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Jute-reinforced polyester composites

P. J. ROE, M. P. ANSELL*
School of Materials Science, University of Bath, Claverton Down, Bath, UK

Raw jute fibre has been incorporated in a polyester resin matrix to form uniaxially reinforced composites containing up to 60 vol % fibre. The tensile strength and Young's modulus, work of fracture determined by Charpy impact and inter-laminar shear strength have been measured as a function of fibre volume fraction. These properties all follow a Rule of Mixtures relationship with the volume fraction of jute. Derived fibre strength and Young's modulus were calculated as 442 MN m^{-2} and 55.5 GN m^{-2} respectively. Polyester resin forms an intimate bond with jute fibres up to a volume fraction of 0.6, above which the quantity of resin is insufficient to wet fibres completely. At this volume fraction the Young's modulus of the composite is approximately 35 GN m^{-2}, the tensile strength is 250 MN m^{-2}, the work of fracture is 22 kJ m^{-2} and the inter-laminar shear strength is 24 MN m^{-2}. The properties of jute and glass fibres are compared, and on a weight and cost basis jute fibres are seen in many respects to be superior to glass fibres as a composite reinforcement.

1. Introduction

Of the commonly available annual crop fibres jute contains one of the highest proportions of stiff natural cellulose, approximately 75 wt % [1]. Jute may be combined with phenolic, epoxy and polyester resins [2–5] to form composite materials, and it has been laminated with glass fibre [6] to form hybrid composites.

The incentive for partially or completely replacing glass fibres with jute fibre originates from the low specific gravity of jute (~ 1.3) compared with glass (~ 2.5). The specific modulus, that is the Young's modulus divided by specific gravity, is about 40 GN m^{-2} for jute compared with about 30 GN m^{-2} for glass. However the specific tensile strength of jute fibre, ~ 340 MN m^{-2}, is considerably less than that for glass fibre, ~ 1.36 GN m^{-2} for E-glass fibre. Nevertheless cost considerations make jute an attractive fibre for the reinforcement of resin matrices.

The purpose of this paper is to report the mechanical properties of jute-reinforced polyester composites containing uniaxially oriented jute fibres. Previous workers have reported the flexural properties [4] of such composites and the tensile properties [5] up to a volume fraction of only 45%. Other papers are concerned with jute cloth [3] as a reinforcement or make no assessment of property changes with variation in fibre volume fraction [6]. Work on practical end-uses for jute composites in Asia [7, 8], although fascinating, contains little information on structure–property relationships.

The variation of tensile strength and Young's modulus are described here as a function of volume fraction V_f of jute between $V_f = 0$ and 0.7. Work of fracture, measured by Charpy impact, and inter-laminar shear strength (ILSS) are also reported for these composites. Visual inspection and examination by scanning electron microscopy assess the influence of fibre content on the mechanism of fracture.

2. Experimental methods

Retted jute fibre was obtained from Bonar Textiles Ltd of Dundee in the form of untwisted parallel fibres or sliver. The jute was dried in an

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*To whom correspondence should be addressed.

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oven at 40° C and kept in sealed polythene bags containing silica gel.

Composites were fabricated in a lossy mould comprising demountable steel plates forming interleaved troughs of dimensions 12.7 mm wide and 40 mm deep. High volume-fraction composites are bulky before pressing, and the 300 mm long composite specimens were pressed to 12.7 mm wide by 3.1 mm thick.

Before laying jute and resin into the mould large pieces of bark were removed from the raw sliver, and it was then combed to a texture halfway between that of hair and wool. The bundle was then cut accurately to the length of the mould and weighed. Finally the bundle was split into two and one half reversed in order to reduce the variation in volume fraction along the length of the composite due to thinning of the fibres towards the top of the plant.

An excess of Strand Glassfibre Resin A and hardener was mixed and the bottom of the mould, coated with mould release agent, was covered with resin. The jute was then carefully placed in the mould and the rest of the resin poured on top of the fibre. A spatula was used to agitate the fibre to ensure thorough wetting and the mould was closed by clamping, forcing out excess resin. After leaving the samples to cure for 16 h they were removed from the mould and post-cured in an oven for 2 h at 80° C. Excess resin was cut off, flashing removed and samples were weighed and measured for volume fraction determination.

The volume fraction of fibre V_f was obtained knowing the mass of constituents M and density of the resin ϱ_r, from the relationship

$$V_f = [V_c - (M_c - M_j)/\varrho_r]/V_c$$

where V_c is the composite volume, M_c is the mass of composite and M_j is the mass of jute. The density of cured resin was measured as $1.18 \times 10^3\,\mathrm{kg\,m^{-3}}$. The value obtained for jute volume fraction includes any porosity as part of the jute, a figure that (although not a volume fraction in the strictest sense) is of optimum value in evaluating practical composites. An added point in favour of this method is that a figure for the apparent density of jute can be obtained which averaged $1.29 \times 10^3\,\mathrm{kg\,m^{-3}}$ between $V_f = 0$ to 0.7. No increase in porosity occurred with increasing V_f, as might be expected, indicating that wetting of fibres by resin was good.

Tensile specimens were prepared by cutting pressed strips into 100 mm lengths, and overlapping aluminium tabs were glued to the sample ends leaving a parallel-sided exposed sample 60 mm in length. Testing was conducted at a cross-head speed of $1\,\mathrm{mm\,min^{-1}}$ using an Instron 1195 fitted with self-tightening grips. Strain was measured with an extensometer. At least nine samples were tested at each volume fraction.

Charpy impact samples were prepared by cutting and sanding to dimensions of 45 mm × 6 mm side × 3.1 mm thick. A central 2.5 mm notch was cut and the notch was sharpened by drawing a fresh scalpel blade across it. Microscopical examination indicated the average cross-sectional area of the notch to be $38 \times 10^{-6}\,\mathrm{m^2}$. A Hounsfield Plastics Impact Machine was used to break 8 to 12 samples of each volume fraction.

Interlaminar shear strength was calculated according to ASTM D2344 [9]. The three-point bend apparatus comprised three 6 mm diameter rollers, with the lower rollers spaced 15.5 mm apart. The samples were 22 mm long, 12.7 mm wide and 3.1 mm thick. The interlaminar shear strength was calculated from the expression

$$\tau_{\max} = \frac{3P}{4WD}$$

for a span to depth ratio of 5, where P is the maximum load, W is the width and D is the thickness of the specimens.

3. Results

3.1. Uniaxial tension

The variation of Young's modulus (Fig. 1) and strength (Fig. 2), with volume fraction of jute demonstrates that Rule of Mixtures relationships are followed, such that

$$E_{\mathrm{comp}} = E_{\mathrm{jute}} V_{\mathrm{f(jute)}} + E_{\mathrm{resin}} (1 - V_{\mathrm{f(jute)}})$$

with a similar expression for tensile strength.

The regression line of Fig. 1 predicts, after extrapolation to a volume fraction of unity, a derived fibre modulus of $55.5\,\mathrm{GN\,m^{-2}}$. The extrapolated results of Chawla and Bartos [5] suggest a fibre modulus of about $70\,\mathrm{GN\,m^{-2}}$, although the composite modulus was only measured to $V_f = 0.3$ and experimental data were

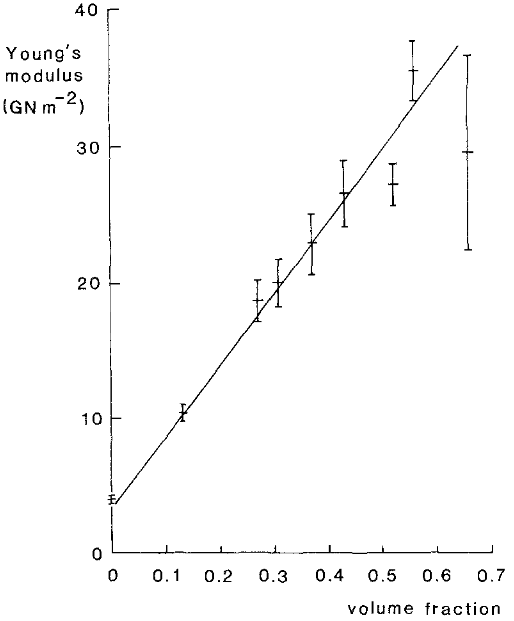

Figure 1 Variation of Young's modulus with volume fraction of jute (error bars represent mean ± one standard deviation).

quite scattered. Wells *et al.* [4] measured the flexural properties of unidirectional jute–epoxy composites and they derived fibre moduli of between 53 and 66 GN m^{-2} for two jute species. The increased variation and fall-off in modulus at the highest volume fraction $V_f = 0.66$ (Fig. 1) resulted from incomplete wetting of fibres. At $V_f = 0.7$ delamination and failure occurred at low stresses, so it is concluded that practical composites should contain an optimum volume fraction of fibre $V_f \approx 0.6$.

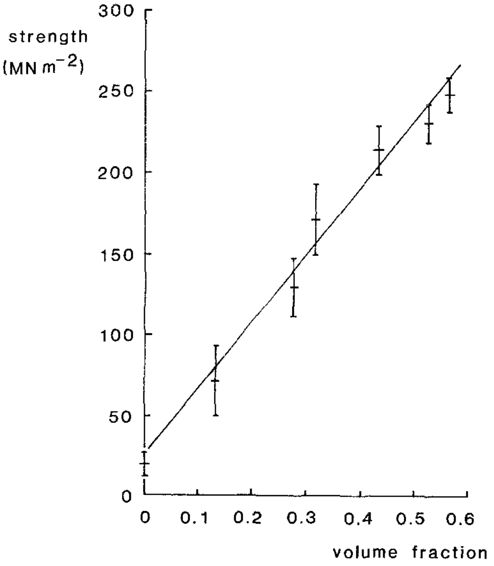

Figure 2 Variation of tensile strength with volume fraction of jute.

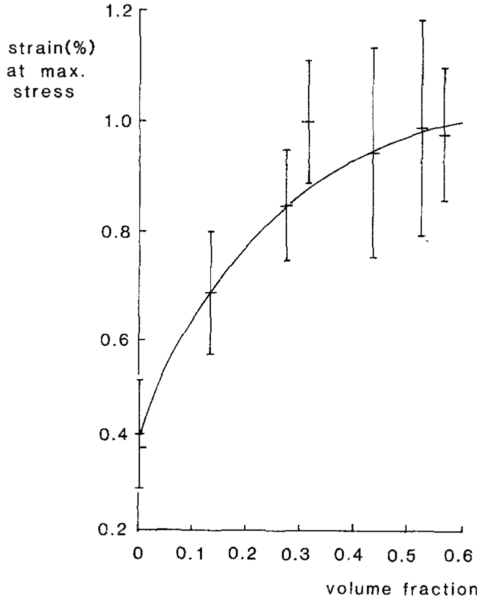

Figure 3 Variation of tensile strain at failure with volume fraction of jute.

The derived jute fibre strength, obtained by extrapolation of the linear regression line of Fig. 2, was found to be 442 MN m^{-2}. This compares with a derived flexural strength for jute–epoxy [4] of between 570 and 640 MN m^{-2} and a derived tensile strength for jute–polyester [5] of ~420 MN m^{-2}.

The failure strain increases with increasing volume fraction of fibre levelling off to a value of about 1% (Fig. 3), similar to other reported literature values [5].

3.2. Work of fracture

Jute–polyester composites containing $V_f > 0.3$ are tough materials. An approximately linear relationship is observed between work of fracture and fibre volume fraction (Fig. 4). Composites with the optimum volume fraction of 0.6 have a mean work of fracture greater than 20 kJ m^{-2}.

3.3. Interlaminar shear strength

The ILSS of jute–polyester composites varies close to linearly with fibre volume fraction. The results of Fig. 4 show two linear regression lines.

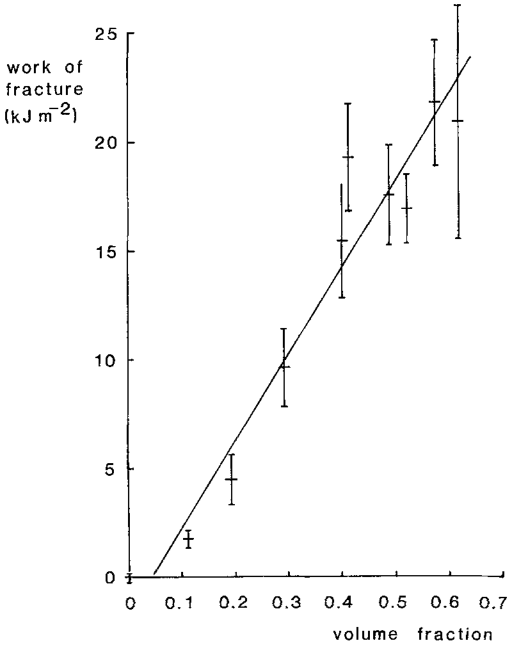

Figure 4 Variation of work of fracture measured by Charpy impact with volume fracture of jute.

The solid line is fitted to all five data sets. Below $V_f = 0.35$ the mode of fracture was tensile, whereas for $V_f > 0.35$ first failure occurred by shear. The three sets of data at $V_f = 0.37$, 0.46 and 0.59 are joined by the dashed line in Fig. 5 giving an improved and more realistic data fit.

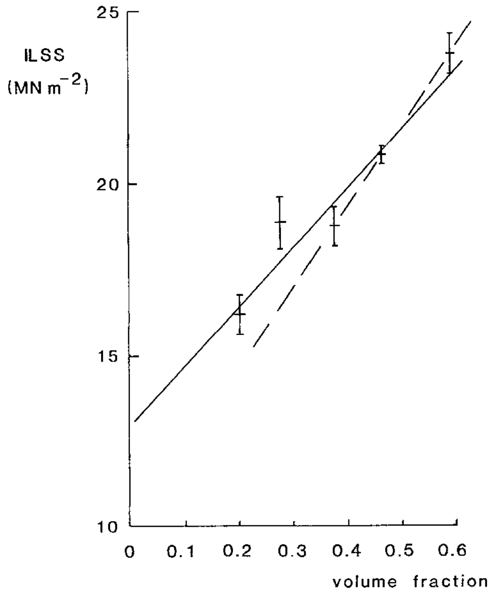

Figure 5 Variation of interlaminar shear stress with volume fraction of jute.

The value of the mean ILSS of 23.8 MN m^{-2} obtained at the maximum V_f of 0.59 is open to criticism. The ASTM test [9] gives only an indication of ILSS. Sattar and Kellog [10], discussing the effect of test geometry on mode of failure, conclude that shear stresses are non-uniform across the beam and significantly higher than the ASTM formula calculates. Similarly Berg *et al.* [11] suggest that the ASTM test could give results up to 100% too low as the formula neglects high shear stresses at the loading points.

As might be expected for a unidirectionally reinforced composite the interlaminar shear strength is nevertheless very low. Where high shear stresses are experienced in engineering applications there is a need to interconnect fibres transversely by, for example, stitch bonding or weaving.

4. Fracture

Up to $V_f = 0.15$ tensile fracture is essentially macroscopically brittle, with little microscopic pull-out of the jute fibres. As the jute content increases the pull-out lengths increase and fracture paths are macroscopically longer and more complex, involving delamination between strands of jute sliver as well as brittle fibre and matrix fracture.

In impact a similar trend is observed (Fig. 6). As the fibre volume fraction increases the failure mode changes from predominantly tensile (V_f = 0.1) to tensile plus shear (V_f = 0.3), increasing in brushiness until at $V_f = 0.6$ the failure is by shear alone.

Interlaminar shear samples containing $V_f <$ 0.35 fail in tension (Fig. 7). The micrograph shows pulled-out jute fibres in a composite with $V_f = 0.27$. Each ridged fibre is made up of a

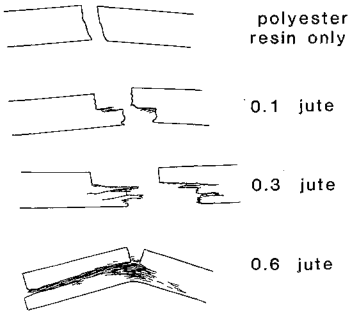

Figure 6 Effect of volume fraction of jute on the fracture of impact specimens.

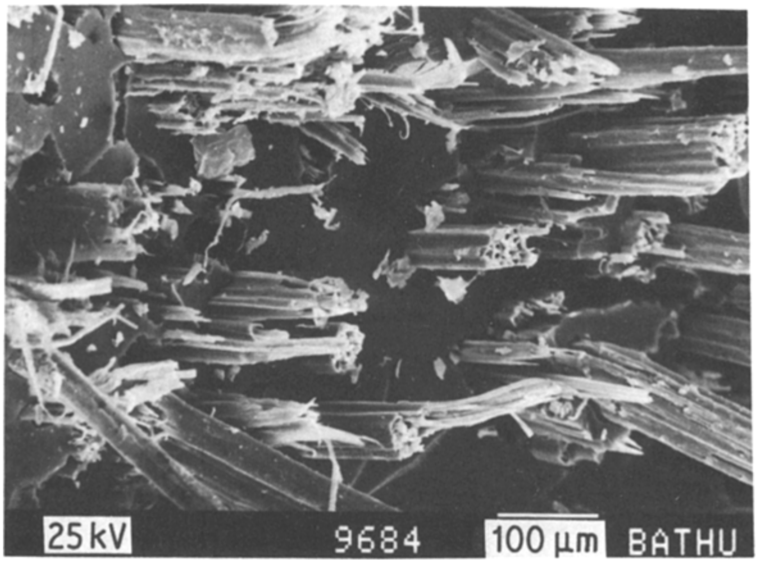

Figure 7 Tensile fracture of a jute-reinforced polyester composite, with $V_f = 0.27$, obtained in an interlaminar shear test.

number of elongated cells about 20 μm across and 2 to 3 mm long. Pull-out lengths average approximately 100 μm. With $V_f > 0.35$ failure occurs entirely by shear.

5. Discussion and conclusions

The strength and Young's modulus of glass and jute fibres are compared in Table I on the basis of specific gravity and cost per tonne (1983 values). The specific modulus of jute fibre is superior to glass fibre, and on a modulus per cost basis jute is far superior. The specific strength per unit cost of jute approaches that of glass fibre.

Where high strength is not a priority jute offers many advantages as a composite reinforcement. Jute fibre forms an intimate bond with polyester resin (Fig. 7), and can fully or partially replace glass fibre without entailing the introduction of new techniques of composite fabrication. The jute composite product is aesthetically pleasing, having an appearance not unlike that of dark-grained wood. Where good biaxial properties are required jute may be spun into yarn for weaving at a price of £650 to £950 per tonne (1983 prices). The toal cost of woven cloth is about £1500 per tonne, which compares very favourably with the equivalent woven glass cloth at over £5000 per tonne.

Jute-reinforced polyester composites are tough at $V_f > 0.3$. However, glass-reinforced plastics (GRPs) at $V_f = 0.6$ have work of fracture $\approx$ 100 kJ m^{-2} compared with 20 kJ m^{-2} for jute-reinforced plastic (JRP). Furthermore GRP is more environmentally stable in moist conditions than JRP [4], although hybrid laminates with GRP facings and JRP cores are almost as stable as for GRP alone. The mechanical properties and environmental performance of laminates of GRP and JRP will be described in a later paper [13].

Overall, jute fibre is readily available in the UK and has a large world capacity for growth in production [14] if demand increases. Good-quality composites with very acceptable specific properties can be formed from jute and polyester resin using existing GRP fabrication techniques. There is thus considerable scope for increased use of this valuable fibre in this country.

TABLE I Property and cost relationships for glass and jute fibres in tension

Property	E-glass [12]	Jute (this work)
Specific gravity	2.5	1.3
Strength (MN m^{-2})	3400	442
Young's modulus (GN m^{-2})	72	55.5
Specific strength (MN m^{-2})	1360	340
Specific modulus (GN m^{-2})	28.8	42.7
Cost (£ tonne^{-1})	1050*	324†
Stength/cost (MN m^{-2} £$^{-1}$ tonne)	3.24	1.36
Modulus/cost (MN m^{-2} £$^{-1}$ tonne)	68.6	171.3
Specific strength/cost (MN m^{-2} £$^{-1}$ tonne)	1.30	1.05
Specific modulus/cost (MN m^{-2} £$^{-1}$ tonne)	27.4	131.8

*Source: Strand Glassfibre Ltd.
†Source: Bonar Textiles Ltd.

Acknowledgement

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