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Multiple cracking in aligned polypropylene fibre reinforced cement composites

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Multiple cracking has been shown to occur in hardened cement paste reinforced with aligned polypropylene fibres of elastic modulus considerably lower than that of the cement paste. The effect of fibre volume fraction on the distribution of matrix cracks has been studied and good agreement found with existing theory. Factors which enable fibre/matrix contact to be maintained during the multiple cracking process, despite the unfavourable Poisson's ratio contraction of polypropylene have been discussed. These include the lateral displacement of one surface of a crack relative to the other and also the lateral displacement of matrix material next to the crack surface relative to the fibre array. This latter mechanism is shown to apply to other aligned composites and calculations based on a simple theory predict that multiple cracking should occur in all composites provided that a critical size is exceeded.

1. Introduction

Fibre reinforcement is a well established technique for improving the mechanical properties of a variety of matrices [1]. In the case of hardened cement pastes, their brittle characteristics, low tensile strength and poor extensibility can be improved to varying degrees by incorporating fibres. Asbestos is the most commonly used fibre but glass, steel, natural cellulose and polypropylene are also employed in commercial products.

It is normally considered that the inclusion of fibres with a modulus of elasticity greater than that of the cementitious matrix improves the tensile strength, strain to failure and impact resistance, whereas a fibre with a modulus lower than the matrix improves only the impact resistance. However it has been shown that low modulus polypropylene fibres [2, 3] or fibrillated film [4] can significantly increase the ultimate flexural strength, compared to that of the unreinforced matrix. The improvement in strength is accompanied by improvements in extensibility and impact resistance.

A necessary phenomenon which allows this strength increase is the multiple cracking of the matrix. Kelly and Zweben [5] and Pinchin [6] have argued theoretically that this phenomenon will not occur in hardened cement paste reinforced with aligned polypropylene fibres because of the unfavourable Poisson's ratio of the polypropylene, unless shrinkage stresses are present. Furthermore they calculated that several other composite systems should not exhibit multiple cracking. However in some of these systems multiple cracking is observed and they suggest that the presence of shrinkage stresses and fibre surface asperities may offset the effect of Poisson's ratio.

In this paper we report the results of preliminary experiments which indicate that multiple cracking of the matrix occurs in aligned polypropylene fibre reinforced cement composites. An alternative description of the role of Poisson's ratio is presented which predicts that multiple cracking should occur in all the aligned composite systems discussed by Kelly, Zweben and Pinchin provided that a sufficiently large specimen is used.

2. Experimental procedures

Ordinary Portland cement paste of water to cement ratio 0.4 by weight was used throughout the investigation. The high water to cement ratio ensured adequate penetration of the aligned fibre lay-up.

The fibrous reinforcement consisted of poly-

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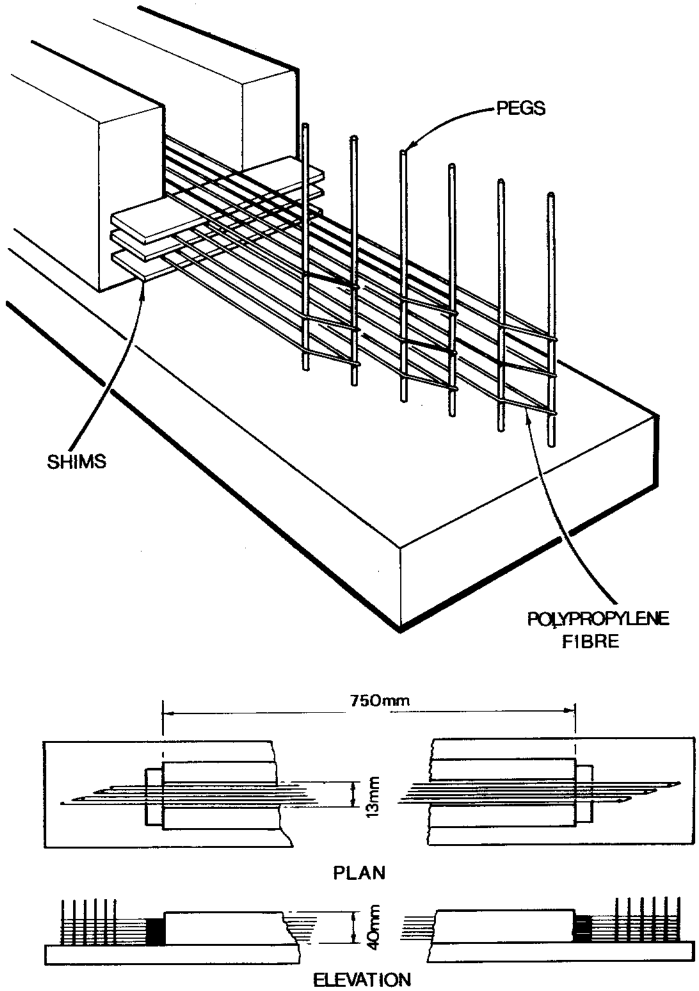

Figure 1 Schematic diagram of aligned fibre lay-up jig.

propylene monofilaments of diameter 340 μm, available in continuous lengths. This fibre diameter allowed the preparation of aligned composites containing up to 8.7 vol% of fibre as follows. Fibre alignment parallel to the long axis of a rectangular section beam was achieved by winding around locating pegs in the perspex jig illustrated in Fig. 1. The pegs also allowed accurate horizontal spacing of the fibres. Vertical spacing was controlled by placing shims between each horizontal plane of fibres, the shims being inserted between the pegs and the mould ends. The shims also acted as ends to the mould. A light tension in each fibre ensured that there was no sagging.

The cement slurry was prepared in a Hobart mixer for a period of 5 min and poured into the mould whilst the whole jig was vibrated. The upper surface was covered with a damp cloth. After 24 h the specimen was demoulded and stored under water at 20° C for six days and then air dried at room temperature for 24 h before testing.

Specimens 40 mm x 13 mm in cross-section and 250 mm long were prepared containing 1.4, 2.4, 4.2, 5.5 and 8.7 vol% fibre.

The specimens were tested in uniaxial tension at a constant rate of cross head movement (0.016 mm sec^{-1}) by means of a servo-hydraulic testing machine (Losenhausen UH6). The extension of the specimen was measured via cross head displacement since an extensometer would have prevented detailed observation of crack development. A typical load/extension curve (Fig. 2) therefore includes the unavoidable bedding down displacement in the linear region.

Crack location was marked on the specimen in the fully extended position. In the event of an irregular crack path across the specimen the average

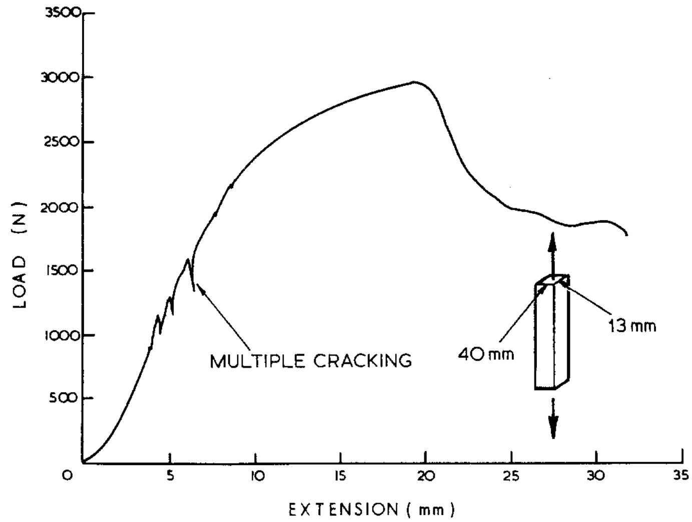

Figure 2 Typical tensile load/extension curve for cement paste reinforced with 5.5 vol % concentration of 340 μm diameter polypropylene fibre.

longitudinal position was used to specify crack spacing. The measurements of spacing were made after unloading.

3. Results

At least three specimens were tested in tension at each fibre concentration and multiple cracking occurred in all fibre reinforced specimens. Fig. 3 illustrates a typical specimen after testing. It can be seen that the multiple cracks run approximately perpendicular to the tensile stress direction and generally at regular intervals along the length of the specimen. A systematic relationship between fibre concentration and crack spacing was observed, the greater the concentration the more cracks per unit length of specimen (see Fig. 4). The general theory derived by Aveston *et al.* [7] for such multiple cracking predicts that this relationship should be of the form

$$x = \left(\frac{1-V_f}{V_f}\right)\frac{\sigma_{mu} r}{2\tau} \tag{1}$$

where x is the average crack spacing, V_f is the volume fraction of fibres, σ_{mu} is the matrix ultimate stress, r the fibre radius and τ the fibre/matrix shear stress. Aveston *et al.* showed that multiple cracking of a matrix would occur provided that

$$\sigma_{fu} V_f > \sigma_{mu} V_m + \sigma'_f V_f \tag{2}$$

where σ_{fu} is the fibre ultimate stress, V_m is the volume fraction of matrix and σ'_f the fibre stress at onset of cracking. i.e. sufficient unbroken fibres must be present to support the total load on the composite, at the first crack. The matrix then divides into blocks of length between x and $2x$ by progressive cracking. This is induced by the transfer of stress from the fibres bridging the initial crack back into the adjacent matrix via shear stresses at the matrix/fibre interface. The assumption is made that the shear stress has a constant limiting value and that the matrix fracture stress will be reached at a distance x from the first crack provided that

$$2N\pi r\tau x = \sigma_{mu} V_m \tag{3}$$

where N is the number of fibres in unit cross-section. Equation 1 is derived from Equation 3, since $N = V_f/\pi r^2$.

A plot of x against $(1-V_f)/V_f$ gives a straight line passing almost through the origin with a correlation coefficient of 0.98 (see Fig. 4). Substituting

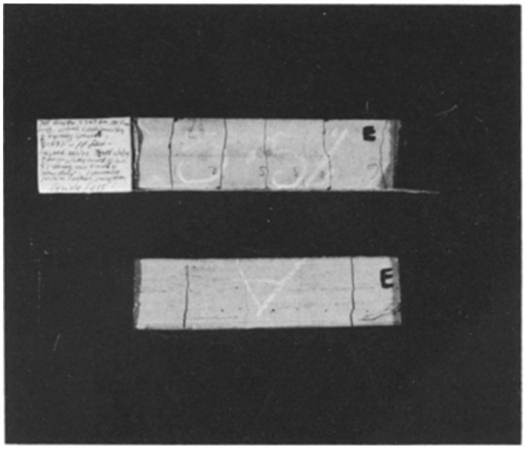

Figure 3 Specimen after test, showing multiple cracking of matrix.

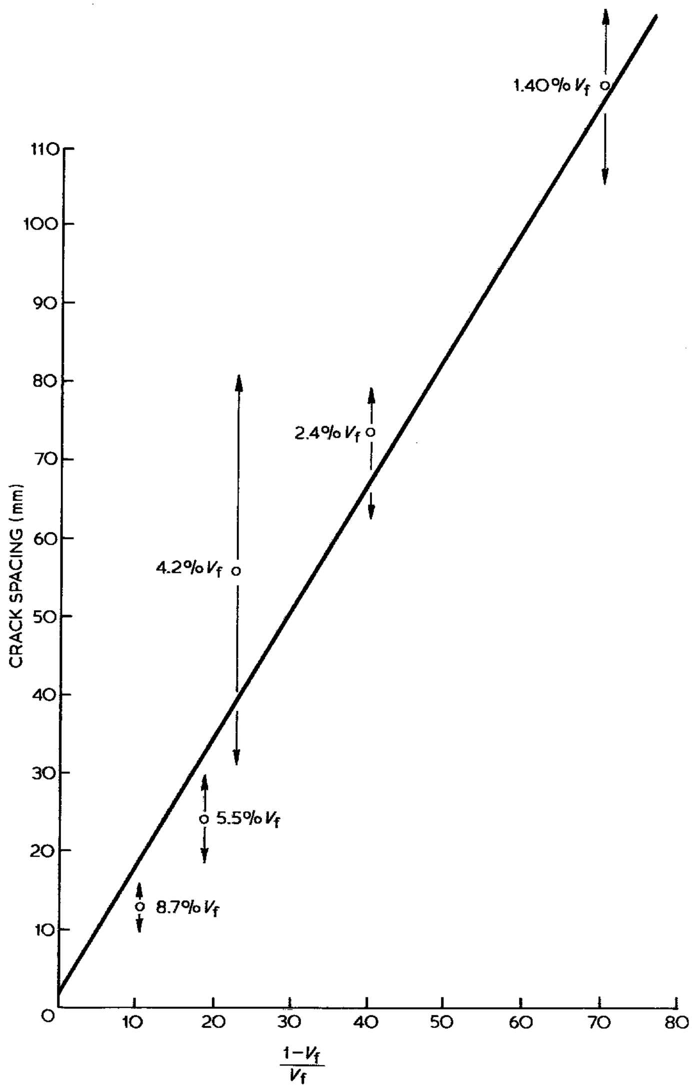

Figure 4 Variation in crack spacing with V_f and $(1 - V_f)/V_f$.

for $\sigma_{mu} = 1.0\,\text{N mm}^{-2}$, and $r = 0.17$ mm a value of $\tau = 0.05\,\text{N mm}^{-2}$ is obtained from the gradient.

4. Discussion

The experimental results demonstrate that the basic phenomenon of multiple cracking in a cementitious matrix reinforced by fibres having a modulus of elasticity lower than that of the matrix is essentially the same as that obtained with high modulus fibres. However two theoretical treatments of multiple cracking have both predicted that it should not occur in the case of polypropylene fibre reinforced cement, unless shrinkage stresses or mechanical fibre/matrix interactions are also present. The high Poisson's ratio contraction of polypropylene fibre compared to cement is considered to lead to unstable debonding of the fibre from the matrix. It is necessary therefore to consider in more detail fibre/matrix interaction during multiple cracking in order to explain why it occurs in the case of polypropylene fibre reinforced cement.

Equation 2 is a necessary condition for multiple cracking to occur but not a sufficient condition. Clearly there must also be fibre/matrix interaction and Equation 3 assumes that a fibre matrix shear stress of constant limiting value can develop as a result of friction. Kelly and Zweben explain that if such a stress is present there must also be a normal compressive force at the fibre surface. In some composite systems such forces arise because of matrix shrinkage during curing or drying. In the absence of compressive forces they consider that if the Poisson's ratio of the fibre (ν_f) is greater

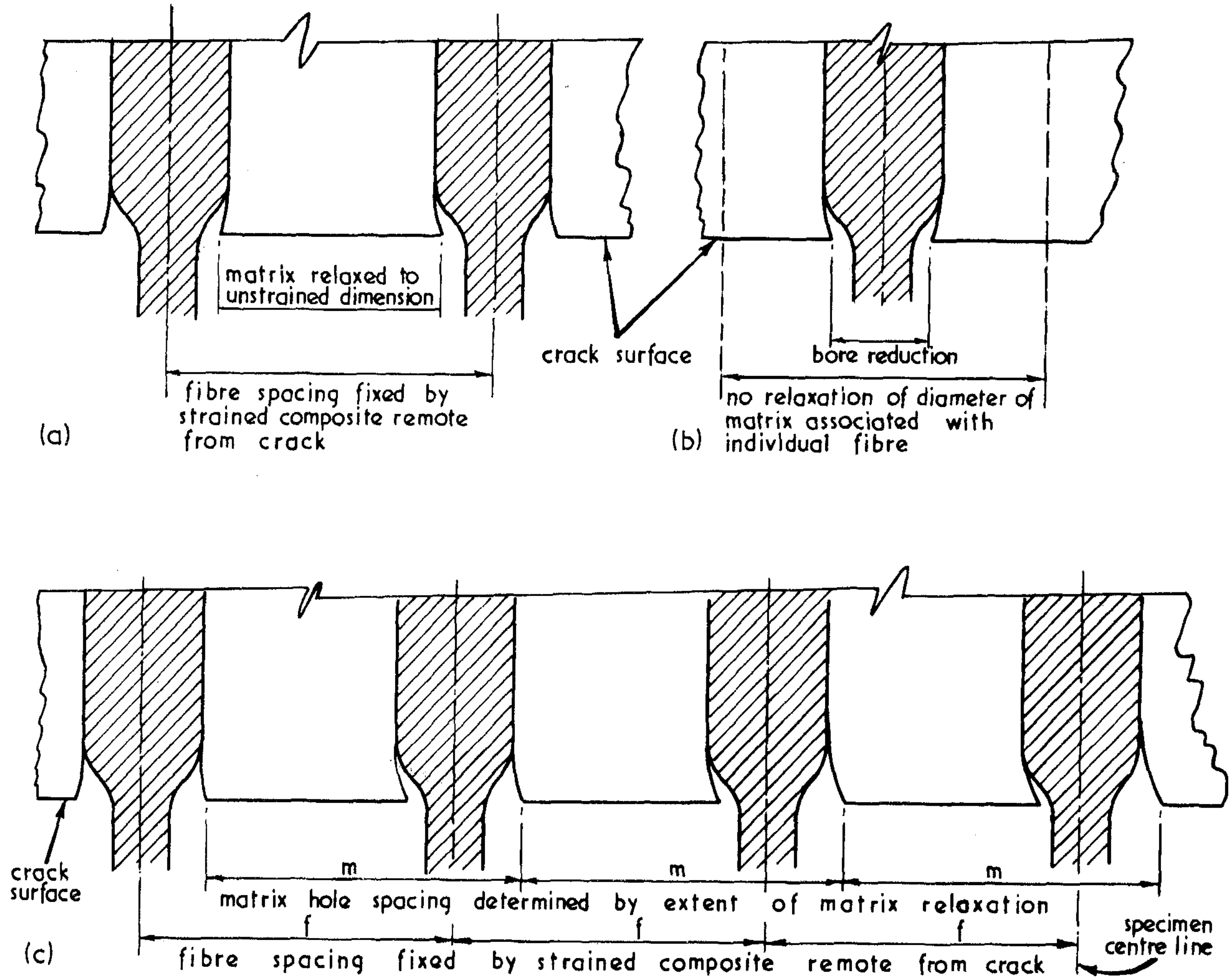

Figure 5 Schematic illustrations of (a) Kelly and Zweben model, (b) Pinchin model, (c) proposed model. The Poisson contractions have been greatly exaggerated for clarity.

TABLE I

System fibre/matrix	V_f	E_f (kN mm^{-2})	ν_f	E_m (kN mm^{-2})	ν_m	ν_c^*	$r^†$ (μm)	d_c (mm)	Multiple cracking predicted		
									Kelly and	Pinchin	d_c criterion
Steel/cement‡	0.05	200	0.28	20	0.23	0.23	150	1.4	Yes	No	Yes
Steel/epoxy‡	0.2	200	0.28	3.5	0.3	0.3	150	0.6	Yes	Yes	Yes
Graphite/cement‡	0.2	200	0.35	20	0.23	0.23	5	0.03	No	No	Yes
Graphite/cement‡	0.05	200	0.35	20	0.23	0.24	5	0.014	Yes	No	Yes
Glass/epoxy‡	0.6	72	0.25	3.5	0.3	0.27	5	0.02	Yes	Yes	Yes
Graphite/glass‡	0.5	200	0.35	72	0.25	0.3	5	0.026	No	No	Yes
Glass/cement‡	0.05	72	0.25	20	0.23	0.23	5	0.08	No	No	Yes
Polypropylene/ cement‡	0.1	10	0.3	20	0.23	0.24	170	8.4	No	No	No
Polypropylene/ cement	0.087	1.5	0.3	10	0.23	0.24	170	30.5	–	–	No
Polypropylene/ cement	0.014	1.5	0.3	10	0.23	0.24	170	200.0	–	–	No

*$\nu_c \simeq \nu_f V_f + \nu_m V_m$.
†Nominal values apart from polypropylene.
‡After Kelly and Zweben.

than a certain value related to the matrix Poisson's ratio (ν_m) then unstable debonding of fibre from matrix will occur and a single crack rather than multiple cracking will result. Fig. 5a illustrates their model. It can be seen that after cracking a longitudinal element of the matrix adjacent to the crack surface is considered to relax laterally to its original unstrained lateral dimensions. The fibres are required to support the total load on the composite and hence suffer an increased lateral contraction. The difference between the matrix expansion and the fibre contraction may result in total loss of contact between fibre and matrix. Table I indicates those composites which should not exhibit multiple cracking because of this effect.

Pinchin considers that an assumption of complete matrix relaxation is not acceptable for actual composite behaviour. Furthermore he points out that the previous model assumes fibre/matrix contact with no interfacial pressure, when the composite is under strain just before cracking. This will not be the case unless ν_f and ν_m have the same value. Pinchin's treatment of the effect of Poisson's ratio is illustrated in Fig. 5b. In this model it is considered that the longitudinal matrix element does not relax laterally after cracking since it must be restrained by adjacent matrix elements. The extreme case is analysed where the matrix lateral expansion is completely prevented. The analysis considers the external forces required to prevent completely lateral expansion of the outside diameter of a hypothetical tube of matrix surrounding a fibre. Such an external pressure will reduce the bore of the cylinder of matrix. The magnitude of this bore reduction is calculated for the same systems as analysed by Kelly and compared with the fibre diametral contraction, in order to establish loss of fibre/matrix contact criterion and hence absence of multiple cracking. Table I compares the results of the two approaches.

It is considered that a limitation of these analyses is the assumption that the forces acting on a fibre are identical wherever the fibre is located, Kelly and Zweben considering a single pair of fibres and extrapolating for the whole array, Pinchin considering a single fibre and its equivalent tube of matrix likewise extrapolated. Furthermore Pinchin's analysis seeks to determine a criterion for loss of fibre/matrix contact in the middle of an array of fibres whilst relying on fibre/matrix contact to prevent the lateral expansion of the matrix.

The influence of fibre location on fibre/matrix interaction can be identified qualitatively by considering a specimen of circular cross section as follows. It is assumed that the composite strain remote from an initial crack is equal to the strain immediately before cracking. This assumption is made in the two previous analyses and also in the general treatment of Aveston *et al.* Some matrix relaxation at the crack surface is assumed, the extent of the relaxation being dependent upon many factors including the elastic modulii of fibre and matrix, fibre volume fraction, fibre diameter and specimen size. Fig. 5c illustrates the implications of these assumptions. The centre line of each fibre is determined by the fully strained system. The centre line of the matrix hole at the cracked surface is determined for a given average lateral relaxation, by its distance from the centre of the whole specimen. It can be seen that the condition for fibre/matrix contact must be reached in any composite system provided that a fibre is located sufficiently far from the centre line of the specimen. Thus there is a critical diameter of specimen which must be exceeded in order to have fibre/matrix contact and an additional thickness of material further increasing the diameter in order that multiple cracking should occur. The additional thickness will be dependent upon the volume fraction of fibres and the fibre/matrix interface strength τ. τ does not have a unique value and is dependent upon several factors. A Coulomb relationship describes the general case i.e.

$$\tau = c + \sigma_n \mu \quad (4)$$

where c is the fibre/matrix cohesion which equals zero in the case of purely frictional interaction, σ_n is the normal compressive force at the interface and μ the coefficient of friction. Several investigators have drawn attention to the variability of μ and σ_n during the deformation process [8–10]. The present work indicates additional sources of σ_n variations. The greater the distance of a fibre from the centre line of a specimen beyond the critical diameter the greater is σ_n, σ_n also varies around the circumference of an individual fibre, being a maximum at the nearest point to the centre of the specimen. Furthermore as specimen diameter increases fibre restraint will begin to restrict lateral matrix expansion.

In the absence of data regarding these various effects it is not possible to calculate the minimum additional diameter to allow multiple cracking. However calculation of the critical diameter d_c enables an assessment to be made of the likelihood of multiple cracking occurring in practical sized composites.

A cylindrical composite containing uniformly spaced longitudinally aligned fibres is considered and it is assumed that the matrix element adjacent to a crack surface will relax laterally to its original unstrained dimensions provided that the diameter is less than or equal to the critical diameter d_c. The basis of the calculation is illustrated in Fig. 6. It can be seen that fibre/matrix contact will occur when the displacement of a matrix hole away from the centre of the specimen plus the fibre radius immediately after cracking is equal to the radius of the unstrained fibre or matrix hole. That is

$$\left(\frac{d_c}{2} - r\right) \nu_c \epsilon_c + r(1 - \nu_f \epsilon_f) = r \quad (5)$$

where ϵ_c is the composite longitudinal strain at the onset of cracking, ν_c is the Poisson's ratio of composite, E_m is Young's modulus of the matrix, E_f is Young's modulus of the fibre and ϵ_f is the fibre longitudinal strain after cracking which equals

$$\epsilon_c \left(1 + \frac{E_m V_m}{E_f V_f}\right).$$

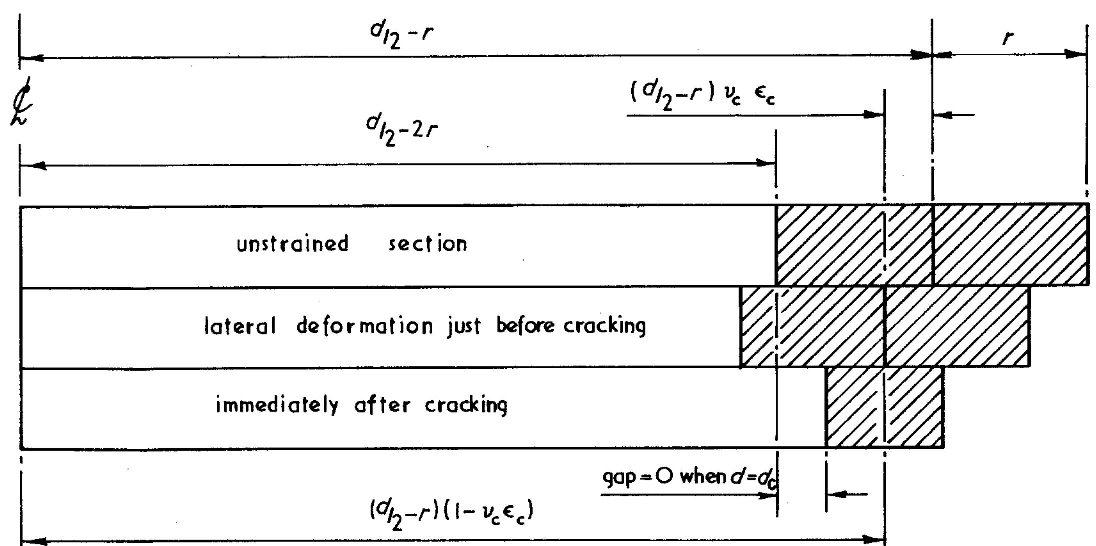

Figure 6 Relationship between fibre and matrix deformations.

Therefore

$$d_c = 2r\left[1+\left(1+\frac{E_m V_m}{E_f V_f}\right)\frac{\nu_f}{\nu_c}\right]. \qquad (6)$$

Table I lists the values of d_c for the various systems considered by Kelly and Zweben. It can be seen that apart from polypropylene reinforced cement all the composites have a d_c less than 1.4 mm. Thus in practical sized composites the majority of fibres will be in contact with the matrix and multiple cracking must occur above a critical volume fraction. This will be slightly higher than predicted by Aveston *et al.* although their general treatment of multiple cracking applies equally as well to an average fibre/matrix shear strength as to a unique value. It follows that the role of Poisson's ratio is not significant in these composites. In the case of polypropylene reinforced cement d_c is 200 mm for 1.4 vol% and 30.8 mm for 8.7 vol% of fibre, since these values are much greater than the dimensions of specimens in which multiple cracking occurred, other factors must contribute to offset the Poisson's ratio shrinkage.

It has been suggested that matrix shrinkage or surface fibre asperities could be responsible. The influence of matrix shrinkage can be estimated. Average lateral shrinkage strains of 0.0006 were measured during the one day air drying period immediately prior to testing. This will result in a precompression of 0.2 μm in 340 μm diameter fibres.

The Poisson's ratio contraction of a 340 μm diameter fibre in a composite with 5% V_f at the onset of cracking is 2.0 μm assuming the same values for E_m and E_f as Kelly and Zweben i.e. 20 000 N mm^{-2} and 10 000 N mm^{-2} respectively, and a matrix cracking strain of 5.0×10^{-4}. However the actual values of the materials employed in the present tests were determined experimentally as 10 000 N mm^{-2} and 1500 N mm^{-2} for cement and fibre respectively. The calculated Poisson's ratio contraction with these latter values is 10.0 μm. Clearly a precompression of 0.2 μm induced by matrix drying shrinkage can be ignored.

Further evidence that multiple cracking in polypropylene reinforced cement is not dependent upon matrix shrinkage is the occurrence of multiple cracking in specimens tested in the saturated condition. Similar crack spacings were observed as in the main investigation. In these specimens matrix expansion rather than contraction occurred. It is possible that some precompression of fibres may have taken place during curing under water due to a build up of reaction products but to date no evidence has been found for such an effect.

Pinchin considers that in the steel/cement system there is a mechanical interaction between the fibre surface asperities and the matrix which is sufficient to develop frictional forces in the absence of direct fibre/matrix contact. Scanning electron microscopic studies of the fibre surfaces of polypropylene indicate that defects of up to 10 μm are present, see Fig. 7. Hence a similar fibre/matrix interaction can take place in the polypropylene/cement system.

A major source of fibre/matrix contact not previously discussed is thought to be the misalignment of the two surfaces of a crack after it has passed completely across a specimen. In the extreme case the misalignment can take the form of a lateral displacement of one crack surface relative to the other. In the later stages of post crack deformation the misalignment can be seen with the naked eye. Several factors will contribute to the misalignment, of which inherent variations of fibre/matrix shear stresses from fibre to fibre remote from the crack are possibly the most important. A slight offset between the upper and lower tensile grips, irregularities in specimen dimensions and the response of the whole test system to the impact type load transfer from matrix to fibre at cracking, will all tend to ensure that the crack surfaces do not displace parallel to the tensile axis. These phenomena will also occur in the other composites but the

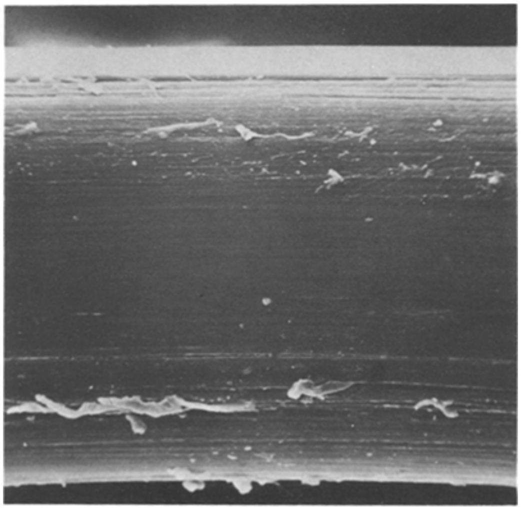

Figure 7 Asperities on the surface of a 340 μm diameter polypropylene fibre.

very low modulus of elasticity of polypropylene gives rise to wider cracks as well as crack spacings and thus a greater opportunity for distortion. Thus fibre/matrix friction is possible even at the point of intersection of the cracked surface and the fibre. Evidence of fibre/matrix interaction is considerable on both microscopic and macroscopic scale. Polypropylene fibres being much softer than the matrix, contrary to most other reinforcing fibres, have their surfaces damaged during deformation. A common type of damage observed was the chiselling out of a long shaving of polypropylene by a matrix particle (Fig. 8). Fibre/matrix contact will also occur if the fibres are not exactly parallel. Clearly slight misalignment will occur in the most accurate lay-up method.

It follows from the above discussion that the value of the fibre/matrix shear stress calculated from Equation 1 is an average value and not a unique value. The linear relationship between x and $(1 - V_f)/V_f$ reflects the dominance of the $1/V_f$ term at low volume concentrations. (A linear relationship also exists between x and $1/V_f$ with a correlation coefficient of 0.98). Therefore it cannot be used as supporting evidence for any of the particular mechanisms proposed. It follows also that values of fibre/matrix shear stress obtained from single fibre pull-out tests are not directly applicable to polypropylene reinforced cement composites. The difference between $\tau = 0.05$ N mm^{-2} determined in the present investigations and the value of 1.0 N mm^{-2} obtained by Walton and Majumdar reflects the wide range of fibre matrix interactions that are possible.

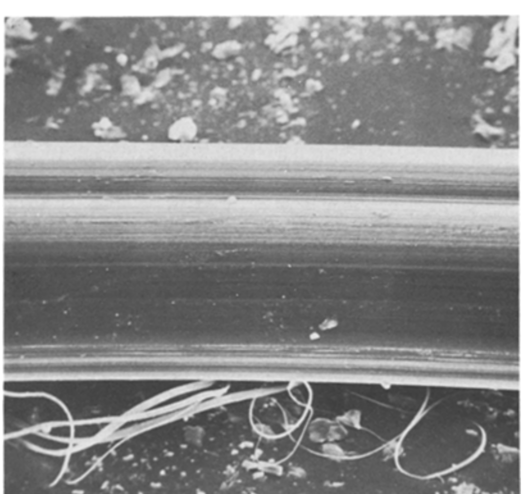

Figure 8 Shavings produced from 340 μm diameter polypropylene fibre during deformation.

Finally it is worth noting that in the case of flexural deformation there will always be fibre/matrix interaction and the exact value of the maximum fibre/matrix shear stress for an individual fibre will depend not only on the above factors but also on the direction of the interacting crack. It is considered that in this mode of deformation, which is the normal mode for board materials, neither Poisson's ratio nor single fibre pull-out shear stress are of major importance in determining deformation characteristics.

5. Conclusions

Multiple cracking occurs in uniaxially aligned polypropylene fibre reinforced cement composites, despite the unfavourable fibre modulus and Poisson's ratio. The fibre/matrix contact necessary to induce this multiple cracking is thought to result from, (1) the presence of asperities on the fibre surface, (2) the surfaces of a matrix crack displacing laterally as well as longitudinally relative to each other and to the fibre array, (3) slight departure from parallelism of reinforcing fibres.

Multiple cracking is predicted to occur in any fibrous composite providing that a critical specimen diameter and a critical volume fraction of fibres is exceeded. In the case of composites utilizing fibres of higher modulus than the matrix, this diameter is less than the likely minimum dimension of practical material, whereas in polypropylene reinforced cement it is much greater. The mechanism by which the Poisson's ratio contraction of the fibres is offset to ensur fibre/matrix contact in these systems arises ᶠom the interaction of the relaxing matrix element at a crack surface with the non-relaxing fibre array.

The normal compressive stress at the surface of a fibre after matrix cracking increases with increasing distance from the centre of a specimen and varies around the surface of a fibre. This ensures that there is not a unique limiting fibre/matrix frictional shear stress. Single fibre pull-out tests to determine the value of such shear stresses therefore are not directly applicable to practical composites.

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