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Fibre toughening of MDF cement

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Fibre reinforced cements are of considerable industrial importance, the production of asbestos cement amounting to about 5 m tonne per annum. The search for fibres other than asbestos has led to the investigation of glass, polypropylene, cellulose (and other fibrous materials) in a cement matrix. Whilst there has been much work on the fibrous component of cement–fibre composites little attention has been paid to the effect on the final composite properties following improvements in the cement matrix. The preparation of macro-defect-free (MDF) cements has recently been reported and the work presented here describes the preparation and the properties of fibre-reinforced MDF cement composites. The Young's modulus of elasticity and the strength of MDF cements are greatly improved and do not need fibrous reinforcement to show benefit. The main purpose of reinforcing MDF cement with fibres is to enhance toughness and impact performance. It is shown that small volume fractions of fibre (~ 2%) in the MDF cement matrix produce composites with excellent toughness and impact properties.

1. Introduction

Fibre-reinforced cement products are of enormous industrial importance, the sales of asbestos-reinforced cement alone amounting to £2000 million per annum. Portland cement, the basis of most products, is cheap and readily available and asbestos cement is fire-resistant, moderately stiff, resists weathering and biological degradation. There is considerable interest in the manufacture of cement–fibre composites using fibres other than asbestos, an activity driven by increasing concern as to the health hazards of asbestos fibres. A variety of fibres has been investigated including glass, where special grades have been produced showing improved durability in the alkaline cement matrix, synthetic organic fibres such as polypropylene and natural fibres such as cellulose. The target has been (and remains) to produce a composite having the mechanical properties realized in asbestos-reinforced materials together with the durability and fire resistance of asbestos cement.

Cement products require reinforcement because the matrix material, the cement paste, has low tensile and bending strength (~ 5 to 15 MPa) and low fracture toughness (10 to 30 J m^{-2}). Whilst in the past, much work has been carried out on the use of various fibrous materials having different properties and chemical characteristics, little has been done to alter the physical properties of the cement matrix within which fibres are dispersed. This is largely because the low tensile strength of cement paste and mortars has been regarded as an intrinsic property of the material.

Recently, however, it has been shown [1–3] that the tensile strength of cement paste is related to the size of macroscopic defects within the material (e.g. residual pores), these flaws arising from the entrainment of air in the water and cement mixture and from poor particle packing. It has been shown that elimination of such defects can give cement paste having a bending strength of about 150 MPa and increased fracture energy of around 200 J m^{-2}. Processes have been evolved for the manufacture of macro-defect-free (MDF) cements that are well adapted for the manufacture of MDF cement–fibre laminates. This paper outlines an investigation of the mechanical properties of MDF cement–fibre laminates made using nylon, glass and Kevlar fibre, and it is seen that composites having excellent properties can be readily produced. An advantage of using MDF cement as the matrix is that the modulus and strength of the unreinforced matrix are high so

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TABLE I

	Parts by weight
Secar 71 (Lafarge)	100
Polyvinyl alcohol–acetate†	7
Glycerol	0.7
Water	9.8

†Gohsenol Nippon Gohsei

that the role of fibre is limited to increasing the work of fracture and impact performance.

In the present study the strength, modulus and fracture toughness of various MDF preparations are examined. Strength, modulus and toughness have already been reported [1–3] but analyses of toughness of fibre–reinforced MDF have not so far been published. It will be shown that MDF reinforced with fibre meets the essential requirements of fibre-reinforced cement – strength, toughness and durability.*

2. Sample preparation

The cement used throughout this study was Secar 71 (Lafarge). A water: cement ratio of 0.098 was used. The mix design was as given in Table I.

A sample premix in an orbital action mixer was followed by twin roll milling. The mix soon formed a cohesive "dough" which was then stripped off and the fibres in the form of mats were inserted in layers between the dough sheets. The sheets were between 1 and 2 mm in thickness. There then followed a hot pressing stage at 80° C for 10 min after which the composite sheets were allowed to cure in an oven at 80° C for 18 to 24 h. The monofilament fibres were found to be entirely surrounded by the MDF cement matrix and there was no evidence of any separation at the fibre–matrix interface. This is shown in Fig. 1a. A multifilament bundle such as Kevlar was also found to be well "wetted" around the periphery, but there was evidence that in the interior of the bundle there was fine voidage. In Fig. 1b the spaces between the individual fibre filaments inside the fibre bundle are filled, not with cement, but with the resin used to prepare the sample for polishing. Fig. 2 shows a typical fibre mat.

The sheets were then removed and cut on a circular diamond saw into strips approximately 250 mm long and 10 mm in width. Thickness varied according to the number of fibre mats which were inserted. Highly filled samples were about 10 mm thick and samples with lower volume fractions of fibres were about 5 mm thick. A notch 300 μm wide was cut into the beams for the purpose of fracture toughness and work of fracture determination.

3. Experimental methods

3.1. Young's modulus

Young's modulus was measured in bending by centre point loading on an Instron 1122. The stiffness characteristics of the machine were taken into account when measuring the deflection of the beams. The span to depth ratio was in all cases in excess of 40:1 in order to avoid shear effects. Young's modulus in bending was determined using Equation 1.

$$E_b = Pl^3/4bd^3y \qquad (1)$$

where P = load, l = span, b = beam width, d = beam depth, y = deflection.

3.2. Flexural strength, σ_f

Flexural strength was measured in bending by centre point loading using the formula

$$\sigma_f = \frac{3Pl}{2bd^2} \qquad (2)$$

The span varied between 250 and 150 mm.

3.3. Stress intensity factor, K

The critical value for K in mode I was determined on single edge notched (SEN) beams where a is the notch depth:

$$K_{Ic} = \sigma_f a^{1/2} \times f(a/d) \qquad (3)$$

where

$$f(a/d) = 1.93 - 3.07(a/d) + 14.53(a/d)^2 - 25.11(a/d)^3 + 25.8(a/d)^4$$

3.4. Work of fracture, R

The work of fracture was determined by dividing the area under the load–deflection curve by the nominal cross-sectional area of the beam. The works of fracture were determined on SEN beams.

3.5. Impact energy

Unnotched Charpy samples were tested on a Zwick impact testing machine using a 4 Joule pendulum and a span of 40 mm.

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*British Patent Application No. 8301450.

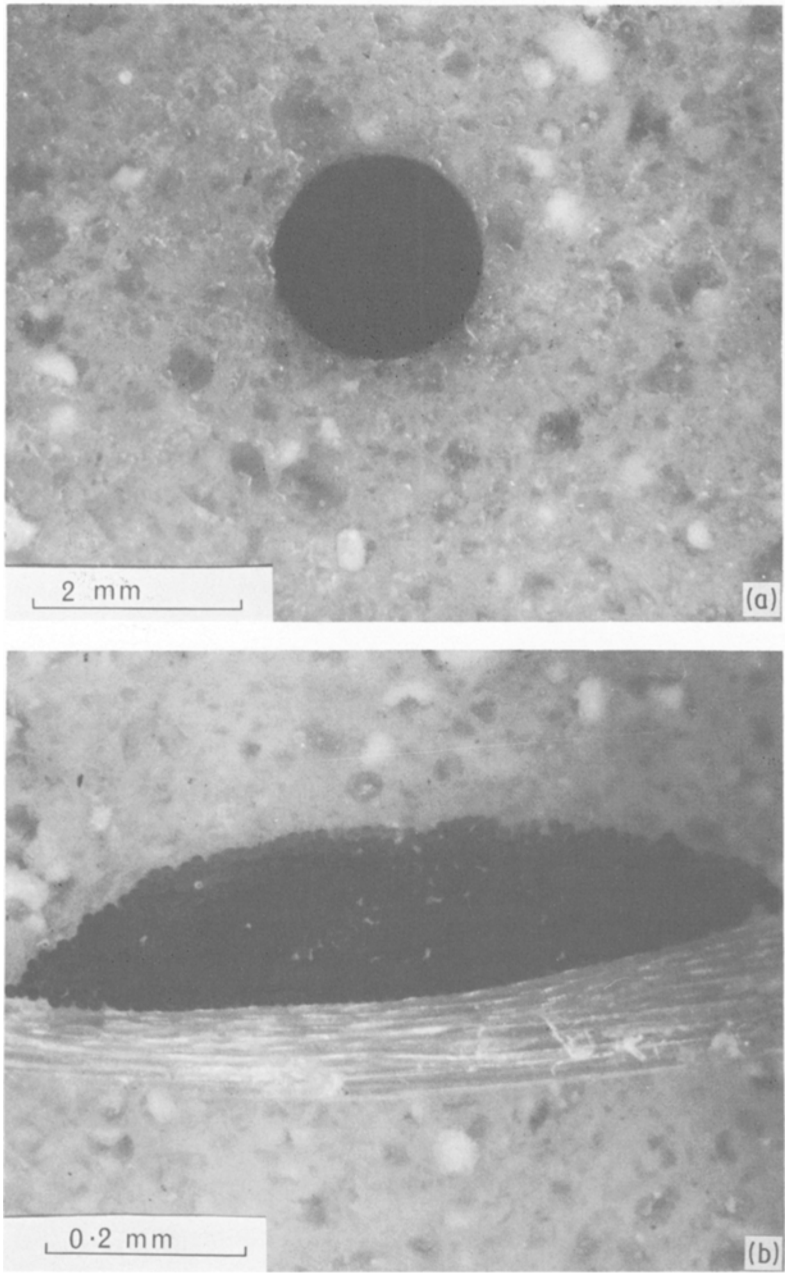

Figure 1 (a) Nylon monofilament in MDF cement matrix, (b) Kevlar tow in MDF cement matrix.

4. Results

4.1. Strength and Young's modulus

The strength and moduli of conventional fibre-reinforced cements are given in Table II. In Table III strength and modulus for the MDF fibre-reinforced cements are given. Young's moduli of MDF preparations are in excess of 30 GPa and the flexural strengths are all in excess of 50 MPa. Young's moduli for cellulose [4] and polypropylene composites [5] are low at around 10 to 25 GPa, and flexural strengths for these are also modest at between 10 to 25 MPa. Cellulose fibres are known to be hygroscopic and will degrade if kept in moist environments for any long periods. Asbestos cement products also have good properties and are known to weather extremely well. However, the purpose of most research on fibrous cements is to find an alternative to asbestos. Glass fibre is the most promising to date with strengths up to 40 MPa in bending, which compares well

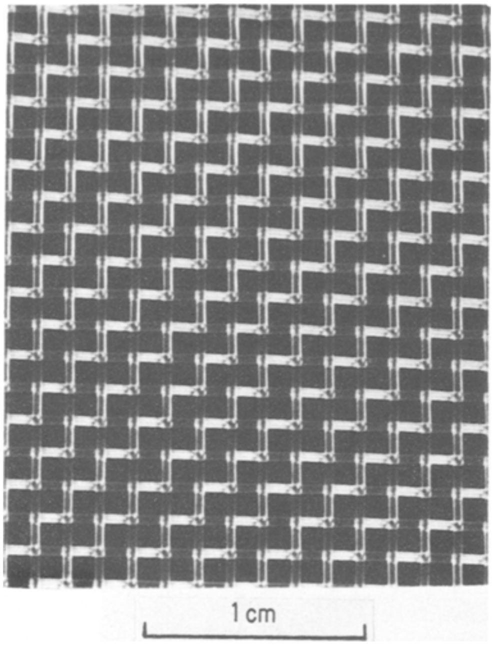

Figure 2 Example of nylon monofilament woven mesh.

with asbestos cements (30 to 55 MPa in bending). The moduli of both asbestos cement [6, 7] and glass-reinforced cement [8] are around 15 to 30 GPa. Unfortunately glass fibres in cement are susceptible to alkali attack and the physical properties can degrade in time.

4.2. Impact properties

The results of impact energies are difficult to compare as often data are unavailable regarding method of test and sample preparation. The impact energies can also be dependent on kinetic energy effects.

The beams tested in this study were unnotched and the results for conventional fibre cements such as asbestos sheet compare well with literature values. Impact energies of conventional fibre-reinforced cements are generally around 1 to 20 kJ m^{-2}. Walton and Majumdar [9] report a value of 17 kJ m^{-2} for Kevlar-reinforced cement. West *et al.* [17] report a value of 23 kJ^{-2} (Izod) for lightweight glass-reinforced cement. The maximum impact energy of the MDF composite beams in this study is 121.5 kJ m^{-2}, and this compares well with fibre-reinforced plastics which have unnotched Charpy impact energies of around 100 kJ m^{-2}.

4.3. Toughness

The critical stress intensity factor, K_{Ic}, for the MDF composites is high at around 3 to 5 MPa m$^{1/2}$. The work of fracture is also high and can be in excess of 70 kJ m^{-2}. Recent work on polypropylene fibre cements [12, 13] suggests that it is more appropriate to use the energy per unit volume. This is because in polypropylene cements multiple cracking occurs and energy is not absorbed by a single fracture surface, but rather, throughout the volume of the

TABLE II Some of the physical properties of commonly used fibre-reinforced cement products

		σ (MPa)	E (GPa)	K_{Ic} (MPa m$^{1/2}$)	R (kJ m^{-2})	Impact (kJ m^{-2})
Asbestos [6]	5 wt%	20	15	1.75	0.43	–
	10 wt%	40	15	3.6	2.0	–
Asbestos [7]	10 wt%	30	–	–	–	2–4
Asbestos	~ 50 wt%	55	25	1.6	1.15	4.5
Cellulose [4]	2 wt%	21	12.8	–	0.18	–
	10 wt%	25	9.9	–	0.97	–
Glass fibre [8]	8 wt%	40	30	2	2	8
Fibrillated polypropylene [5]	6–10 vol%	20	25	–	–	–
Carbon [10]	8 vol%	100	20–30	–	–	–
Kelvar [9]	1.9 vol%	40	20–30	–	–	17

TABLE III Physical properties of MDF fibre composites

Fibre		σ (MPa)	E (GPa)	K_{Ic} (MPa m$^{1/2}$)	R (kJ m^{-2})	Impact (kJ m^{-2})
Glass A		145.9	44.8	2.21	3.54	9.2
2 layers	1.92 vol %	± 17.3	± 3.1	± 0.1	± 0.4	± 1.5
Glass A		123.8	42.8	2.54	2.62	13.4
5 layers	3.36 vol %	± 8.3	± 1.1	± 0.3	± 0.5	± 2.7
Glass B		151.8	48.9	3.52	1.79	5.87
	1.44 vol %	± 5.9	± 1.1	± 0.1	± 0.4	± 0.4
Nylon A		119.5	46.9	2.99	15.9	38.1
0.4 mm monofil	5.4 vol %	± 7.7	± 1.2	± 0.03	± 3.0	± 7.7
Nylon B		127.5	48.3	2.89	9.17	23.53
0.2 mm monofil	5.2 vol %	± 8.2	± 1.8	± 0.4	± 0.8	± 3.8
Unreinforced		150.32	52.43	3.29	0.402	4.34
control		± 4.6	± 1.2	± 0.1	± 0.06	± 0.29
Nylon C		54.15	31.09	2.78	44.37	121.24
0.4 mm monofil	15 vol %	± 2.8	± 0.25	± 0.4	± 12.1	± 16.9
Nylon D		76.82	30.3	2.56	16.0	56.18
0.2 mm monofil	10.4 vol %	± 8.8	± 6.3	± 0.62	± 2.3	± 1.7
Kevlar 29 A	4.2 vol %	128.33	52.8	2.1	21.32	
		± 6.4	± 0.72	± 0.13	± 3.2	
Kevlar 29 B	9.0 vol %	94.2	37.4	5.25	78.55	88.6
		± 6.8	± 1.4	± 0.35	± 2.75	± 21.5

body. The theory applies strictly to continuous aligned fibres and is due to Aveston, Cooper and Kelly (ACK) [11]. Following [12] the ACK theory may be written thus. The energy absorbed by the composite is

$$U = E_c\epsilon_{\text{mu}}^2(0.5 + 0.659\alpha) + 0.5[\epsilon_{\text{fu}} - \epsilon_{\text{mu}}(1+\alpha)](E_c\epsilon_{\text{mu}} + \sigma_{\text{fu}}V_f) \tag{4}$$

where E_c = Young's modulus of the composite, ϵ_{mu} = matrix failure strain, α = ratio E matrix × volume matrix/E_{fibre} × volume fibre, σ_{fu} = ultimate tensile stress of fibre.

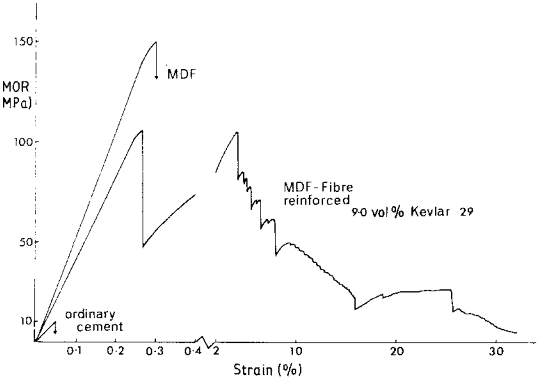

Figure 3 Stress–strain curve of ordinary cement, MDF cement and fibre-reinforced cement.

The energy contribution of the matrix is considered to be small and the fibres are not believed to increase the failure strain of the matrix. Then, energy absorption is predominantly elastic strain energy stored in the fibres which may be given by

$$U = 0.5\sigma_{\text{fu}}\epsilon_{\text{fu}}V_f. \tag{5}$$

The energy supplied for multiple cracking in addition to the elastic strain energy of the fibres is the difference between Equations 4 and 5, i.e.

$$\Delta U = 0.159\alpha E_c\epsilon_{\text{mu}}^2. \tag{6}$$

Equation 4 may then be written as

$$U = 0.5\sigma_{\text{fu}}\epsilon_{\text{fu}}V_f + 0.159\alpha E_c\epsilon_{\text{mu}}^2. \tag{7}$$

Using this approach Hibbert and Hannant [12] estimate the energies of various fibre composites and find that for polypropylene composites the energy is around 1.036 MJ m^{-3}, and for glass, around 1.125 MJ m^{-3}. These energies are not realised for glass and in practice glass-reinforced cement is found to have an energy of about 0.15 MJ m^{-3}.

If the appropriate properties for glass and nylon MDF composites are inserted into Equation

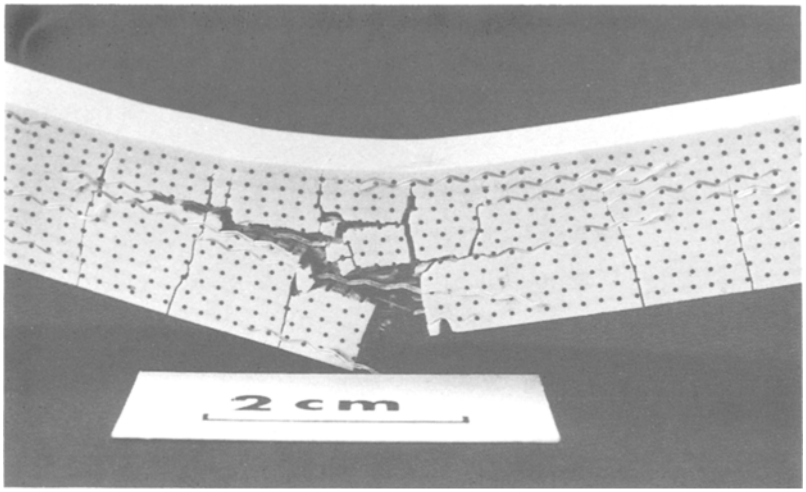

Figure 4 Multiple cracking in 15.0% vol. nylon-reinforced MDF cement.

4 we find that for nylon A and MDF the energy absorbed is theoretically 23.56 MJ m^{-3}, and for glass 2.73 MJ m^{-3}.

These values are not realised and the value measured is for both nylon A and glass about 0.115 MJ m^{-3}.

A comparison of the works of fracture in Tables II and III indicates that the toughness of MDF composites can greatly exceed the values for conventional cement composites. The stress–strain curve of unreinforced MDF and ordinary cement is compared with fibre-reinforced MDF in Fig. 3.

The use of an energy per unit volume approach raises certain questions. In order to use this approach, the sample under test must undergo multiple cracking throughout its volume. This is shown to occur [12] in polypropylene cement composites under tension. However, the mode of loading of cement composites is rarely in direct tension and it is more common for a bending moment to be applied. This being the case, a much smaller volume of material will be under high stresses, and failure can result by the propagation of either one or a small number of major cracks. To use the energy per unit volume approach will, in such cases, be invalid and we may justifiably use the energy per unit area, as has been done in this study.

The MDF beams made with higher volume fractions of nylon, i.e. nylon C and nylon D *were* seen to exhibit multiple cracking in bending. Fig. 4 shows the multiple cracking observed in nylon C (15% volume of 0.4 mm nylon monofilament). The Kevlar-reinforced beams also exhibited multiple cracking.

4.4. V_{crit} and the application of ACK theory

The criterion for the application of ACK theory is given by Equation 8.

$$V_{\mathrm{crit}} = \frac{E_c \epsilon_{\mathrm{mu}}}{\sigma_{\mathrm{fu}}}. \tag{8}$$

In the present study the critical volume of fibres, V_{crit}, is exceeded in only one case, the Kevlar-reinforced MDF cement. The increased strain in the matrix from around 0.025% for ordinary cement to 0.3% for MDF cement will result in a greatly increased V_{crit}, as Equation 8 shows. Table IV shows V_{crit} for various fibres for both ordinary and MDF cement.

TABLE IV Approximate V_{crit} (Equation 8) and ordinary fibre-reinforced cement

Fibre	σ_{fu} (MPa)	Ordinary cement V_{crit} (%)	MDF cement V_{crit} (%)
Polypropylene	200	3.38	60
Steel	1000	0.75	12
Glass	1250	0.6	9.6
Nylon	400	1.9	30
Kevlar	2900	0.26	4.1

TABLE V Theoretical and observed fracture energies of nylon beams

	Fibre diam. (mm)	No. fibres ($m^{-2} \times 10^{-5}$)	W_p from Equation 10 ($kJ\,m^{-2}$)	W_p from Equation 11 ($kJ\,m^{-2}$)	R observed ($kJ\,m^{-2}$)
Nylon A	0.4	2.8	13.9	10.8	15.9 ± 3.0
Nylon B	0.2	5.6	3.5	5.2	9.2 ± 0.8
Nylon C	0.4	6.0	29.8	30.0	44.37 ± 12.1
Nylon D	0.2	13.2	8.2	10.4	16.0 ± 2.3

E_C for ordinary cement composites has been assumed to be 27 GPa and for MDF 40 GPa. ϵ_{mu} for ordinary cement has been taken to be 250×10^{-6} and for MDF 3×10^{-3}.

From Table IV it may be seen that V_{crit} for MDF fibre-reinforced composites is exceeded only in the case of Kevlar-reinforced composites. ACK theory may be applied, therefore, only to these composites. If the appropriate values are inserted into Equation 7 we find that the theoretical energy absorbed for a 4.2% vol. loading of Kevlar in MDF is 2.1 MJ m^{-3} and for 9% vol. is 3.3 MJ m^{-3}. In direct tensile tests of Kevlar-reinforced MDF cement the 9.0% vol. beams gave values of around 3 MJ m^{-3}. These compare very favourably with other fibre-reinforced cements and have the additional advantage of undergoing a first flexure crack at between 95 and 120 MPa, compared with 5 to 15 MPa for composites made with a conventional cement matrix.

The use of a concept such as V_{crit} implies that there is a critical volume fraction of fibres above which properties such as strength will be enhanced. In MDF beams we have seen from Table IV that V_{crit} is high. However, V_{crit} is of less importance now because the flexural strength and modulus of unreinforced MDF are such that incorporation of fibres to enhance these two properties is quite unnecessary. The incorporation of fibres in volume fractions well below V_{crit} will cause large increases in toughness, and it is this quantity which above all we should wish to improve upon. Conventional cements have a fracture energy of around 20 to 50 J m^{-2} and MDF cements range between 200 and 500 J m^{-2}. Incorporation of fibres well below V_{crit}, such as 15% nylon monofilament, increases the work of fracture to ~ 45 000 J m^{-2}, an increase of three orders of magnitude over ordinary cement.

Furthermore, it should be noted that 15% vol. of nylon is laid in two directions at right angles to one another so the true volume in the direction of maximum stress is only about 7.5%. If this is borne in mind the only fibre cement in which V_f is exceeded is the 9.0% vol. Kevlar-reinforced MDF cement giving 4.5% vol. in the direction of applied stress.

4.5. Sources of toughening

MDF fibre-reinforced cements owe their toughness to the strain energy of the matrix and to the work of pull out of the fibres. In fact, the contribution to the total work of fracture by the strain energy of the matrix is small (~ 5 to 10%). The contribution due to the pull out of aligned fibres should therefore be explored. The fibre will be restrained during pull out by a shear stress, τ, and will rupture when the load transfer length reaches a critical value [15]. This is given by [14, 15]

$$l_c = r\sigma_{fu}/\tau \tag{9}$$

where l_c is the critical fibre length, r is the fibre radius and τ is the shear stress. l_c may be estimated by taking $l_c/2$ to be equal to the largest observable pull out length [15].

In preparing the MDF nylon monofilament composites fibre of two diameters was used, 0.4 and 0.2 mm, each at two volume fractions.

Thus for nylons A and C we see that $l_c/2 = 6$ mm, $r = 0.2$ mm, $\sigma_{fu} = 400$ MPa. For nylons B and D $l_c/2 = 3$ mm, $r = 0.1$ mm, $\sigma_{fu} = 400$ MPa. τ is in all cases 6.6 MPa. The work of pull out over a distance l which we will take as being equal to $l_c/2$ may be estimated by [14, 15]

$$W_p = \pi r \tau l^2/12. \tag{10}$$

Another approach due to Cottrell [14] relates the volume fraction of fibres to the work of fracture as shown in Equation 11:

$$W_p = \frac{V_f \sigma_{fu} l_c}{12}. \qquad (11)$$

Table V gives the calculated and observed results, and both equations give fair agreement with the experimental results for nylon monofilament.

The use of Equations 10 and 11 to predict the work of fracture of multifilament fibre-reinforced cements poses problems. The shape of a fibre bundle in MDF cement is ellipsoid, so that Equation 10 may be written

$$W_p = \pi \frac{[\frac{1}{2}(a^2 + b^2)]^{1/2} \tau l^2}{12} \qquad (12)$$

where $2a$ and $2b$ are the lengths of the major and minor axes of the fibre bundle cross-section, see Fig. 1b. For Kevlar these axes were found to measure 0.8 and 0.2 mm. The shear stress, τ, of a Kevlar tow in MDF cement was measured in a pull out test and found to be 4.4 MPa. l_c was 60 mm. This gives W_p of 4.2% vol. Kevlar-reinforced MDF of 0.48 MJ m^{-2}. However, only about 27% of the fibres are in contact with the matrix so this value is reduced to 0.13 MJ m^{-2} for the 4.2% vol. Kevlar and about 0.26 MJ m^{-2} for the 9.0% vol. Kevlar-reinforced MDF cement. It is clear that this approach, while satisfactory for nylon monofilament, cannot predict the toughness of multifilament Kevlar-reinforced MDF cement. Similarly, application of Equation 11 gives values of 0.3 and 0.65 MJ m^{-2} for 4.2% (2.1% in the direction of stress) and the 9.0% (4.5% in the direction of stress) vol. Kevlar-reinforced MDF, respectively.

It is interesting to observe that, for nylon monofilament, the work of fracture increases with increasing fibre diameter. This is observed by Cooper and Kelly [16] who showed that for a constant volume of 53% for vaccum-cast copper reinforced with tungsten wires the fracture energy increased with fibre diameter.

4.6. Weathering

Long term weathering tests are in their infancy, so it is impossible to predict the outcome accurately. However, the permeability of the matrix material is very low indeed, ~ 10^{-18} m sec^{-1} compared with that of a conventional cement matrix at ~ 10^{-13} m sec^{-1}, and the ingress of aggressive fluids is limited in this respect. The material may be treated in such a way that stiffness and strength are maintained while the material is immersed in water. So far, tests indicate that both modulus and strength are maintained to within 10% of the starting value for periods up to 50 days under water.

5. Discussion

MDF cement pastes have high values of Young's modulus, tensile and flexural strength and an elevated fracture toughness. However, for many applications it is advantageous that work of fracture and impact performance are as high as possible. Whilst in terms of Young's modulus and flexural strength there will be little advantage in the incorporation of fibre into an MDF cement matrix, small volume fractions of fibre should greatly enhance work of fracture and impact resistance. In the present study the mechanical properties of MDF cement–fibre laminates have been investigated using glass, nylon and Kevlar mats. It has been shown that such laminates can have impact energies greater than 100 kJ m^{-2} with flexural strengths greater than 100 MPa and Young's modulus in the range 35 to 45 GPa.

6. Conclusions

1. The strength in flexure and the Young's modulus of fibre-reinforced MDF cement are significantly improved in comparison with conventional fibre-reinforced cements. Flexural strength is between 60 and 140 MPa and Young's modulus is about 30 to 45 GPa.

2. Impact energy can be increased to around 120 kJ m^{-2} in the case of nylon fibre-reinforced MDF cement.

3. The stress intensity factor for MDF fibre composites is generally higher than conventional fibre cements at around 2 to 5 MPa m$^{1/2}$.

4. The work of fracture has been expressed in Tables III and V in terms of energy per unit area. This is because in lower fibre contents, e.g. nylons A and B, fracture occurs by the propagation of a single crack or with very little multiple cracking. In bending, multiple cracking was observed in the higher volume fractions of nylon filled beams, e.g. nylons C and D. However, in direct tension, multiple cracking, even in the highly filled nylon beams, was not observed. In the Kevlar-reinforced beams multiple cracking was always observed.

5. Multicracking of the matrix is inhibited because the properties of the matrix are significantly improved. It was shown that impact energy and toughness could be increased to 35 and

$15\,kJ\,m^{-2}$, respectively, for beams with as little as 5.5% volume of nylon. The flexural strength of such beams is over 100 MPa and Young's modulus is in excess of 45 GPa.

Increasing the volume of nylon (0.4 mm diam) to 15% reduced strength to ~ 60 MPa and modulus to ~ 30 GPa. However, the fracture energy was found to be in excess of $40\,kJ\,m^{-2}$ and the impact energy greater than $100\,kJ\,m^{-2}$. Multicracking was observed in bending.

6. 9.0% vol. Kevlar gave flexural strengths of about 100 MPa and a modulus of ~ 40 GPa. The fracture energy of 9.0% vol. Kevlar-reinforced MDF cement was measured at $78.55\,kJ\,m^{-2}$.

It was shown that unless microcracking occurred throughout the whole volume of the beam, the use of an energy per unit volume approach would be invalid. Furthermore, it was suggested that in most fibre cements loading was unlikely to be in direct tension but, rather, in bending. In such cases cracking might be expected to be confined to a limited volume.

7. The search for an alternative to asbestos cement has been concentrated in research into new or different fibres. This paper suggests that what is required is an improvement in the matrix material.

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