrix was studied to resolve yarn–matrix interaction mechanisms. Pull-out tests were carried out to determine the mechanical characteristics of bonding. Pre-tensioning of the yarns was applied prior to the production of the composite specimens. The tension loads were removed at different stages, during the hardening process and at a later stage. Two types of specimens were designed for a pull-out test: (i) the yarn is fully embedded in the specimen and extends at the rear side with a tail; (ii) the yarn is fully embedded but has no tail. The microstructure of the yarn's groove in the matrix and the yarn's surface prior to and after the pull-out were examined by a scanning electron microscope. It was found that the pull-out resistance of the straight yarn was controlled by frictional as well as anchoring effects. When the pulled yarn length was equal to the matrix length, the pull-out resistance was found to decrease with increasing the initial tension, due to Poisson's effect on the yarn–matrix interaction. When the pulled yarn was longer than the embedded length, the yarn's tail was found to considerably improve the pull out resistance due to wedging induced by the Poisson effect. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: cement composite, reinforcement, bond, pull-out, polyethylene yarn (fiber), Poisson's effect, microstructure, monofilament, duplex-film.

*To whom correspondence should be addressed

INTRODUCTION

Fibers are incorporated in brittle cementitious matrices to enhance the tensile strength, to provide toughness and to control cracking. Although it is generally accepted that the fiber modulus of elasticity should be higher than that of the matrix to induce these influences, in particular enhanced strength, there is a considerable bulk of experimental data, as well as theoretical analysis, showing that even low modulus fibers can be effective, in particular with respect to enhanced toughness and crack control.[1] In many applications, these characteristics are of much greater significance than a modest increase in tensile or flexural strength.

So far, many studies on low modulus fibers for cement reinforcement were focused on short discontinuous fibers. The nature of bonding in such systems was characterized with special attention to interfacial effects associated with the matrix microstructure and the fiber surface. The developments in the textile industry have increased interest in the use of low modulus continuous fibers which are placed in the form of a mat. Here the reinforcing unit is a continuous fiber (i.e. yarn) rather than a short discrete fiber. In such systems the production method of the composite may considerably influence the nature of bonding, which is different from that obtained in discrete short fibers mixed with the matrix. For example, the production of the composite may require some pre-tensioning of the mat, which may augment bonding influences, due to Poisson's effect, which are significant in low modulus fibers. Such influences may not exist in composites reinforced with short low modulus fibers produced by mixing where no pre-tensioning of the fiber is required.

Bonding will depend on the structure of the fiber–matrix interface. Cementitious composites are characterized by a transition zone in the vicinity of the fibers, in which the microstructure of the paste matrix is considerably different from that of the bulk paste away from the interface.[1] The development of the microstructure in the transition zone in the case of monofilament fibers separated one from the other, is different from that of bundled filaments. With monofilament fibers, the entire fiber surface is surrounded by the matrix; whereas in the case of bundled filaments, only the external filament surfaces are partially in contact with the matrix. The microstructure of the transition zone with monofilament fibers has been studied primarily in steel fiber reinforced cement paste.[2–6] It was observed that the transition zone in the mature composite is rich in $Ca(OH)_2$ (usually in direct contact with the fiber surface), and is also quite porous, making it different from the microstructure of the bulk paste. The $Ca(OH)_2$ layer may be as thin as 1 μm,[4] resembling the duplex film suggested by Barnes *et al.*[5] The duplex film may be observed in the vicinity of the porous zone.

It was the purpose of the present work to resolve the above-mentioned effects which are likely to be imposed on the more 'conventional' aspects of bonding associated with the nature of the microstructure of the matrix in the vicinity of the fiber surface (interfacial transition zone) and the roughness of the fiber surface. To reduce the complexity of the problems under study, it was decided to use smooth monofilaments of polyethylene. The pre-tensioning effects were evaluated through pull-out tests and the nature of bonding was studied by analyzing both the load-displacement curves in the pull-out tests and the microstructure at the interfacial zone.

In the present paper the term yarn would be used rather than fiber, as the latter usually implies a short and discrete reinforcing unit.

EXPERIMENTAL

The yarns used in this study were 0.25 mm diameter monofilaments of polyethylene, with a modulus of elasticity of 1765 MPa and a tensile strength of 260 MPa.

Specimens (20 mm wide) of different lengths (2.5, 5, 10, 20 mm) were prepared for the pull-out tests by hand-laying individual yarns in the cement matrix in a special rig that enabled controlled pre-tensioning of the yarn before placing the cementitious paste. The yarn was covered by 8 mm thick cement paste on both sides. The bond between the polyethylene yarn and cement matrix was determined by performing pull-out tests with the geometry shown in Fig. 1. In one set of specimens (series I) the desired embedded length was obtained by cutting the specimen in a way that the specimen length was equal to the embedded length (Fig. 1a).

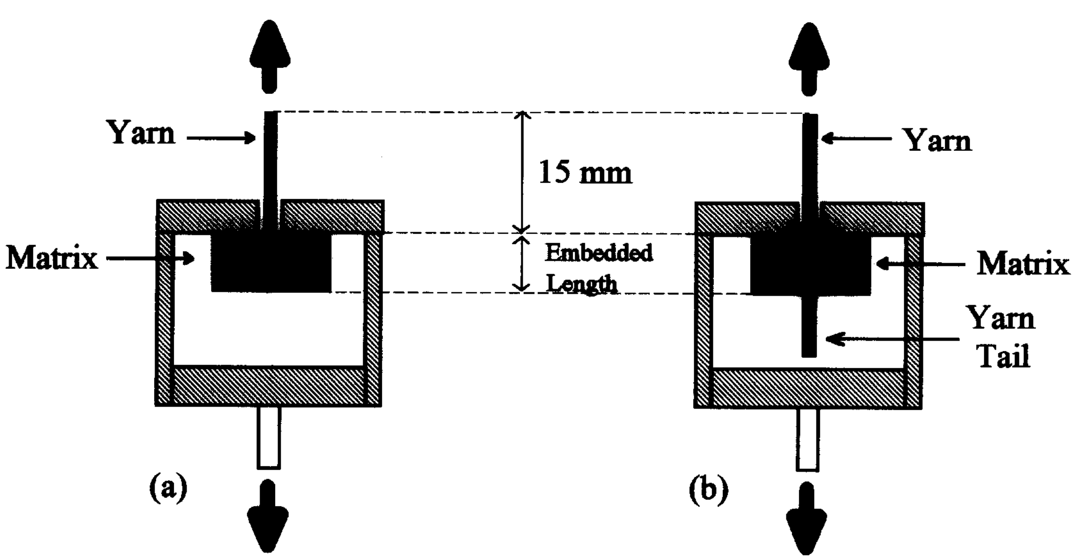


Fig. 1. Schematic description of the pull-out testing arrangement: (a) the length of the yarn is equal to matrix length; (b) the length of the yarn is greater than the embedded length.

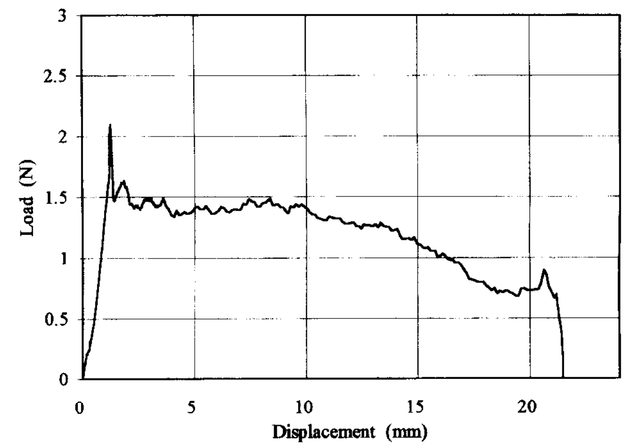


Fig. 2. Typical load–displacement curve (embedded length 20 mm).

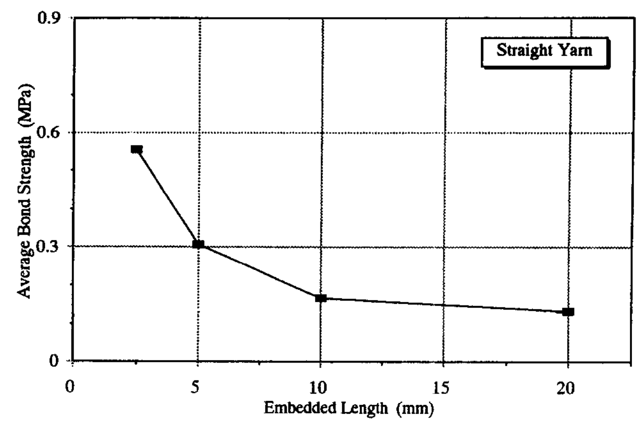


Fig. 3. Average bond strength versus embedded length.

Another set of specimens (series II) was prepared in a different rig to obtain a yarn with a 'tail', as shown in Fig. 1b. The pull-out was carried out in an Instron testing machine at a crosshead speed of 15 mm/min. The load–displacement curve was recorded continuously during the test. Typical curves are shown in Fig. 2. The bond strength was calculated from the maximum pull-out load by dividing it by the surface area of the embedded yarn. This is a value that has physical significance only if the bond is generated by uniform friction.

The cement matrix was made of a paste having a 0.3 water/cement ratio. ASTM type I Portland cement was used. The specimens were kept sealed for the first day and then in water at 20°C. Pull-out tests were carried out after 7 days. At that stage the paste had already gained 80% of its standard 28 days strength.

Three levels of the initial tensioning load were applied, 0.1, 0.3, and 0.6 N. These loads produce initial stresses of about 2, 6 and 12 MPa (i.e. 0.8, 2.3 and 4.6% of the yarn's tensile strength). The pre-tension loads were released after 1 or 6 days for the 0.1 and 0.6 N pre-tensioning loads, and after 1 day for the 0.3 N pre-tensioning load.

The interface microstructure was studied by means of scanning electron microscope (SEM) observations of specimens before and after the pull-out tests. Preparation of specimens for SEM examination required drying at 60°C, splitting and then gold-coating. The observations were employed to characterize the microstructure of the interface (the groove in the matrix) and of the outer surface of the yarn before the pull-out test and afterwards.

RESULTS

Series I

Effect of embedded length

The effect of the embedded length on the average bond strength is presented in Fig. 3. It can be clearly seen that the average value of bond strength decreases with increase of the embedded length. This result suggest that the uniform friction is not the only mechanism responsible for bonding.[1,7]

Effect of initial tension

The effect of initial pre-tension on the pull-out behavior is shown in Figs 4 and 5. Figure 4 presents results of several yarns, pre-loaded to several different levels of pre-tension which has been removed 1 day after casting the specimen. One may observe that in both cases the bond

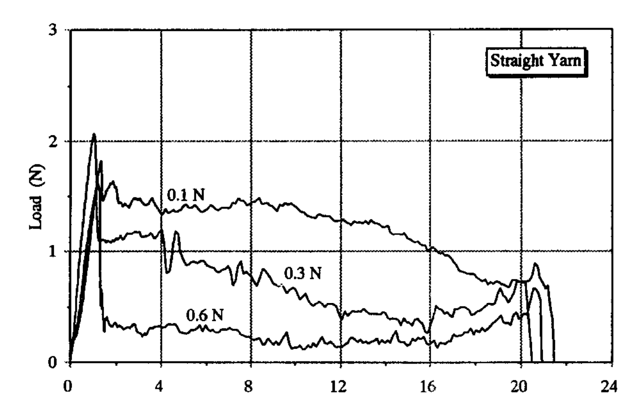


Fig. 4. Load–displacement curves for different levels of initial tension, 0.1, 0.3, and 0.6 N, released after 1 day (embedded length 20 mm).

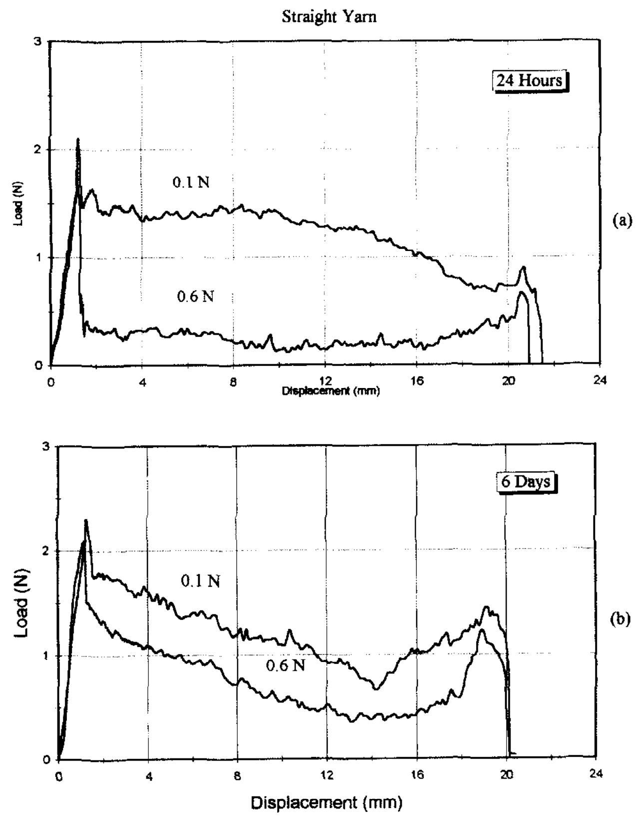


Fig. 5. Load–displacement curves at an initial tension of 0.1 and 0.6 N, released after: (a) 1 day; (b) 6 days (embedded length 20 mm).

strength is almost independent on the pre-tensioning level (Table 1). However, when pre-tension is removed after 1 day a significant influence on the post-peak behavior may be observed where lower pre-tension produces higher post-peak resistance. When the pre-tension is removed after 6 days the effect of the pre-tensioning level on the post-peak resistance is considerably smaller.

The period of pre-tension loading has almost no effect on the resistance of yarns pre-tensioned by low level tensile load (0.1 N) (Fig. 6), but it considerably affects the resistance of yearns pre-tensioned by higher loads (0.6 N).

Table 1. Maximum pull-out load for different initial tension released after 1 day and 6 days

	Maximum pull-out load (N)		
	Initial tension 0.1 N	*Initial tension 0.3 N*	*Initial tension 0.6 N*
Initial tension release			
1 day	2.1	1.8	1.8
6 days	2.3	–	2.4

The pre-tension release at an early age of the specimen is associated with bond deterioration which appears in a pronounced reduction in post-peak resistance.

Microstructural characteristics

Closer inspection of the yarn and the surrounding matrix indicates that the yarn's cross-section is not ideally circular and is not uniform along its entire length. Bulges were observed at several locations (Fig. 7) and their imprint on the grooves' shape is clearly evident (Fig. 8).

Observations on specimens prior to the yarns' pull-out indicate that the surface of the groove is continuous and flawless when the initial tension is low (0.1 N), regardless of the duration of the pre-tension load (Fig. 9b and Fig. 10b), while at higher pre-tension levels (0.6 N) damage in the groove is observed both when the pre-tension has been released after 1 day as well as after 6 days (Fig. 9a and Fig. 10a). Observations show that uniform contact exists

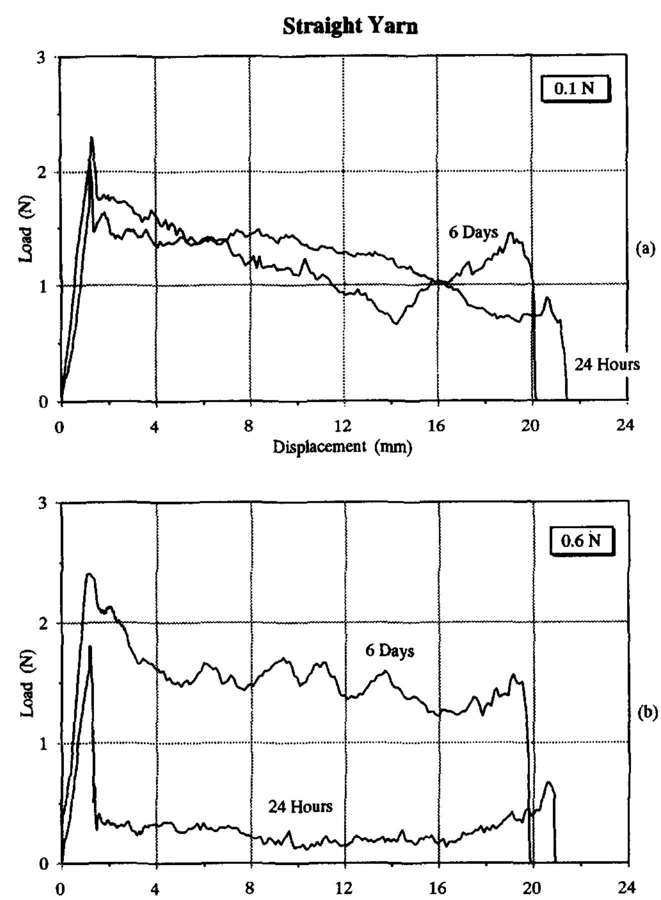


Fig. 6. Load–displacement curves for different initial tension of: (a) 0.1 N (b) 0.6 N, released after 1 and 6 days (embedded length 20 mm).

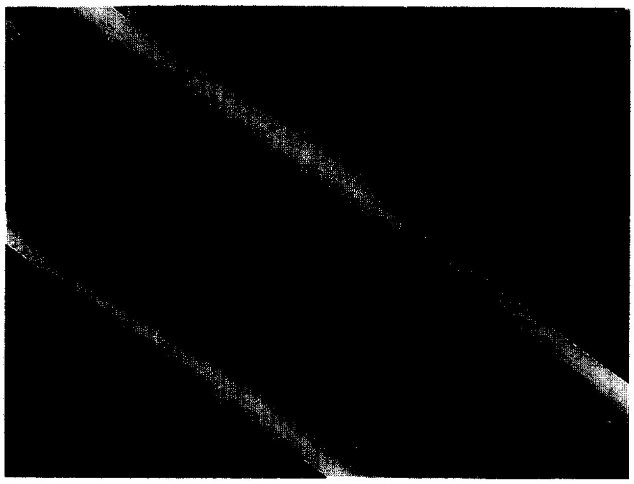


Fig. 7. Non-uniformity in the yarn diameter observed as bulge along the yarn (before pull-out, no tension).

when the groove is not damaged (Fig. 11a — 0.1 N pre-tension) and non-continuous contact when the grove has been damaged (Fig. 11b — 0.6 N released after 1 day).

Observations at the groove surface after pull-out show damage due to an abrasion process (Fig. 12). The damage is more severe at the specimen's edge (Fig. 13a), while at the rear side the groove surface remains intact (Fig. 13b).

Series II

This series of tests had been carried out for specimens with 0.1 N pre-tension only, which was released after 1 day. Typical pull-out resistance curves are shown in Fig. 14 indicating considerable enhancement in the pull-out resistance with increase in the length of the 'tail'. For a short tail (20 mm, (B) in Fig. 14), only the maximum pull-out load is enhanced. For longer 'tails' the enhancement in the magnitude of the maximum pull-out load is similar; however, the subsequent resistance in the post-peak zone (30 mm and 40 mm curves in Fig. 14) is improved as well.

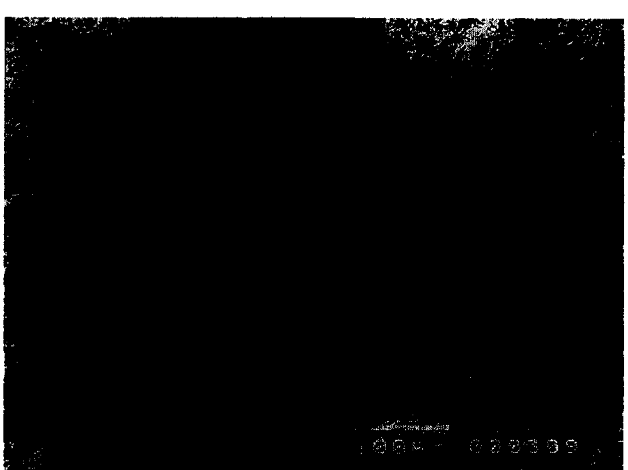


Fig. 8. The groove of the non-uniformity yarn in the matrix.

SEM observation of the pulled-out yarn shows considerable damage to the yarn tail's outer surface (Fig. 15a) and a relatively smooth surface on the part of the yarn which was embedded in the specimen (Fig. 15b).

DISCUSSION

The observations and trends observed in this study might be explained by influences due to

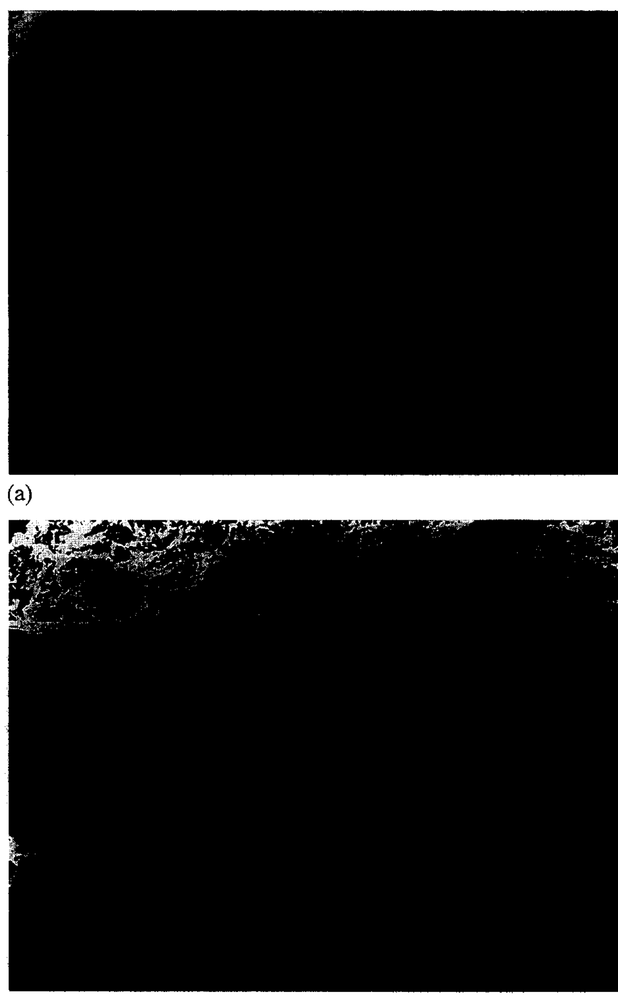
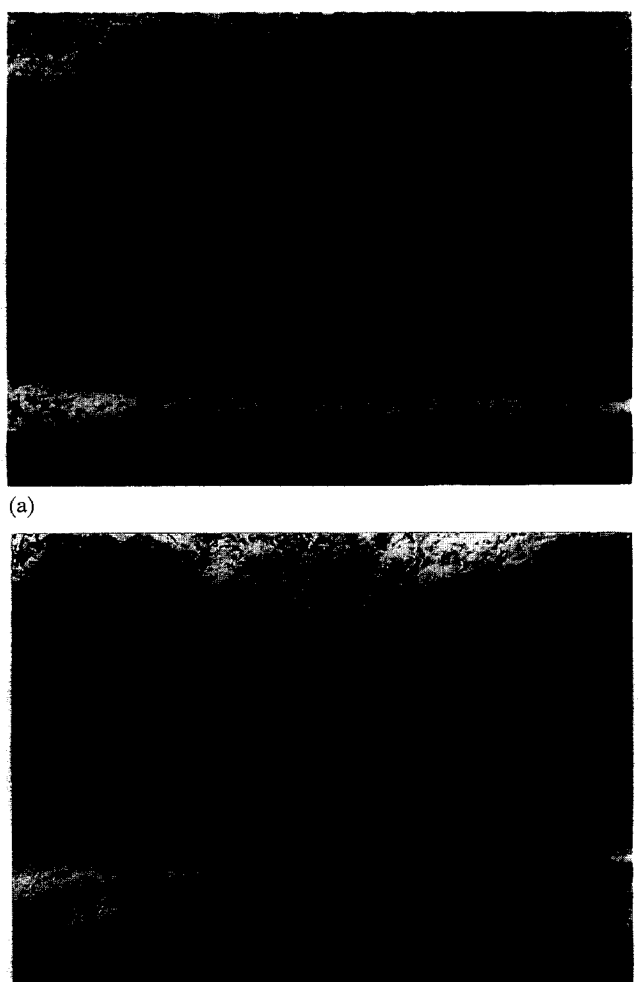


Fig. 9. The groove in the matrix around the yarn prior to pull-out at different initial tension, released after 1 day: (a) 0.6 N; (b) 0.1 N.

the Poisson effect. The concepts of the influence of the Poisson effect on bonding have been addressed in several publications, e.g. refs [8,9]. Although the levels of pre-tension are low, less than 5% of the yarns strength, they produce considerable Poisson contraction in the cross-section of the yarn, due to its low modulus of elasticity. The calculated values are about 0.1 μm for the 0.1 N initial tension, which is of the order of magnitude of the thickness of the duplex film in the interfacial transition zone. The smooth surface in Figs 9 and 10 is that of the duplex film.

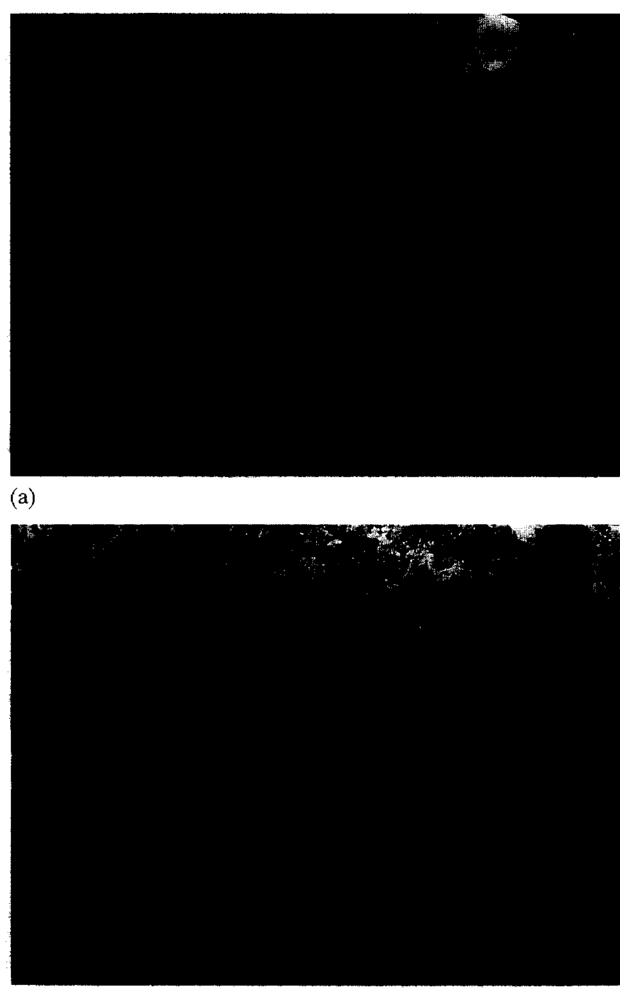
On release of the initial tension the yarn will tend to expand laterally, due to the Poisson effect. This expansion is obviously restrained by the surrounding matrix; the extent of the expansion and the lateral stresses which may develop will depend on the rigidity of the surrounding matrix and the relaxation that may have occurred in the yarn prior to the release.

Generally, a tendency for bigger Poisson expansion against a stronger and more rigid matrix will lead to higher lateral compressive stresses. This is expected to result in enhanced bond performance if it is assumed that the origin of the bond is largely frictional. The results in Fig. 3 suggest that the bonding is not purely frictional. However, for the embedded length tested in this work (10 and 20 mm) it can be assumed that the frictional mechanism is the over-riding one, as might be deduced from the leveling of the curve in Fig. 3 for embedded length values greater than 10 mm. The observation of the damage to the duplex film surface of the grove after the pull-out process (Fig. 12) may be due to abrasive type action resulting from friction.



(a)
(b)

Fig. 10. The groove in the matrix around the yarn prior to pull-out at different initial tension, released after 6 days: (a) 0.6 N; (b) 0.1 N.

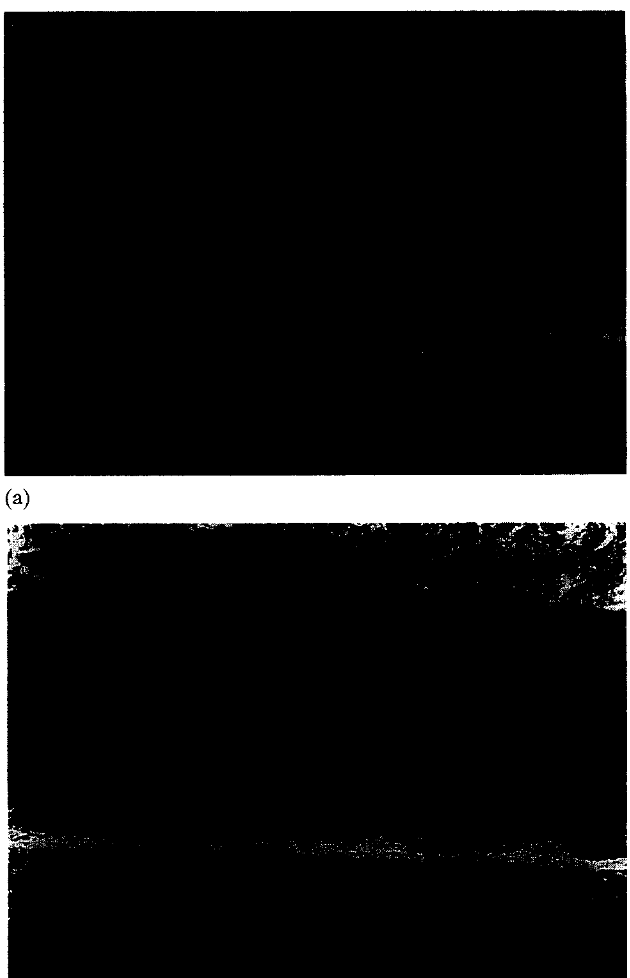


(a)
(b)

Fig. 11. The yarn–matrix interface before pull-out at different initial tension: (a) 0.1 N; (b) 0.6 N (the load released after 1 day in both cases).

With this concept in mind the trends in pull-out resistance and the microstructural observations can be explained qualitatively.

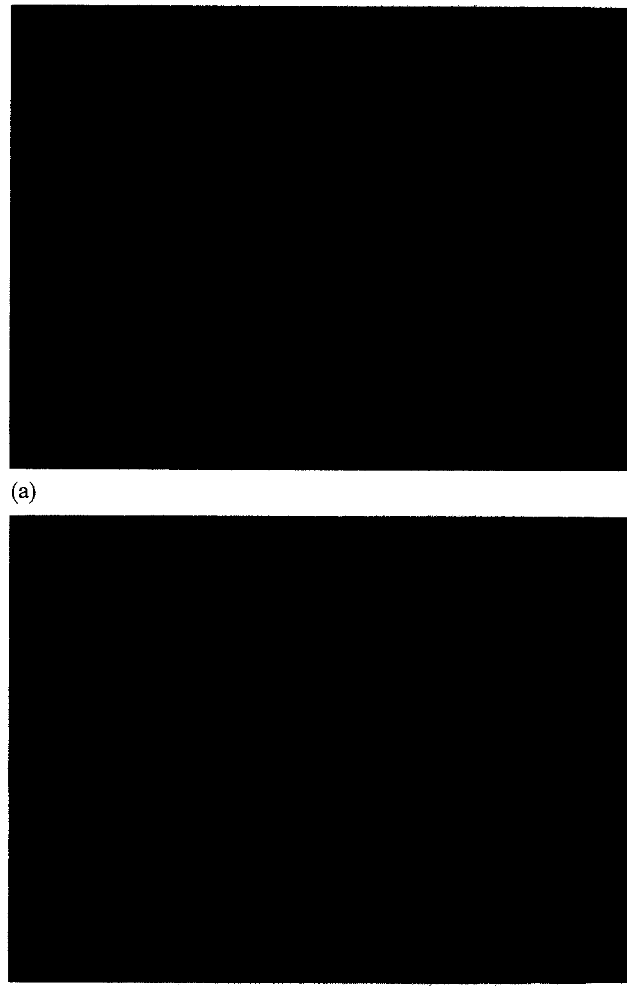
In series I the release of the high pre-tension (0.3 N and 0.6 N) at 1 day resulted in damage to the surrounding matrix which at this stage was apparently not sufficiently strong to resist the lateral Poisson stresses (Figs 9 and 11). As a result the bonding performance for the 1 day released systems decreased with increase in the initial pre-tension (Fig. 4 and Fig. 5a). By 6 days, the strength of the matrix is sufficiently high to prevent such damage and therefore the bonding performance for the 0.6 N pre-tension is better for the 6 days release than for the 1 day release (Fig. 6b). When comparing the bonding behavior of the 0.1 N and 0.6 N at 6 days one might have anticipated a better performance for the 0.6 N pre-tensioned system



(a)

(b)

Fig. 12. The groove in the matrix around the yarn, after pull-out, at different initial tensions, released after 1 day: (a) 0.6 N; (b) 0.1 N (yarn is fully in matrix).



(a)

(b)

Fig. 13. The groove in the matrix around the yarn, after pull-out: (a) specimen edge close to pull-out zone; (b) specimen edge at rear zone (initial tension 0.1 N, released after 1 day).

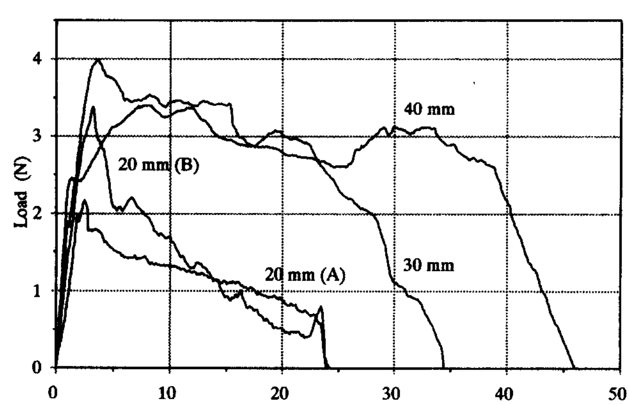


Fig. 14. Load–displacement curves of yarns with 'tail', embedded length is 20 mm and total length is 40, 30, 20 mm: (B) very short 'tail'; (A) no 'tail'.

which is expected to have higher lateral compressive stresses. This however is not the case (Fig. 5b), suggesting that perhaps other factors have still to be considered, such as additional damage for the higher pre-tension (although at a lower intensity than occurring at 1 day release) and some relaxation which have taken place during the 6 days of pre-tension.

In the case of series II two effects should be noted: the increase in the maximum pull-out load and the horizontal shape of the curve in the post peak zone suggesting a frictional type of behavior for an embedded length which is effectively constant throughout the test, as long as there is a 'tail'. The contribution of the yarn tail to bond capacity can be explained by the lateral expansion of the tail in the yarn due to the Poisson effect when the pre-tension is released, before the pull-out test (Fig. 16). In these specimens the yarn tail is free to expand, while the portion of the embedded yarn is restricted because of the adjacent matrix around it. The increase in the diameter of the yarn tail, the thicker free 'tail' of the yarn might perform as an anchor, accounting for the enhanced pull-out performance compared to a yarn with the same embedded length but without a 'tail'. Indirect evidence for the role of the 'tail' can be obtained when observing the surface of the yarn in the tail after the pull-out process, showing a roughened surface (compared with the smoother surface of the embedded part of the yarn, Fig. 15).


(a)

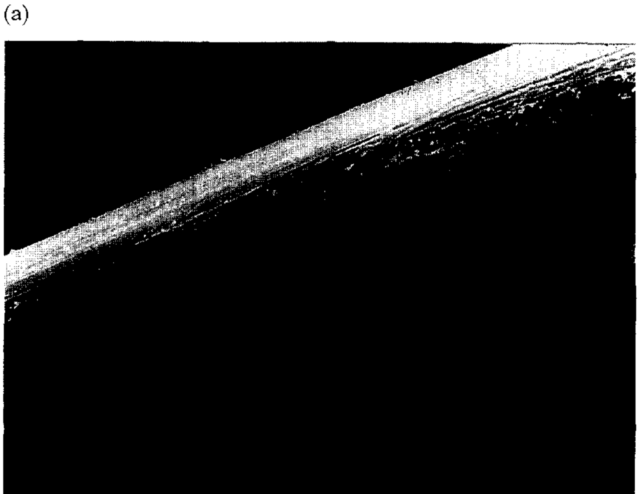

(b)

Fig. 15. Yarn surface at different zones: (a) fibrillation along yarn 'tail' surface; (b) smooth surface along the rear embedded part.

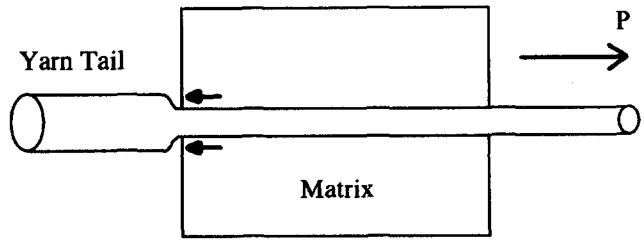


Fig. 16. Schematic description of mechanical anchoring caused by Poisson effect on yarn's 'tail'.

CONCLUSIONS

1. When the pulled yarn length is equal to the matrix length, the post-peak pull-out resistance decreases with increasing initial tension, mainly when the load is released at an early age of 1 day. This can be accounted for by damage caused to the surrounding matrix when the Poisson expansion is occurring at an early age against a relatively weak matrix.
2. When the pulled yarn was longer than the embedded length, the tail of the yarn considerably improves the bonding capacity. This improvement might be the result of an anchoring effect induced by the lateral Poisson expansion of the 'tail'.
3. The magnitude of the Poisson effects in these systems depends on the preparation and production process of the specimens. In view of the significant role of this effect on the pull-out resistance as seen in the nature

of the pull-out–displacement curve, the bonding in such composites cannot be considered as a materials parameter.

REFERENCES

1. Bentur, A. & Mindess, S., *Fibre Reinforced Cementitious Composites*. Elsevier Applied Science, New York, 1990, pp. 1–170, 309–377.
2. Al Khalaf, M. N. & Page, C. L., Steel mortar interfaces: Microstructural features and mode of failure. *Cem. Concr. Res.*, **9**(2) (1979) 197–208.
3. Page, C. L., Microstructural features of interfaces in fibre cement composites. *Composites*, **13** (1982) 140–144.
4. Bentur, A., Diamond, S. & Mindess, S., The microstructure of the steel fibre-cement interface. *J. Mat. Sci.*, **20** (1985) 3610–3620.
5. Barnes, B. D., Diamond, S. & Dolch, W. L., The contact zone between Portland cement paste and glass 'aggregate' surfaces. *Cem. Concr. Res.*, **8** (1978) 233–244.
6. Bentur, A., Interfaces in fibre reinforced cements bonding. In *Cementitious Composites*, Mindess, S. and Shah, S. P. (Eds.), Materials Research Symposium Proceeding 1988, Vol. 114, Materials Research Society, Pittsburgh, PA, pp. 133–144.
7. Balaguru, P. N. and Shah, S. P., *Fibre Reinforced Cement Composites*. McGraw-Hill, New York, 1992.
8. Kelly, A. & Zweben, C., Poisson contraction in aligned fibre composite showing pull-out. *J. Mat. Sci. Letters*, **11** (1976) 582–587.
9. Pinchin, D. J. & Tabor, D., Inelastic behavior in steel wire pull-out from Portland cement mortar. *J. Mat. Sci.*, **13** (1978) 1261–1266.