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Transition points in steel fibre pull-out tests from magnesium phosphate and accelerated calcium aluminate binders

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Abstract

Results are reported on the pull-out characteristics of two distinct types of steel fibre from two different rapid strengthening matrices, magnesia phosphate and accelerated calcium aluminate. The procedure incorporated a novel method of identifying the force necessary to initiate whole fibre movement relative to the matrix, one of the key transition points in the force/displacement relationship. Significantly different force/displacement relationships were obtained with each fibre/matrix combination. The two types of fibre were of similar length and section diameter but one type was of regular circular cross-section and smooth surface finish whereas the other type was of irregular kidney shaped cross-section and rough surface finish. The two different matrices had similar strengths but were completely different chemically. The results are discussed in the context of transition points of fibre/matrix interaction.

Keywords: Rapid strengthening cementitious binders; Transition points; Adhesional (chemical) debonding; Frictional bonding; Initiation of fibre movement; Fibre pull-out; Dynamic friction

1. Introduction

The mechanical property benefits achieved by fibre reinforcing cementitious matrices are determined to a large extent by the pull-out behaviour of fibres once the matrix has cracked. In practical application of composites this behaviour is complex and the starting point in developing micromechanical models is the characterisation of the simplest pull-out situation: that of a single fibre aligned and pulled out perpendicular to a matrix surface. This characterisation has been the subject of considerable research [1–10] which has now advanced sufficiently to allow theoretical treatment enabling the individual fibre pull-out stress/displacement relationships to be incorporated in composite behaviour models.

The processes occurring between the transition points are envisaged as follows:

- Fibre/matrix adhesional debonding comprises gradual fibre matrix separation starting at the entrance point of the embedded fibre into the matrix.
- The partially de-adhered zone (often referred to as the debonded zone in the literature) is subjected to frictional resistance to local relative movement between fibre and matrix.
- The completion of adhesional debonding corresponds to the elimination of any chemical bonding along the length of the fibre.
- At this stage pull-out forces may be resisted by static friction and probably mechanical interlocking (frictional bonding) sufficient to prevent any fibre movement.
- When sufficient force is applied the subsequent initiation of fibre movement is resisted by dynamic friction. This could be made up of several components (such as micro and macro matrix shearing and fibre deformation).

However, there are still details of the simple pull-out condition that have not been resolved completely. These particularly concern the location on pull-out

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force/displacement curves of the initiation of fibre/matrix adhesional debonding, the completion of adhesional debonding and subsequent initiation of frictional bonding. Also the initiation of fibre movement and the maximum pull-out force, otherwise known as the basic phenomenological transition points. The influence of certain individual fibre parameters on the position of these points and the contribution of tensile/compressive interface stresses operating in addition to the imposed shear stress have been made on the basis of assumptions derived from the shape of the pull-out curves.

The majority of the investigations into single fibre pull-out in cementitious materials have been undertaken with ordinary Portland cement based matrices. Although it can be anticipated that many features of such tests will be of general application, numerical values will vary from matrix to matrix as may particular phenomena. Magnesia phosphate cements and accelerated calcium aluminate cements offer very rapid strength development. For example compressive strengths of up to 25 MPa can be obtained within 1 h of mixing, which has advantages in rapid repair applications. The incorporation of fibres in such materials provides the same range of benefits as with normal cements [11]. No data has been reported in the literature of fibre pull-out characteristics from such matrices.

A considerable variety of fibres is now available as reinforcement. For instance, steel fibres have excellent reinforcing features in terms of strength and stiffness. In addition they are available in a wide range of geometric shapes which provide different anchoring capability. Although considerable amounts of data on pull-out behaviour have been reported, a conceptual framework relating transition points with fibre/matrix characteristics, to the best knowledge of the authors, has not yet been presented.

This paper reports the results of work directed at the various issues referred to above and presents data on the pull-out of two types of steel fibre. In particular, the behaviour of fibres of similar length and cross-section dimension but with significantly different geometry, from two chemically different matrices is discussed. A novel feature of one of the pull-out tests is the incorporation of a device to record the exact initiation of fibre movement. The results are placed in the context of transition points along the force/displacement curve and fibre anchorage capability.

The main objectives of this study were:

- To identify the force at which the completion of adhesional debonding and subsequent initiation of frictional bonding occurred.
- To identify the force at which the initiation of fibre movement occurred, that is the transition to dynamic friction; this point is subsequently referred to as "the onset of fibre pull-out".
- To compare the overall force/pull-out behaviour of the four different systems.

2. Experimental procedure

2.1. Materials

One type of matrix was a magnesia phosphate based cement [12], namely ASR-1 supplied by FEB International plc, Manchester, UK, whereas the other was an accelerated calcium aluminate cement, namely Ultracrete RSC-1 supplied by Instarmac Repair Services, West Midlands, UK. One type of fibre was a drawn low carbon steel of regular section, smooth-surfaced round-shaped, 25 mm long and diameter 0.5 mm, the other was a melt overflow chromium stainless steel alloy fibre, of irregular section, rough-surfaced kidney-shaped, 25 mm long and variable maximum cross-section dimension averaging around 0.4 mm. Both types were supplied by Fibre Technology, Nottingham, UK. The data reported are for fibre surfaces in the as-received condition.

2.2. Test specimens

Type 1: In this specimen type the fibre was embedded into two matrix blocks prepared with a central region of free fibre, Fig. 1(a).

Type 2: The matrix was cast into a mould with a locating hole and external jigs to ensure correct fibre alignment, that was central and parallel to the block faces. Additional locating holes enabled an embedded insulated wire to be located making electrical contact with the embedded end of the fibre. The wire had to be insulated to eliminate short-circuit due to conductivity of the matrix. Slight axial pressure was applied along the

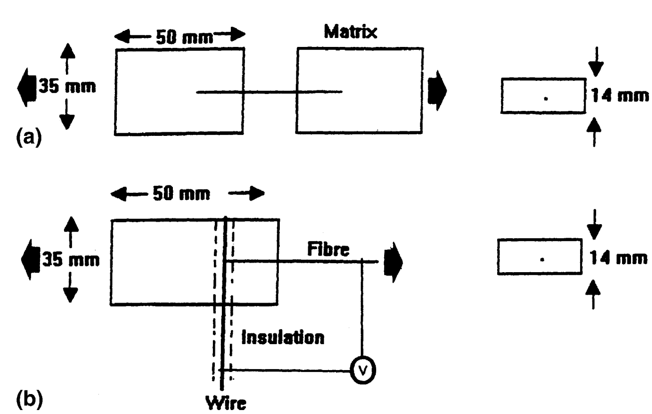

Fig. 1. (a) Basic pull-out test specimen configuration, and (b) Modified pull-out test specimen configuration with electrical instrumentation.

fibre to maintain fibre/sensor wire contact during cement hardening. The resulting specimen was therefore anchored in a single block of matrix with a free fibre end for subsequent gripping (Fig. 1(b)). Fibre embedment length of up to 14 mm was used in both types of specimen.

2.3. Pull-out tests

Type 1: Both matrix blocks were loaded via screw tightened plate grips on that part of the matrix block free from fibre.

Type 2: The matrix block was loaded via screw tightened plate grips acting on that part of the matrix block sufficiently beyond the fibre to ensure freedom from grip induced compressive forces along the fibre length. The free end of the fibre was clamped (using non-conducting pads between fibre and grip) as close as possible to the matrix. At the beginning of the test the circuit was completed via the exposed section of fibre and its resistance continually monitored using a voltmeter, V. The onset of fibre pull-out was identified by the instantaneous increase in electrical resistance. Force and displacements were measured by the test machine load cell and cross-head movement transducer. The use of the electrical device accounted for the high accuracy of the method. Slip between grips and the matrix block was eliminated with the set up used since the force that would induce slippage was found to be much greater than that at fibre onset.

Tests were undertaken 3 h after casting the matrix using a computer-controlled Instron tensile-testing machine. The cross-head movement was taken at a constant rate of 0.5 mm/min recording force and displacement continuously.

3. Results and discussion

3.1. Pull-out curves

Figs. 2 and 3 illustrate the shape of the typical pull-out curves obtained for the four systems.

The four types of curves are quite distinct, the characteristic differences being observed at all embedded lengths. It can be seen in Fig. 2(a) that there are three stages of deformation with the kidney section fibres embedded in magnesia phosphate. A linear region, part O–A, followed by a rising curve of decreasing gradient up to the maximum force, part A–B, which in turn is followed by a linearly decreasing force/displacement region, part B–C. Points A, B and C are not determined, merely they are reference points on the curves distinguishing a change in appearance. Part A–B shows a gradually increasing stick-slip behaviour (repetitive fibre obstruction followed by rapid movement) which develops into a regular, relatively large amplitude. Stick-slip deformation in part B–C was an approximate linear relationship between force and displacement. The onset of pull-out, point L, occurs significantly before that of maximum force in the early part of region A–B.

With round fibres in magnesia phosphate (Fig. 2(b)) the linear region O–A is followed by region A–C, initiated after a rapid drop in force, region A–B, and proceeding with an increasing amplitude of stick-slip and a non-linear force/displacement gradient, region B–C, indicating an increase in localised resistance as pull-out progressed. The onset of pull-out occurred at the maximum force, points A and L.

In the case of the calcium aluminate matrix, the kidney section fibres were pulled out with a similar overall curve shape to that of pull-out from magnesia

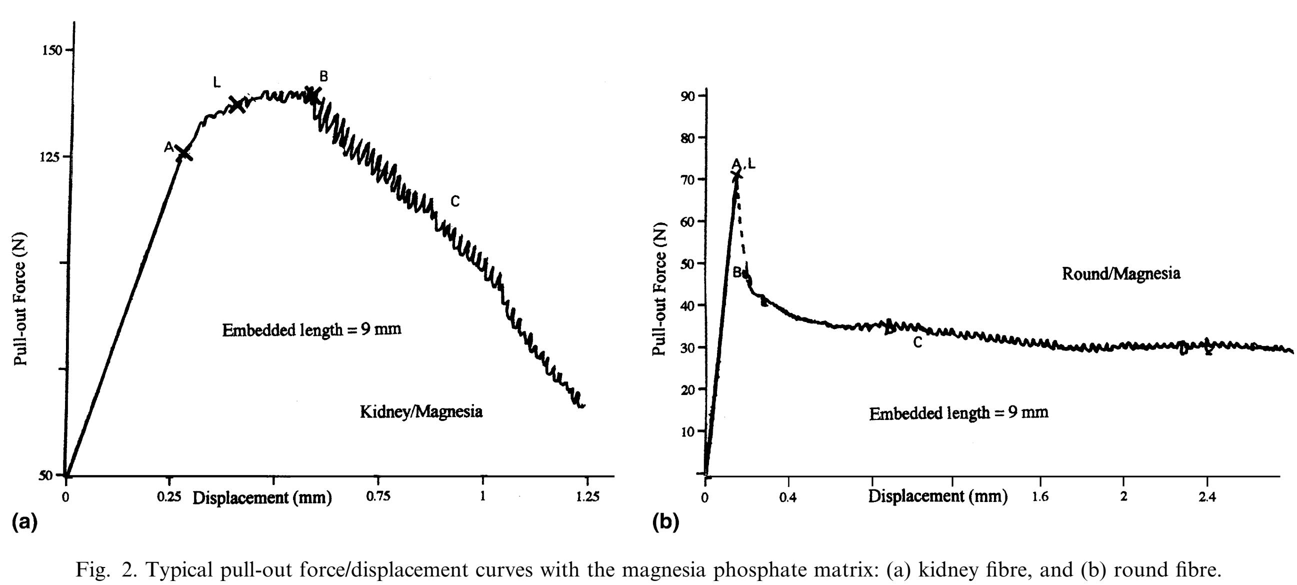

Fig. 2. Typical pull-out force/displacement curves with the magnesia phosphate matrix: (a) kidney fibre, and (b) round fibre.

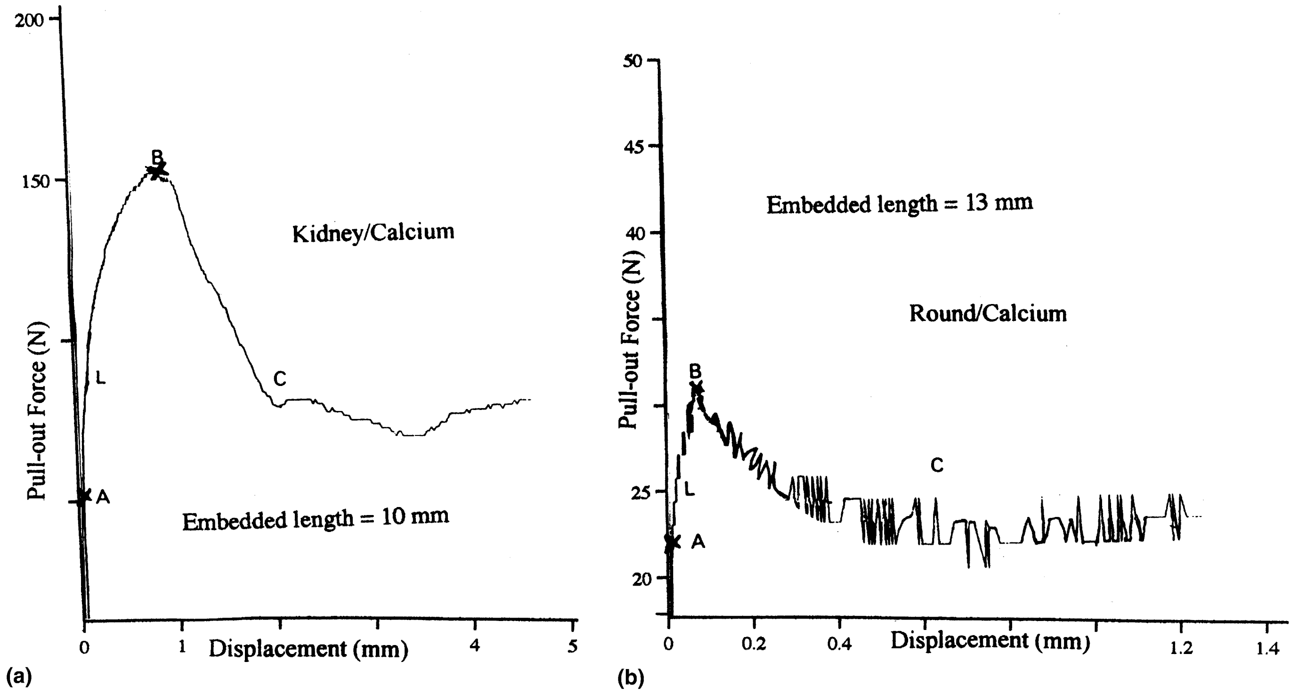

Fig. 3. Typical pull-out force/displacement curves with the calcium aluminate matrix: (a) kidney fibre, and (b) round fibre.

phosphate (Fig. 3(a)). However, the onset of pull-out, point L, occurred earlier within the non-linear region of deformation, region A–B. Another difference was the smoother nature of the curve during the linearly decreasing force/displacement region compared to the pronounced stick-slip with the magnesia phosphate.

The round fibre started to pull out from the calcium aluminate matrix well before the maximum force was reached (Fig. 3(b)). Although there was a distinct transition at maximum force there was no catastrophic drop in force before the normal frictional region which occurred with larger stick-slip displacements than with magnesia phosphate.

Finally, a substantially greater maximum pull-out resistance was observed with the kidney shaped fibres than with the round fibres and sufficient resistance to pull-out could be developed to fracture fibres.

3.2. Semi-quantitative data

Tables 1 and 2 summarise the maximum pull-out force and the nominal shear stress for different embedded lengths of the various systems. Each data point is the average of at least six tests. There was no significant difference in the data produced by the two test methods and the results are combined. The greater scatter (about 15%) in the data of the kidney sectioned fibres is due to the irregularities of their cross-section. In order to make comparisons maximum nominal shear stresses were calculated from the maximum force, using a fibre perimeter equivalent to a circular cross-section of 0.4 mm nominal diameter for the kidney section fibres. This is equivalent to shear flow [4] as the irregularity of the cross-section along the length of fibres and the influence of surface roughness precluded accurate perimeter cal-

Table 1
Summary of pull-out test results from the magnesia phosphate cement matrix

Kidney fibres								
Embedded length (mm)	2.5	3	6	6.5	9	10	12	14[a]
Ultimate force (N)	38	40	90	110	137	156	149	164
Shear stress (MPa)	12.1	10.6	11.9	13.5	12.1	12.4	9.9	9.3
Force at end of debonding (N)	0.63	0.75	1.5	1.6	2.3	2.5	3	3.5
Round fibres								
Embedded length (mm)	8.5	9	9.5	10.5				
Ultimate force (N)	57	72	77	87				
Shear stress (MPa)	4.3	5.1	5.2	5.3				
Force at end of debonding (N)	2.6	2.8	3	3.3				

[a] Fibre fracture.

Table 2
Summary of pull-out test results from the accelerated calcium aluminate cement matrix

Kidney fibres					
Embedded length (mm)	6[a]	9	10	11[a]	12
Ultimate force (N)	64	97	155	175	143
Shear stress (MPa)	8.5	8.6	12.3	12.7	9.5
Round fibres					
Embedded length (mm)	<10	10	13	14	
Ultimate force (N)	–	21	32	36	
Shear stress (MPa)	–	5.1	5.2	5.3	

[a] Fibre fracture.

culations. Since displacements were determined from cross-head movement they include displacements in addition to actual specimen extensions. These are significant primarily in the linear regions of the curves.

3.3. Transition points

All pull-out tests have three fundamental transition points [3,5], that is to say: (i) the initiation of fibre/matrix adhesional debonding, (T1), (ii) the completion of adhesional debonding and subsequent initiation of frictional bonding, (T2), and (iii) the onset of fibre pull-out, (T3).

Until recently it was generally assumed that all three points were more or less coincidental in the case of straight fibres and that they occurred at the maximum force or at the force at which there was a gross change in gradient to a much flatter slope. This was justified on the grounds that the force/displacement curve was usually linear to maximum force. The transition points can be related to the force/displacement curves by direct observation in the case of transparent matrices. Conversely, with opaque matrices they can be related either by inference, for example from the shape of the curves [6,10], from acoustic emission and in situ video imaging [13], or by exposing part of the fibre at the surface and using optical microscopy and scanning electron microscopy [8,14]. When using the latter approach it has been shown that T1 and T2 occurred in the linear region well before the maximum load was reached [14]. It has also been identified in the same tests, where steel melt extracted smooth surfaced fibres were used, that initiation of fibre movement, T3, occurred before the maximum load.

On the other hand, other investigations indicated T2 (full fibre debonding) occurring beyond the maximum force [15], where the modelling of pull-out behaviour of aligned, straight, smooth, round steel fibres from an ordinary cement matrix containing a polymer (airvol-203) as an additive, was based on analysis of the pull-out curves. It was then concluded that, the addition of the polymer improved frictional resistance to pull-out in this type of fibres and thus catastrophic debonding was avoided.

The present data indicates that the position of maximum force identifies in effect a fourth transition point corresponding to a change of micromechanical pull-out from interactive locking to conventional frictional pull-out, which is discussed below.

The form of the curve for round fibres pulling out of magnesia phosphate can be considered as representative of one end of the spectrum observed in practise. That is a linear region to maximum force followed by a drop in force and a curve of decreasing force approximately linearly related to pull-out. The conductivity monitor indicated that the onset of pull-out, T3, occurred at maximum force thereby confirming the usual theoretical assumption although not supporting other observations [14]. This confirms the interpretations made in the literature for similar systems where catastrophic debonding occurs at maximum force [10]. No knowledge could be gained from the literature regarding T1 and T2 because of the linear nature of the force/displacement relationship. In other words, there are no features corresponding to a change in mechanism of force transfer from fibre to matrix. It cannot be assumed that all three transition points occur almost simultaneously because of the linearity, unless the fibre displacement profile is mapped in detail along its length as undertaken by some investigators [14]. The explanation for the linear relationships frequently observed is the insensitivity resulting from measuring gross displacement from a point on the fibre well outside the embedded region. It should be noted that A, B and C are distinguishing points on the curves whereas, T1, T2 and T3 are transition points which may or may not coincide with A, B and C.

The form of the curves obtained in all other cases in the present work can be considered as transitional towards that of the other extreme, a fibre mechanically locked at the embedded end for example that of a hooked ended fibre. The conductivity monitor identified T3 as occurring at point L on a typical curve which was located significantly before the maximum force. In this case the observations made in the literature were confirmed [14]. It is not possible to establish unambiguously from the force/displacement curves where T1 is occurring, but T2 can be located from previous work [16], where a novel tensile test method was developed. This allowed direct measurements to be made of the average force, to separate a fibre from a matrix, and thus to evaluate the average fibre/matrix interfacial chemical bond strength magnitude. The nature of the bonding between the fibre and the matrix in that test was purely adhesional and the interfacial chemical tensile bond strength was calculated as the nominal perpendicular stress on the curved surface of the fibre. This has been quantified by considering the average force to separate a fibre from the matrix and including both the tensile component and the shear component created at the interface by restrained shrinkage of the matrix. It was found that a maximum interfacial bond stress of 0.2 MPa could be measured for the magnesia phosphate matrix [16]. In the case of the calcium aluminate material, the chemical bond tests revealed the very poor bonding of this matrix and no value of the interfacial bond stress could be measured [16]. Turning to the pull-out tests, then at the end of the debonding process the tensile component may be considered to be zero in magnitude and that the shear component will approximately be equal to the maximum interfacial bond stress, that is a value of 0.2 MPa. Thus, the forces at which adhesional bonding resistance was entirely replaced by frictional resistance during the pull-out process could be estimated and are given in Table 1. These forces, which fell in the linear regions thus confirming observations made in the literature [14], define the end of the adhesional debonding process and the subsequent beginning of purely frictional resistance to pull-out, that is T2. Since the forces resisting pull-out continue to increase for significant displacements it is clear that there are additional micromechanical processes occurring than conventional frictional resistance since once pull-out initiates embedment length must be decreasing. Collectively, these processes can be termed "interactive locking".

In the case of the fibres pulling out of the calcium aluminate matrix, the onset of pull-out before maximum force with the round fibres and the mixture of pull-out/fracture with the kidney fibres, are indicative of yet further mechanisms of interactive locking. That is more matrix (calcium aluminate matrix is by nature a more brittle material than magnesia matrix) or interface frictional bond dependent than due to fibre shape.

It follows that once the first transition point is reached, T1, the subsequent shape of the force/displacement curve is fortuitous resulting from the combination of three separate unrelated force/displacement relationships: one for elastic shear resistance across the unbonded interface until T2, one for frictional resistance as pointed out in the literature throughout the subsequent deformation [15], and more importantly one for interactive locking.

The implications of this for modelling lie in the need to identify mechanisms for interactive locking in addition to dynamic frictional resistance in order to develop constitutive relationships.

3.4. Numerical values

A comparison of the nominal maximum shear stresses of the two fibre types indicates a doubling of resistance to pull-out of the irregular sectioned, rough surfaced kidney section fibre compared to that of the regular smooth circular sectioned fibre with both the magnesia phosphate and calcium aluminate matrices.

The kidney fibres fractured at a 14 mm embedment length with the magnesia phosphate matrix whereas a mixture of pull-out/fracture was observed with the calcium aluminate matrix at almost all embedment lengths. Fibre fracture could not be induced with the round fibres with the maximum possible embedment length of 14 mm. The values of maximum nominal shear stress were up to twice those of initiation of fibre movement, the latter not shown in Tables 1 and 2. The maximum values shear stresses compare to data reported in the literature for ordinary Portland cement based systems [5,10,14,15].

3.5. Mechanisms of pull-out failure

The region of increasing force to produce pull-out indicates the substantial forces that can be imposed on the fibres by the locally fractured matrix. It is envisaged that crushing damage with extensive and continuing matrix cracking enables wedging/plug forces to develop between the uncracked matrix and the sliding fibre [8].

The eventual increase of pull-out shear stress obtained in most cases, is in contrast to the constant post maximum pull-out shear stress. An explanation for this could be the eventual enhancing of matrix cracking and accompanying build-up of debris after significant sliding had occurred.

3.6. Limitation of test procedure

While similar testing arrangements reported in the literature are two-dimensional in nature and therefore differ from the actual situation in the composite [8,14], the testing arrangement used in this study is three-dimensional in nature since the fibre is surrounded on all sides by the cement matrix. However, a limitation of the present test method is the conductive nature of the fibre.

4. Conclusions

1. The force at which adhesional bonding resistance was entirely replaced by frictional resistance during the early stages of the pull-out process laid in the linear regions of the force/displacement curves. It defined the end of the adhesional debonding process and the subsequent beginning of purely frictional resistance to pull-out, that is T2.
2. The forces resisting pull-out continued to increase for significant displacements after T2 had been reached. It is concluded that there were additional micromechanical processes occurring than conventional frictional resistance. Collectively these processes can be termed interactive locking.
3. The initiation of pull-out, that is T3, occurred in most cases before the maximum force was reached and identified unambiguously the start of sliding pull-out, one of the key parameters necessary for pull-out modelling. The region of increasing force to produce sliding pull-out indicates the substantial forces that can be imposed on the fibres by the locally fractured matrix.
4. The eventual increase of pull-out resistance with most fibres and matrices after T3 was reached, was in contrast to the constant post maximum pull-out shear stress. An explanation for this could be the eventual enhancing of matrix cracking and accompanying build-up of debris around the maximum force.
5. The position of maximum force identified in effect a fourth transition point corresponding to a change of micromechanical pull-out from interactive locking and conventional frictional pull-out.
6. A comparison between the two types of fibres used, indicated a doubling of resistance to pull-out of the irregular sectioned, rough surface kidney fibre compared to that of the regular sectioned, smooth circular fibre.
7. The shapes of the curves highlighted the effect of increasing mechanical interlocking on pull-out characteristics. The circular sectioned, smooth straight fibres embedded in the magnesia phosphate matrix showed the typical behaviour reported in the literature. However, an increased amount of stick slip was observed. In all other cases, a more complicated behaviour transitional along the route to that of a fully mechanically anchored fibre was observed.

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