Ultra high modulus polyethylene composites

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Abstract – The availability of adequate quantities of ultra high modulus
polyethylene (UHMPE) fibres has provided the possibility of creating a new
range of polymer composites with high energy absorption capabilities.   In
this paper several aspects of recent research at Leeds University are
described.   First, there are the possible requirements of the UHMPE
fibres in terms of strength, resistance to creep and adhesion to suitable
polymeric resins.   It has been found that plasma treatment of the fibres
with oxygen as the carrier gas produces substantial improvements in
adhesion.   Although the interlaminar shear strength of composites made
with treated fibres is increased it is found that there are only small
changes in the mechanical behaviour of the composites.   Secondly,
comparative data are presented for unidirectional fibre composites where
the fibre phase is either wholly UHMPE, Kevlar 49, Carbon EXAS or E-type
glass.   Results are also presented for hybrid composites which
incorporate both UHMPE fibre and one of the commercial fibres.   It is
shown that these hybrid composites can combine in a useful way the good
qualities of UHMPE fibres, especially their very high energy absorption,
with other good qualities of the commercial fibres.

INTRODUCTION

The development of practical processes for large scale production of ultra–high modulus
polyethylene fibres has raised the possibility that such fibres might be used to advantage
in composite materials, where their unique combination of properties could be utilized.   In
this paper we will discuss first the properties of UHMPE fibres in the context of other high
modulus and high strength fibres.   This discussion sets the scene for the major part of the
paper which is to describe an extensive investigation into the preparation and properties of
thermosetting resin composites reinforced with UHMPE fibres.   Here also it is most valuable
to compare the behaviour of the UHMPE fibre composites with composites incorporating other
high modulus fibres.   It will be shown that this comparison led us to a study of hybrid
composites where the reinforcing fibre phase includes UHMPE fibre and one other fibre.   The
behaviour of these hybrid composites shows novel features, which are likely to be of some
technological value, as well as being very interesting from a scientific viewpoint.

ULTRA HIGH MODULUS POLYETHYLENE FIBRES

A series of investigations on the tensile drawing of isotropic polyethylene, either as
monofilament or dumbbell specimens cut from compression moulded sheets, defined the
conditions for producing ultra high modulus polyethylene (refs. 1,2).   In general, the
drawing behaviour is sensitive to the molecular weight and molecular weight distribution of
the sample, initial morphology and the temperature and rate of drawing.   It is, however,
possible to produce fibres with a Young's modulus in the range 40-70 GPa and strengths of at
least 1 GPa with comparative ease.   The modulus is uniquely related to the draw ratio, so
that by drawing 25x moduli of ~ 40 GPa are obtained, and by drawing 40x moduli of ~ 70 GPa
are obtained.

The basic research at Leeds University provided the guidelines for an industrial pilot plant
process (ref. 3).   Initially, both monofilaments and multifilament yarns were drawn in a
glycerol bath at 120°C at rates up to 500 m/min. In this way kg quantities were produced
for preliminary evaluation.   More recently pilot plant production by the Celanese Research
Company has provided adequate quantities for the preparation of fibre composites and it is
these materials which have been used in the present investigation.

Fibre properties

It is of particular interest to compare the key mechanical properties of UHMPE fibres, i.e. modulus, strengths and extension at break, with the corresponding properties for other reinforcing fibres, carbon, glass and Kevlar.   In making this comparison, which is shown in Table 1, we have deliberately chosen the best available properties for carbon, glass and Kevlar and given a range of properties for the UHMPE fibres which can be readily achieved in practice at economical production rates.

The most useful comparison is based on specific properties where the densities of the different fibres are taken into account.   In these terms, the UHMPE fibres are better in every respect than glass fibres, and are close to Kevlar 49 in terms of both specific stiffness and specific strengths.   The UHMPE fibres have a greater extension to break than any of the other fibres.   These results suggest that the UHMPE fibres will be very useful for energy absorption where a high strength and high extension to break give a large fracture energy to failure.   We will show that this expectation is realised in the properties of the UHMPE composites.

TABLE 1.   Properties of reinforcing fibres (room temperature)

Property Fibre	Tensile Modulus (GPa)	Tensile Strength (GPa)	Elong- ation at Break %	Density ρ g/cm^3	Specific Modulus GPa/ρ	Specific Strength GPa/ρ	Maximum Working Temperature $^\circ$C
Carbon	250	3.6	1.5	1.80	139	2.0	>1500
Glass	75	3.0	2.5	2.54	30	1.2	250
Kevlar 49	125	3.0	3.0	1.45	85	2.1	~ 180
Polyethy- lene	40-70*	1-1.5	4-18**	0.96	42-73*	1-1.5	130

* Depending on draw ratio.
** Depending on strain rate.

Recent developments in property enhancement of UHMPE fibres

The mechanical properties of UHMPE fibres, in the absence of any special treatment, are very dependent on the applied strain rate and the temperature of test.   It was shown by Cansfield et al (ref. 4) that even low molecular weight UHMPE fibres of modest draw ratio reach strengths well in excess of 1 GPa at high strain rates.   For ballistic applications this is very valuable, and shows that even untreated UHMPE fibres may challenge Kevlar in this respect.   The behaviour of these UHMPE fibres falls off with decreasing strain rate. Looked at in another way, which is equivalent, UHMPE fibres show creep under continuous loading, so that their long term strength is only a fraction of the 1 GPa measured in a rapid loading test.   Extensive studies of the creep behaviour of these UHMPE fibres has shown that worthwhile improvements in creep behaviour can be obtained by selecting polymers of higher molecular weight, or changing from homopolymers to copolymers with a small degree of branching (~ 1 branch/1,000 carbon atoms) or by subjecting the polymer to γ or electron irradiation prior to drawing (ref. 5).   It was found that these improvements lead to fibres which can be safely subjected to stresses ~ 0.1 GPa for prolonged periods to time. Although these stress levels are adequate for some Civil Engineering applications, and indeed have been utilized for such (ref. 6), this nevertheless presents a severe limitation to the application of UHMPE fibres.

Recent research has shown that it is possible to virtually eliminate creep and at the same time markedly reduce the temperature sensitivity by using electron-irradiation to produce controlled cross-linking of the drawn fibres (ref. 7). Figure 1 illustrates some key results.   It can be seen that at room temperature the cross-linked fibres show an elastic-brittle load-extension curve at all strain rates, whereas the untreated fibres show yielding and failure at low stresses for low strain rates.   At higher temperatures, the cross-linked fibres still retain an appreciable proportion of their room temperature strength.   Although the properties at high temperatures are significantly reduced, the fibres can be exposed to temperatures at least up to 130°C for long periods and probably much higher temperatures for short periods, which is of advantage in processing e.g. the manufacture of composites.

One possible limitation of the UHMPE fibres is their lower level of specific strength compared with Kevlar.   The strength of the UHMPE fibres in common with other textile fibres of lower modulus, depends primarily on the molecular weight of the polymer, assuming that comparable draw ratios can be achieved.   Although this limitation can be reduced by

adopting the gel spinning and drawing route (ref.8) the latter is intrinsically a more expensive process. It is likely that the final cost of the fibres produced by this route
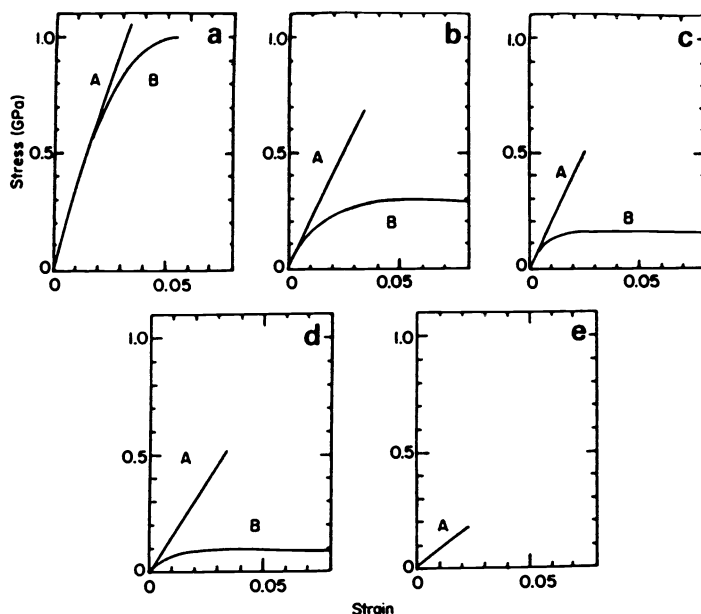

Fig. 1. Stress-strain curves for (A) electron irradiated fibres (200 kGy in acetylene); (B) unirradiated fibres. Strain rate (s^{-1}): 8.3×10^{-3} (a); 8.3×10^{-5} (b), (d), (e); 2.1×10^{-6} (c). Temperature ($^{\circ}C$): $23^{\circ}C$ (a), (b), (c); $70^{\circ}C$ (d); $130^{\circ}C$ (e). Reproduced from Polymer Communications, 25, 298-300 (1984) by permission of the publishers Butterworth & Co. (Publishers) Ltd. (C).

would be similar to Kevlar fibres, whereas the commercial costs of UHMPE fibres produced by the melt spinning and drawing route would be similar to other melt spun and drawn fibres such as polypropylene and polyester. For this reason, recent research at Leeds University (ref. 9) has focussed on the effects of molecular weight and molecular weight distribution on fibre strength. It has been shown that although the strength depends predominantly on the number average molecular weight $\bar{M}_n$, higher strengths are obtained for higher weight average molecular weight $\bar{M}_w$ at a given level of $\bar{M}_n$. The results suggest that strengths at ballistic speeds in the range of 1.5 GPa can be obtained, for materials which can be produced on a satisfactory scale.

STUDIES OF UHMPE FIBRE COMPOSITES

Fibre/resin adhesion (ref. 10)

Prior to the preparation of UHMPE composites it appeared essential to ensure that a satisfactory bond was achieved between the fibres and polymer resins. It was anticipated that in the absence of any surface treatment there would be a poor bond, due partly to the chemical inertness of polyethylene and the absence of polar groups. It is also known that isotropic polyethylene has a low surface energy.

In the first instance the adhesion was studied on monofilaments with diameters in the range 0.55-0.26 mm diameter, depending on the draw ratio. A pull-out test was devised to measure the adhesion, by embedding one end of a 20 cm length of monofilament in a disc of resin. A low viscosity resin (Ciba-Geigy XD 927) intended for high strength composite structures was used throughout. It was cured for at least 16h at room temperature and post-cured for 5h at $80^{\circ}C$ in an air oven. The pull-out adhesion was defined as (failure load)/$\pi D \ell$ where D is the filament diameter and ℓ the immersion length.

Two principal surface treatments have been explored:
(1) Immersion in chromic acid at room temperature.
(2) Plasma treatment in the presence of a carrier gas.

Preliminary measurements showed that chromic acid treatment increased the pull-out adhesion strength, and that there was a systematic increase as the treatment became more drastic, either by increasing the length of time of treatment or by increasing the $K_2Cr_2O_7$ concentration. However it was soon apparent that the improvements obtained were much less than those which could be achieved by plasma treatment with oxygen as the carrier gas.

Although the adhesion was generally increased by increasing the rigour of the plasma treatment, the main variables were found to be the flow of gas, the time of exposure and the input power, in order of decreasing importance.   To obtain the comparative behaviour of different draw ratio monofilaments it was convenient to examine the effect of two standard treatments:

(1)   Chromic acid: 1 min in standard composition acid
      $(K_2Cr_2O_7$ - 7 parts; H_2SO_4 (concentrated) - 150 parts H_2O - 12 parts) at room temperature.
(2)   Plasma: with Plasmaprep 100 (Nanotech Ltd, Manchester, UK), 10 W input power for 10 min with 10 $cm^3 min^{-1}$ gas flow.

The pull-out adhesion results are shown in Table 2, together with the data for untreated monofilaments.   It can be seen that both acid and plasma treatment produce significant increases in the pull-out adhesion over the values obtained for untreated material.   It is interesting to note that the acid treatment is most effective for the lower draw ratio materials, where plasma treatment also produces similar improvements.   For high draw material where the acid treatment is less effective, the plasma treatment is most effective, and produced a pull-out adhesion of 4.9 MPa, which is about ten times the value for untreated monofilament.

TABLE 2.   Pull-out adhesion (at 19.5 ± 1.0°C)

Draw Ratio	Treatment	Pull-out adhesion (MPa)
8:1	None	0.6
	Acid	2.4
	Plasma	2.6
15:1	None	0.5
	Acid	2.2
	Plasma	2.7
30:1	None	0.5
	Acid	1.4
	Plasma	4.9

Examination of the surfaces of the monofilaments, using scanning electron microscopy, shows that the mechanisms for improvement of the adhesion are quite different for the acid and plasma treatments.   Both untreated and acid treated monofilaments show comparatively smooth surfaces, the fibrillar texture being the most marked feature.   Examination of samples subjected to the pull-out test suggests that failure involves sliding along the monofilament/resin interface.   Plasma treated monofilaments on the other hand show a marked cellular texture (Fig. 2) which is less marked for low draw ratio material.   The resin penetrates this surface structure to give a mechanical bond between monofilament and resin. In this case failure in the pull-out test involves peeling off the surface layer of the monofilament, so that the adhesion is essentially limited by the shear strength of the monofilament.

In the case of monofilaments it was shown that the most severe acid and plasma treatments caused a significant reduction in tensile strength.   In subsequent research on composites, where multifilament yarns have been used throughout, care was taken to produce effective surface etching with a very small or undetectable reduction in yarn strength, as will be apparent from the results to be presented.

Preparation of fibre composites

Fibre composites were prepared by three methods:
(1) The leaky mould technique where a bundle of fibres is placed in a rectangular mould, fully wetted with the liquid resin, and then compressed with a smooth fitting top to the mould.   During the initial stage of compression the excess resin is squeezed out of the mould and the system is then allowed to cure. The final product is a rectangular bar containing about 55% by volume of fibres, the orientation of the fibres being along the length of the bar.
(2) The wet lay-up technique where layers of square weave fabric are laid down between layers of liquid resin in a rectangular mould.   The procedure for compressing the system and curing is similar to that already described for the leaky mould technique in (1).   The woven fabric layers are laid up so that the fibres in the warp and the weft of each layer of fabric are as near as possible parallel.
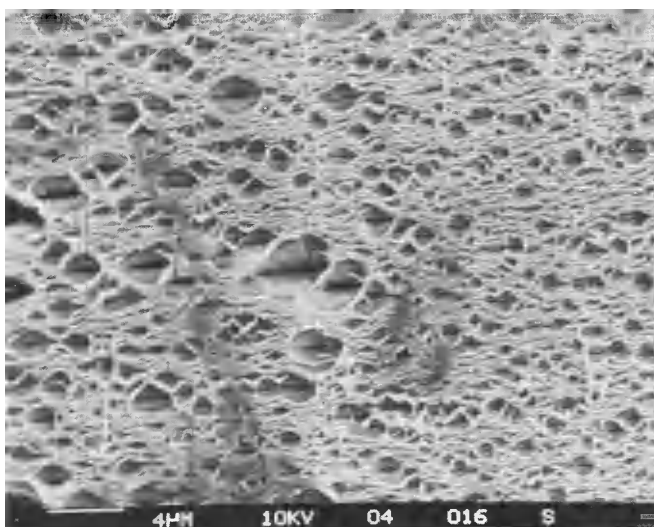
Fig.2. Plasma-treated monofilament, draw ratio 30:1.
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       permission of the publishers Chapman & Hall Ltd. (C).

(3) Lamination of pre-impregnated sheets of fibre (pre-pregs). In this case pre-pregs of
UHMPE, carbon, glass and Kevlar fibres were prepared by Rotorways, Bridgewater UK using an
epoxy resin designated as Code 91, supplied by Fothergill and Harvey, UK. The pre-pregs
were moulded in a hot press to obtain laminates containing 55% fibre by volume. Both homo-
fibre and hybrid fibre laminates were produced, some of them combining fibres oriented in
various directions. In this paper we will report on laminates having all the fibres
parallel to one chosen direction.

Mechanical tests on composites

In general terms, the mechanical tests on the composites were carried out following
established procedures developed at RAE, Farnborough.

Three point bend tests were undertaken using specially constructed jigs to determine the
interlaminar shear strength (ILLS), the flexural modulus (FM) and the ultimate flexural
strength (UFS). In all cases the sample thickness and width were 2 mm and 10 mm
respectively. For the ILLS test, which is a measure of the fibre/resin interface strength
in the composite, the sample length was 15 mm, with a gauge length (distance between the two
supports) of 10 mm. For the FM test, the equivalent dimensions were 200 mm and 160 mm
respectively, and for the UFS test the dimensions were 110 mm and 80 mm respectively. The
FM was determined for an equivalent tensile strain of 0.03%. Further details are given in
ref.11.

The measurements of tensile modulus (TM) and tensile strength (TS) were carried out on
samples of length 200 mm, width 10 mm and thickness 2 mm. To ensure effective stress
transmission by the grips of the tensile testing machine, the ends of the samples were
sandwiched between soft aluminium alloy plates bonded to the sample surfaces, covering a
length of 50 mm at each end of the sample. For TM measurements the gauge length was 50 mm
and the modulus was determined at 0.03% strain. For TS measurements the thickness
dimension was wasted with a continuous radius of 1000 mm, giving a minimum thickness
of ~ 1.2 mm. For the CS measurements the sample gauge length was 10 mm, the total sample
length including the sandwiched ends being 110 mm. The strain rates for the failure
properties were chosen to ensure that failure occurred between 15 and 45 s. Further
details of all these tests may be found in refs. 12 and 13.

Charpy impact tests were also undertaken, using an impact tester specially constructed at
Leeds University. Following the convention of such tests on composites at RAE Farnborough,
unnotched specimens of dimensions 8 cm x 1 cm x 2 mm were impacted on the broad surface of
the bar, rather than on the edge. Essentially this form of the Charpy impact test takes
cognizance of the two features of these composites 1) the absence of notch-sensitivity
2) the very high strengths, which mean that they would not fail in the conventional edges on
Charpy test. Further details of this test may be seen in ref.14.

Results of mechanical tests on UHMPE fibre composites

Table 3 shows results for the mechanical properties of the laboratory composites, prepared by the leaky mould and the wet lay-up techniques.   These composites were prepared from UHMPE fibres with moduli ~ 55 GPa and strengths ~ 1 GPa.

TABLE   3.   Mechanical properties of "leaky" mould composite systems –
continuous UHMPE yarn/epoxy XD927 resin

Reinforcement Orientation	Reinforcement Treatment	ILSS MPa	UFS TEST		FM GPa	TM GPa	TS GPa	CS MPa	"Flat" Charpy Test Energy Absorption	
			Value MPa	Decrease after 3 successive tests (%)					At 1st Impact kJ/m^2	Decrease after 3 successive tests (%)
	Untreated	15	165	8	22	19	0.31	80	160	70
Unidirectional	Acid Treated	20	145	7	–	20	0.33	83	–	–
	Plasma Treated	27	150	5	19	21	0.33	85	120	85
Woven Reinforcement (0/90)	Untreated	17	85	5	8	9	0.12	70	60	85
	Plasma Treated	24	95	4	9	9	0.13	80	45	80

1. All measurements at room temperature.
2. All composites about 55% reinforcement by volume.

The unidirectional composites show tensile and bending (flexural) moduli of about 20 GPa, which is broadly in line with expectations based on the fibre modulus.   The tensile strengths of these undirectional composites is rather lower at ~ 0.3 GPa than might have been anticipated.   The compressive strength is 80–85 MPa, which is low, and reflects the low compressive strength of UHMPE fibres, in common with other organic fibres, such as Kevlar.

The interlaminar shear strengths of the composites do relate to the expected changes in adhesion suggested by the monofilaments with regard to acid and plasma treatment, but the magnitudes of the effects in the composites are much smaller.   The ILLS of the composites changes by only a factor of about two between untreated and plasma treatment in oxygen, compared with an order of magnitude change for monofilaments.   These changes in ILLS do not affect the tensile, flexural or compressive behaviour to any great extent.   It is important to note that samples do not break in the first ultimate flexural strength (UFS) test, instead they bend and if straightened by hand can be retested with only a small reduction in the UFS value.   Table 1 shows reduction of 5–8% in UFS for 3 successive tests.

The flat Charpy impact tests show high values of impact energy.   Again the samples do not break and can be straightened by hand and retested with the hammer always hitting the same face.   The subsequent impact energies are however much lower than that observed initially, so that the major advantage of the UHMPE fibre composites over many similar composites is that they do not shatter on impact, because of the high extension to break of the fibres. The behaviour is more akin to that of a ductile material than a brittle material.

Visually, there are differences in appearance after the impact tests for composites made with untreated and with surface treated fibres.   Essentially, the damaged area in the treated composites is much more localised, consistent with the observation of somewhat lower energy absorption.

The comparatively small difference between the untreated fibre composite and the treated fibre composites is consistent with the view that most of the energy absorption relates to deformation of the UHMPE fibres.   This conclusion is supported by the results for the wet lay-up composites reinforced with square weave UHMPE fabric.   The results here are consistent with the much lower fibre orientation in the axial direction of the test specimens, where now only half of the reinforcing fibres contribute and moreover these fibres are not perfectly aligned.   The tensile moduli and strengths are now less than 25% of the values for the UHMPE fibre.

The woven yarn composites show values for interlaminar shear strength and compressive strength which are similar to those of the unidirectional fibre composites.   The ILLS test measures adhesion at the resin/fibre interface, and relates to shear deformation so that the reinforcement direction is not expected to be very significant compared with say a tensile test where any contribution from shear reduces the stress observed.   In the woven yarn

composite the resin penetrates the weave and this may also enhance the interface strength. The compressive strength results can be interpreted as follows. The compressive strength of the pure resin is 120 MPa i.e. significantly higher than the CS of the composites, so that for this mode of deformation the UHMPE fibres are weaker than the resin. The CS value for the composites is therefore determined primarily by the CS of the resin, so that the results are only affected to a first approximation by the volume fraction of fibres and not by their orientation.

Table 4 shows the mechanical properties of the fibre composites prepared by the pre-preg route. Comparative data are presented for unidirectional fibre composites where the fibre phase is wholly UHMPE, Kevlar 49, Carbon EXAS or E-Type Glass. Results are also presented for hybrid composites where 3 layers of pre-pregs made from commercial fibre are sandwiched between 2 layers of pre-preg made with UHMPE fibres.

TABLE 4. Mechanical properties of pre-preg composite systems – various continuous reinforcements/Code 91 epoxy resin

Reinforcement	Density kgm⁻³ (x10⁻³)	ILSS MPa	UFS TEST		FM GPa	TM GPa	TS GPa	CS MPa	"Flat" Charpy Test- Energy Absorption	
			Value MPa	Decrease after 3 successive tests (%)					At 1st Impact kJm⁻²	Decrease after 3 successive tests (%)
UHMPE (untreated)	1.08	15	165	27	41	41	0.43	75	135	85
Kevlar 49	1.35	53	532	28	66	75	1.30	277	175	90
Carbon EXAS	1.56	66	1600	Break	104	137	1.95	1050	75	Break
E-Type Glass	1.95	66	1145	Break	41	56	1.56	975	320	Break
UHMPE (untreated)- Carbon EXAS	1.28	34	495	2	48	85	-	410	155	90
UHMPE (untreated)- E-Type Glass	1.45	28	245	22	42	46	-	255	240	30
UHMPE (untreated)- Kevlar 49	1.19	22	285	5	41	57	-	160	135	90

1. All measurements at room temperature.
2. All composites about 55% reinforcement by volume.
3. Hybrids: 2 x UHMPE fibres/3 x commercial fibres/2 x UHMPE fibres.

There are a number of important points to be made about the results shown in Table 4. First, the ILLS values for the UHMPE composite and for the hybrids are significantly lower than the values for the three commercial fibre composites. The discussion above suggests that this may not be a disadvantage because the properties of UHMPE composites are not very dependent on the level of adhesion as shown in Table 3. However, if a substantial increase in interface adhesion were required, it could be obtained by plasma treatment of the yarn prior to incorporation into the composite.

Secondly, Table 4 shows that commercially prepared UHMPE composites possess markedly better mechanical properties than those made under laboratory conditions by the leaky mould technique. In particular, the flexural and tensile moduli are 41 GPa and the tensile strength is 0.43 GPa, showing that the fibre properties are now being realised in the composites, when the volume fraction factor of 0.55 is taken into account. The absolute values for modulus and strength are, however, lower than for the commercial fibre composites as anticipated on the basis of absolute fibre properties shown in Table 1. The only absolute value for homo-fibre composites in Table 4 which is remarkable is the high impact energy of 135 kJm⁻² for the UHMPE composite.

These conclusions suggest that it will be of greater interest to examine carefully the data for the hybrid composites, and it is here that the advantages of the UHMPE fibre with regard to toughness become apparent. For example, the UHMPE/carbon fibre hybrid composite shows a very high value of impact strength (155 kJm⁻²) and does not shatter, with higher CS than the commercial Kevlar composite.

The results for the hybrids look even more impressive when the low density of the UHMPE fibres is taken into account. Table 5 shows the results of Table 4 expressed in terms of specific properties. For example, the specific CS and UFS of the UHMPE/carbon fibre hybrid are not much less than the specific properties of the glass fibre laminate, with the advantage that the hybrid does not break at the first impact or in the first UFS test as in the case of both carbon fibre and glass fibre composites. The specific FM and TM of the UHMPE laminate, and the hybrid laminates from UHMPE/carbon fibre and UHMPE/glass fibre are all higher than the respective specific properties of the glass fibre laminate. Moreover

the specific TM of the UHMPE/carbon fibre hybrid is almost as great as the specific TM of the carbon fibre laminate.

Bearing in mind that the tensile properties of the hybrids are at very acceptable levels, it is of particular interest to examine the energy absorption data in Table 5.   The UHMPE/glass fibre hybrid shows the highest value for this quantity.   It is even higher than

TABLE 5.   Specific mechanical properties of pre-preg composite systems –
           various continuous reinforcement/Code 91 epoxy resin

Reinforcement	ILSS MPa/ρ (x10³)	UFS MPa/ρ (x10³)	FM GPa/ρ (x10³)	TM GPa/ρ (x10³)	TS GPa/ρ (x10³)	CS MPa/ρ (x10³)	"Flat" Charpy Test-Energy Absorption at 1st Impact kJm⁻²/ρ (x10³)
UHMPE (untreated)	14	155	38	38	0.40	70	125
Kevlar 49	39	394	49	56	0.96	205	130
Carbon EXAS	42	1025	67	88	1.25	675	50
E-Type Glass	34	585	21	29	0.80	500	160
UHMPE (untreated)-Carbon EXAS	27	385	38	66	-	320	120
UHMPE (untreated)-E-Type Glass	19	170	29	32	-	175	165
UHMPE (untreated)-Kevlar 49	18	240	34	48	-	135	115

ρ : Density as given in Table1.

the value for the glass fibre composite, with the added advantage that it retains a very appreciable impact energy in subsequent impacts.   This latter result is shown diagrammatically in Fig. 3.   It is interesting to note that on this comparison the UHMPE/glass fibre hybrid is significantly better than the Kevlar 49 composite.   The advantage of the UHMPE/carbon fibre composite is also very clear from the comparison of specific properties, and shows some advantages over the Kevlar composite.
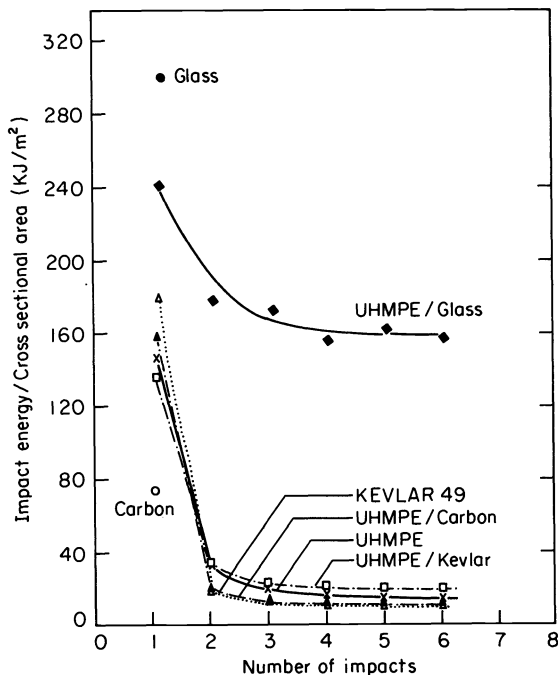

Fig. 3.   Pre-preg composites reinforced with continuous
          unidirectional fibres.

CONCLUSIONS

In this paper we have shown how the unique combination of fibre properties possessed by UHMPE fibres does lead to a new range of fibre composites. UHMPE fibres show a useful portfolio of properties, i.e. low specific mass, high tensile modulus and strength, and high extension at break.

From the viewpoint of composites it is the combination of high strength and high extension at break which leads to high energy absorption capabilities, which is enhanced by the near impossibility of breaking composites containing UHMPE fibres in a bending or compressive mode of deformation. It has been found that hybrid composites, especially those containing carbon or glass fibre as well as UHMPE fibre, offer an exciting new range of composite materials. These hybrid composites open up the possibility of fabricating composites combining the light weight, low production costs, high energy absorption and non-shattering capabilities associated with UHMPE fibre composites with the good compressive properties and exceptional stiffness and strength of carbon fibre composites, or the high energy absorption and good compressive properties of glass composites without the disadvantage of shattering on first impact.

ACKNOWLEDGEMENTS

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