Mechanical and Impact Properties of Untreated Jute Fabric Reinforced Polyester Laminates Compared With Different E-Glass Fibre Reinforced Laminates

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ABSTRACT

In recent years, the improvement of properties of natural fibre reinforced laminates over the pure polymeric matrix has been thoroughly investigated with the aim of providing a possible replacement of E-glass fibre reinforced composites for some large-volume applications. In the present study, the properties of a jute/polyester laminate are compared with those yielded by two E-glass fibre woven laminates. These are an E-glass/polypropylene commingled twill weave laminate (®Twintex) and a plain woven-roving E-glass/polyester composite. These two materials are representative of a large part of glass fibre reinforced laminates currently used, since Twintex is widely used e.g., in automotive industry, while glass mat/polyester laminates are still very popular in naval applications. All the materials have a 60% wt. fibre content.

A number of tests were carried out, including mechanical tests, interlaminar shear strength tests, Charpy impact and falling weight impact tests. After that, the consolidation of the composites was investigated by interlaminar shear strength tests and observing the porosity present in the materials under an optical microscope. The results confirm the concerns regarding impact performance of natural fibre reinforced composites. Moreover, mechanical and impact properties on jute fibre reinforced composites show significant scattering, that makes it difficult to measure the maximum load values that can safely be applied to these materials during their service. This variation of properties is due mainly to irregular fibre fraction in the composite and to the scattering in properties between the single fibres and fibre bundles. In spite of this, the mechanical and impact properties of jute/polyester laminates as a whole proved promising.

INTRODUCTION

The use of natural fibres (e.g., straw, flax, hemp, banana and jute) as material reinforcement has aroused considerable interest in recent decades /1-4/. The most common concerns about the use of these fibres relate to their coupling with a polymeric matrix, which needs to be compatible with the cellulose contained in the fibres /5/. A number of thermoplastic and thermoset matrices were used with this aim /6,7/. However, the best results so far were obtained with polyester and some phenolic resins /8-10/. Another issue widely investigated is the weathering behaviour of natural fibre reinforced composites, including the study of the influence of water sorption on the mechanical properties of the laminate /11/. A number of fibre surface treatments, involving slivers bleaching e.g., with alkali (NaOH) or silane coating, are capable to reduce the sensitivity of these composites to weathering /12-14/.

Jute is among the best natural fibres in terms of tensile strength and flexural properties, due to its longer continuous length. In addition, jute fibres are versatile, since they can be combined with different polymeric resins (e.g., phenolic, polyester, epoxy). Jute reinforced laminates are currently used e.g., to produce wood replacement panels, insulators and automotive components /15/.

However, jute fibre reinforced composites are not always very stiff. A number of studies are already available on impact and mechanical properties of these laminates /16-18/. Most commonly reported problems include a large amount of scattering in mechanical properties, due to the highly non-uniform cross-section of jute fibres, and the reduction of performance observed after water absorption, that is believed to affect the dimensional stability of fibres /19/. Moreover, the limitations imposed on the mechanical performance of the composite, due to internal porosity, are not well known /20/. Jute reinforced composites may be used in combination with biodegradable polymers /21/ or to replace conventional E-glass fibre reinforced composites. In this case, the main concern is their impact resistance. The production of hybrid laminates by coupling layers of E-glass fibre reinforced with jute reinforced laminates also proved effective in improving the mechanical characteristics /22-24/. In recent years, a number of studies have been carried out, aimed to compare properties of jute fibre reinforced laminates e.g., with E-glass or N-glass chopped strand mats (CSMs) and GMT (glass mat thermoplastic) composites /25/.

EXPERIMENTAL

Materials and processing

A balanced 0°/90° plain weave jute fabric/polyester laminate (density 1.3 ± 0.03 g/cm^3) with 60 (±1.5) % mass of fibres was tested. To produce the composite, an unsaturated polyester matrix (Lonza 1629) with styrene as crosslinking monomer has been used. The composite was manufactured by vacuum assisted resin transfer moulding (RTM). The mould temperature was 30°C at the beginning of resin injection, carried out at 2 bars, followed by a post-curing period of 12 h. at 80°C.
Fibres were dried before the production of composite, while the surface of the jute fibres was unbleached. These composites were obtained by laminating 8 or 13 plies of polyester-jute based on a jute fibres fabric, yielding a laminate thickness of 3 (±0.2) or 5 (±0.3) mm. respectively. The weave structure of the jute fibre reinforced composite is shown in Fig.1.

For comparative purposes, two further materials have also been studied. The first was a commingled E-glass/polypropylene with a balanced 0°/90° twill woven laminate of superficial density 745 g/m^2 (®Twintex, manufactured by Vetrotex). A non-isothermal

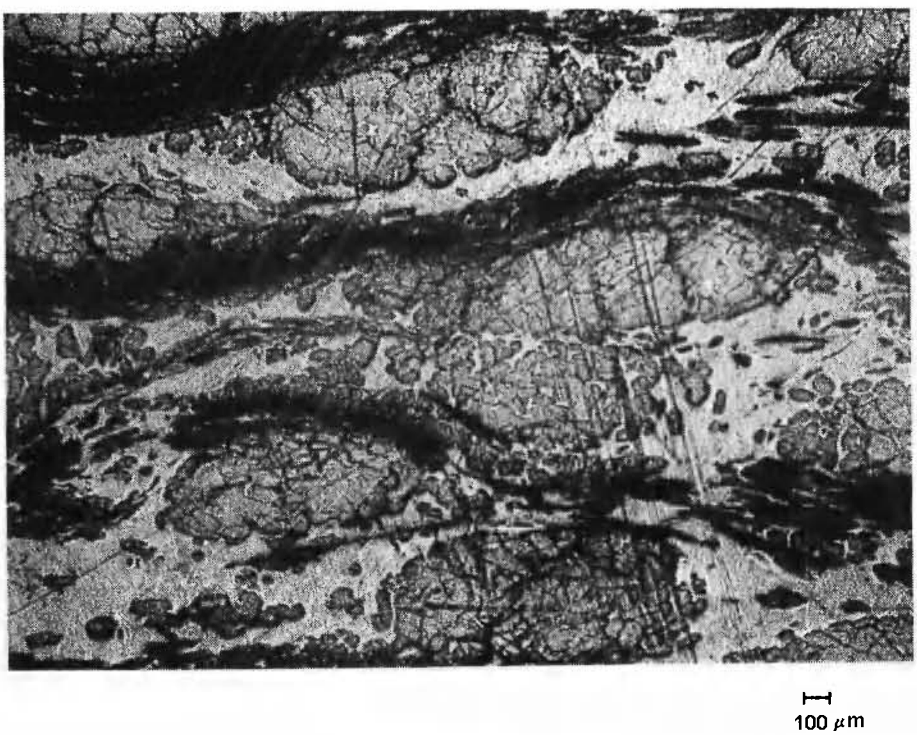

Fig.1: Weave structure of the jute fibre reinforced composite

Table 1
Woven laminates geometry

Laminate	Weave structure	Superficial density (g/m^2)	Layer thickness (mm)	Fabric count / cm
Jute/polyester	Plain balanced	590	0.45	6
Twintex	Twill balanced	735	0.53	2
E-glass/polyester	Plain balanced	570	0.38	2

compression moulding was used to produce this laminate from the preconsolidated sheets supplied by the manufacturer. The material was first preheated for six minutes, setting the oven temperature at 245°C, so that the highest temperature in the material exceeded 200 °C for no more than four minutes. After preheating, the material is disposed by hand under the press, where consolidation takes place at 30 bars with a tool temperature of 100 °C. A plate of 260 × 120 mm. was so obtained. The laminate was moulded with different thickness, using either 6 or 10 layers of preconsolidated material and yielding a thickness of 3 (±0.15) or 5 (±0.25) mm. respectively.

The second laminate investigated was an E-glass polyester woven roving (K1555 from Vetrotex) with a 0°/90° plain weave, obtained from an unsaturated polyester (1629 NT from Lonza) with styrene as cross-linking monomer, and laminated by hand lay-up. The laminates yielded square plates with dimensions 600x600 mm, from which the specimens were cut, laminating up 10 or 17 plies, so to yield a thickness of either 3 (±0.2) mm or 5 (±0.3) mm.

Both these materials have the same fibre content as the jute fibre reinforced composite (60±1.5% wt.). Details about the woven laminates geometry are presented in Table 1.

Mechanical tests

A number of mechanical tests have been carried out on the two materials at room temperature using an Instron 1195 machine fitted with a 50 kN load cell. A displacement control mode has been used throughout. The experimental set-up is described in Table 2.

Concerning in particular interlaminar shear strength, none of the test methods that have been developed for use with composite materials over the years, provide pure uniform shear, or provide the entire stress-strain response to failure from a single specimen. In addition, some limitations are specific to the short beam shear test, in what it was developed for non-woven laminates, having lower interlaminar properties than the woven one. In spite of these limitations, short beam shear test is still preferable for its simplicity. However, the accuracy of the results obtained for ILSS on jute fibre reinforced composites needs to be verified, as it will be discussed

Table 2
Mechanical testing set-up

Test	Standard	Cross-head Speed (mm/min)	Sample dimensions (mm)	Sample geometry
Tensile	ASTM D-3039	0.5	Grip length 60x15x3	Dog bone
Three-point bending	ASTM D-790	10	80x10x3 Span=46 mm	Flat beam
Interlaminar shear strength (ILSS)	ASTM D-2344	1.3	30x5x5 Span=20 mm	Flat beam

below.

In short beam shear tests /26/, where span-to-thickness ratio is not less than 5, so to have interlaminar shear failure, the value of the apparent interlaminar shear strength is obtained from the value of maximum load attained during the test, using the formula:

$$ILSS = \frac{3F_{max}}{4bd} \quad (1)$$

where F_{max} is the maximum load
b is the specimen width
d is the specimen thickness

Impact tests

Different impact tests were carried out, including Charpy impact and falling weight impact tests. Two types of falling weight impact tests were performed: the first test procedure involved high energy impact (150 Joules on E-glass fibre reinforced laminates and 70 Joules on jute fibre reinforced laminates) to measure the energy absorbed at penetration, while the second test involved a staircase procedure to measure the dynamic stiffness of the material and to assess the evolution of damage in the materials. The staircase procedure included impact tests at energies ranging from 10 Joules to penetration, with 5 Joules increments. Values obtained for penetration energy were normalised, dividing them by the specimen sections and obtaining values in kJ/m², the same unit used for Charpy impact test results. Impact testing set-up is described in Table 3.

Void content measurements

To measure void content, a method based on optical microscope observation has been used /27/. In recent years, computer based image analysis has been widely used to measure void content on polymer matrix composites /28/. The voids obtained with this analysis are usually classified, due to their size and orientation, as co-planar and bundle cracks, interfibre cracks and matrix pores.

Square samples (20 mm side) were cut at 45° from the moulded plaques. This allowed observation of the fibre sections in both longitudinal and transversal orientation in the 0°/90° laminates, After that, the samples were cast in polyester resin and polished mechanically using glass paper disks (decreasing in grain size), then a fluid containing very fine alumina particles (diameter 0.1 μm). To remove dust from polishing, a final cleaning stage was carried out in an ultrasonic bath.

The microscope used was an Axiolab by Zeiss and the image could be processed using Aphelion software creating a binary image to highlight voids. A 50 times magnification was used for the observations on the optical microscope. To obtain a void percentage, an image is grabbed, and then a threshold is applied to it, in order to highlight the voids. To calculate the void content, the number of pixels in the original grey scale image (size 512 x 512 pixels) was compared with the number of pixels in binary image, representing the void content.

Water absorption tests

Water absorption tests were also carried out on jute fibre reinforced composites, according to ASTM D570-98. The tests involved 14 days of water immersion at

Table 3
Impact testing set-up

Test	Standard	Impact velocity	Sample dimensions (mm)	Sample geometry
Charpy impact	BS 179	3.46 m/s	80x10x3 Span = 61 mm	Unnotched flat beam
Falling weight impact (penetration)	BS 2782 part 3	2.35 m/s (jute) 3.46 m/s (glass) Mass =25.4 kg	70x70x5 Anvil = 40 mm	Flat plaque

room temperature and removal of excess water with tissue paper. After water absorption tests, samples were tested to Charpy impact and interlaminar shear strength tests to compare their results with those yielded by the dried jute fibre reinforced composite specimens.

RESULTS AND DISCUSSION

Mechanical and impact properties

Mechanical and impact results on the materials are summarised in Table 4. As expected, the mechanical properties of Twintex are much higher than obtained for jute fibre reinforced laminates. The highest difference is obtained in the case of tensile strength, due to the typical mode of failure of jute reinforced laminates, already observed. This involves little or no delamination and mainly driven by matrix damage, owing to the very limited elastic deflection of these laminates /29/. The comparison of the falling weight impact curves (Force vs. Deflection) for Twintex and jute (Fig.2) impacted at 20 Joules confirms this pattern: the initial slope of the two curves is very similar, but jute shows a far shorter elastic phase. In addition, as expected, the peak load of falling weight impact curves for Twintex exceeds by

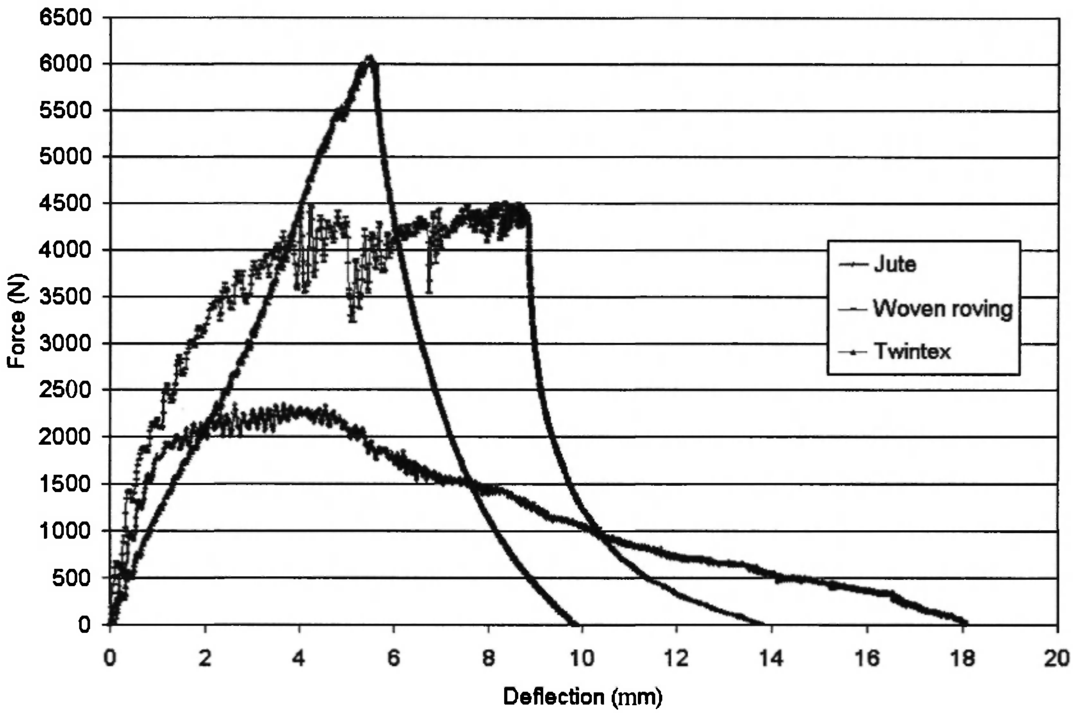

Fig.2: Falling weight impact curves (20 Joules)

Table 4
Mechanical and impact results
(average and standard deviation on 10 specimens)

Mechanical properties	Jute	Twintex	Woven roving
Tensile ultimate stress (MPa)	60 ± 3.5	225 ± 6	285 ± 9
Tensile modulus (GPa)	5.6 ± 0.2	12 ± 1.3	12.9 ± 0.9
Flexural ultimate stress (MPa)	116 ± 5.2	230.5 ± 13	450 ± 35
Normalised penetration energy (kJ/m²)	27 ± 3	90 ± 14.5	85 ± 16

more than three times that observed on jute (7200 N vs. 2150 N for impact at 20 Joules).

During dart penetration tests, the jute fibre reinforced laminates appeared slightly curved at energies not exceeding 30% of the measured penetration energy. This observation would suggest the presence of internal damage, although not appearing at the surface. However, the material does not undergo penetration until a wide amount of matrix cracking takes place and drives the fibre to be torn off; this happens at a much higher energy (around 25 N: see Table 3). This shows that this material has a good damage tolerance, even after damage initiation. From the visual observation of impact, the impacted area is not easily distinguishable, unless the impact energy is very close to penetration. However, fibre bundles appear very clearly bent and loose in the impacted region: in addition, the impact-damaged area seems preferentially follow the direction of fibre bundles (see Fig.3, showing the effect of an impact at 15 Joules on the surface of a 3 mm. thick specimen).

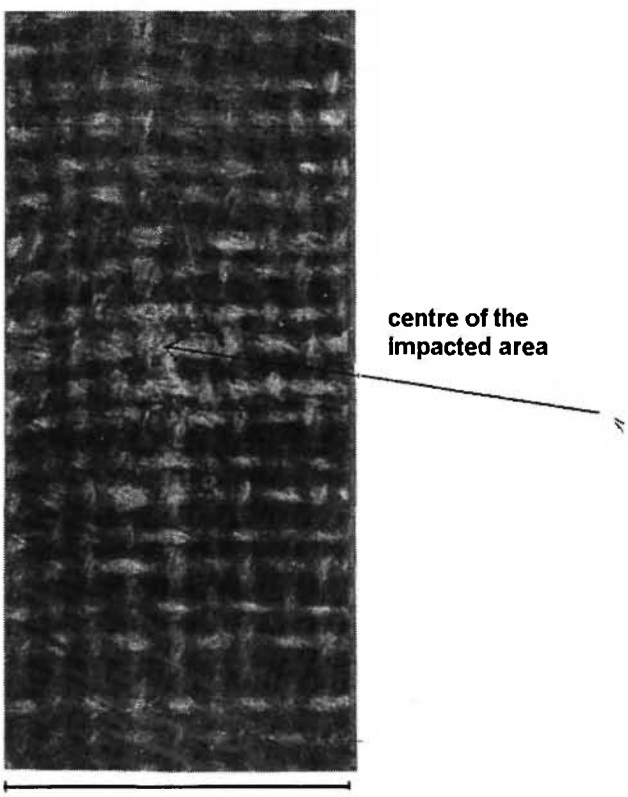

Fig.3: Region of a jute/polyester specimen impacted at 15 Joules

A recent study on post-impact damage /30/ on jute fibre reinforced laminates pointed out that their interlaminar adhesion is sufficient to yield an impact damage pattern typical of stronger composites, often referred to as *reversed-pine tree* pattern /31/. The jute reinforced composite also yields an interlaminar shear strength which is inferior to that shown by the E-glass fibre commingled laminate, but its average value is quite promising, around 13 MPa (Fig.4). Another recent study on interlaminar shear strength of untreated jute reinforced composite (45% vol.), also measured using the short beam shear test, supplied similar results /32/.

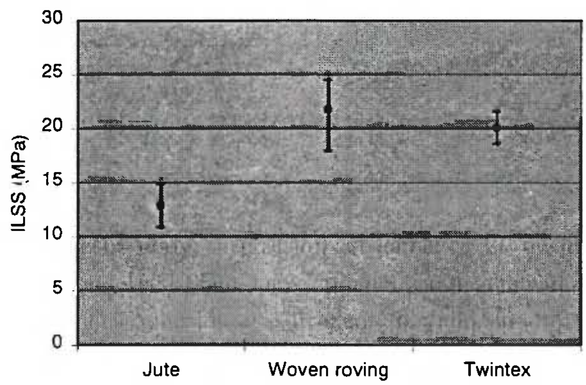

Fig.4: Interlaminar shear strength results (average and standard deviation on 20 samples)

Interlaminar shear stress curves on jute fibre reinforced laminates, as opposed to what is observed on E-glass reinforced composites, do not appear to be approximately linear up to the maximum load. In contrast, during short beam tests, a sudden deformation with no further increase in load, indicating damage, was typically observed at a load much lower than the maximum one (see Fig. 5 around 9 MPa stress). This corresponded, as observed visually on the samples, to the onset of delamination. In contrast, the interlaminar failure of the laminate is matrix-driven and takes place at much higher load (over 14 MPa in the curve shown in Fig.5). This may prove the significant damage tolerance of these laminates, which appear to be bent for impact energies not exceeding a half of their real penetration energy, as discussed above.

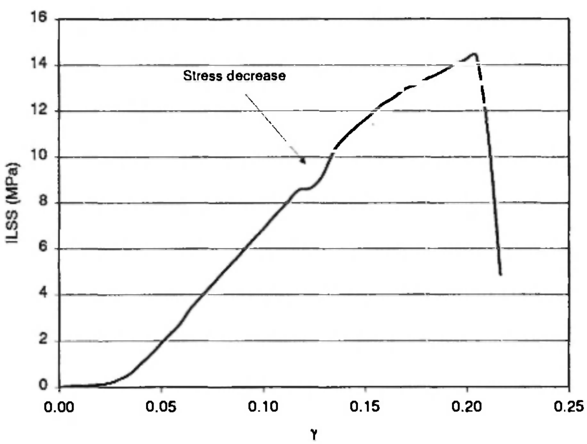

Fig. 5: Typical short beam shear curve for jute fibre reinforced laminate

Absorbed energy during Charpy impact tests is around 200 kJ/m² for the E-glass reinforced laminates and around 30 kJ/m² for the jute fibre reinforced laminates, as shown in Fig.6. In this case the difference is therefore much greater than that observed on interlaminar properties and stiffness. An explanation for this behaviour can be that both the mode of failure of the material and the typical geometry irregularities in the jute fibre bundles allow the reinforcement to absorb only a small part of the impact energy. Moreover, as often happens for Charpy impact tests, the dispersion of results is not negligible, exceeding, for both materials, ±10 %. The largest dispersion of results in yielded by the E-glass/polyester woven roving and has most likely to be correlated to the local variation in properties

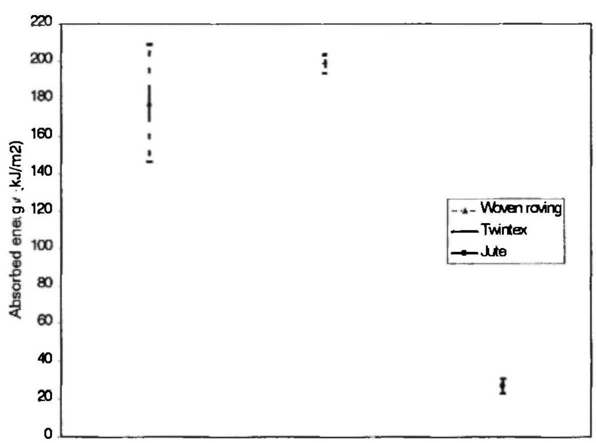

Fig. 6: Charpy impact results (average and standard deviation on 20 samples)

(curvature of the plies, coplanar voids) yielded by the stacking procedure by hand lay-up.

Charpy impact tests and interlaminar shear strength tests have been carried out also on jute laminate specimens after 14 days of exposure to water. Results shown in Table 5 indicate a serious reduction (exceeding 25%) of Charpy impact absorbed energy and a less important reduction of interlaminar shear strength value.

Table 5

Charpy and ILSS properties of dry and wet jute composite (average and standard deviation on 20 specimens)

Test	Dry jute composite	Wet jute composite (14 days)
Charpy absorbed energy (kJ/m²)	25.8±4.3	18.1±2.1
Interlaminar shear strength (MPa)	12.8±2.1	10.5±2.3

Microstructural void content

From a micro-structural point of view, the irregularities present in the fibre bundles in jute reinforced composites, in comparison with the smooth edges of the E-glass fibres, are deemed to reduce their impact properties. These irregularities are usually reflected in the presence of bundle voids. The void content measurements, performed through image analysis from optical micrographs, revealed that none of the laminates had a particularly high void content (results are reported in Table 6).

Table 6

Void content measurement results (on sets of 100 images from the same plaque, average value and 95% confidence value)

Material	Void content (%)	Prevalent void location
Twintex	2.4 ± 0.2	Interfibre, coplanar
E-glass roving	3.5 ± 0.5	Dispersed (no prevalent location)
Dry jute	4.6 ± 0.5	Bundle, matrix pores
Weathered jute	5.3 ± 0.7	Bundle, matrix pores

However, the void content measured on jute reinforced laminates exceeded that measured on the two E-glass fibre reinforced laminates, showing not only a large presence of bundle voids (Fig.7), but also matrix pores, not exceeding a diameter of a few µm (Fig.8). The presence of air trapping, most likely causing these

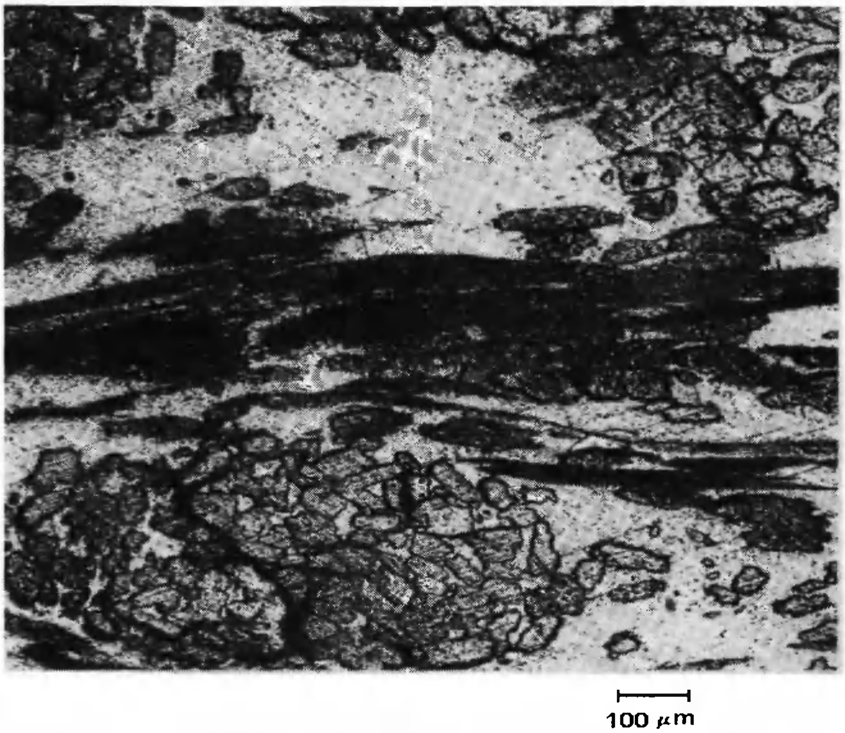

Fig.7: Micrograph of the jute/polyester laminate showing a number of bundle voids

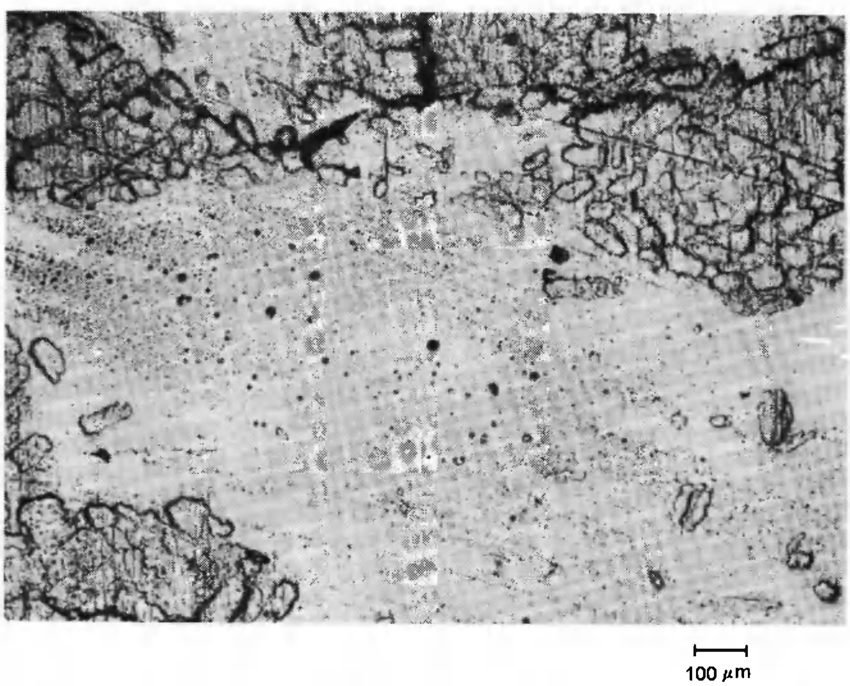

Fig. 8: Micrograph of the jute/polyester laminate showing matrix pores

pores, would suggest that the RTM process used to manufacture the composite needs to be optimised. The internal irregularities of the fibre bundles, typical of untreated fibre reinforced laminates and that may affect their stiffness, are also apparent from the micrographs.

On weathered jute composites, as shown above, an increase in void content was found that can justify the reduction in impact properties. Microstructural observation evidenced that bundle voids are much wider than in the same composite before weathering, as is shown in Fig. 9.

E-glass roving also shows a quite significant percentage of voids to be attributed to the hand lay-up process. In this laminate, the voids are present throughout the structure, particularly in and around the fibre bundles and as matrix pores, as can be observed in Fig. 10.

During the non-isothermal compression moulding process of Twintex, an oven-press transfer time (from the opening of the oven to the application of pressure) of 15-20 seconds was applied, due to the manual loading of the material under the press. The manufacturer suggests a value of 5 seconds /33/. This longer transfer time may have slightly affected

Fig. 10: Micrograph of the E-glass/polyester woven roving showing voids at the fibre edges and matrix pores

Fig.9: Micrograph of the jute/polyester laminate after weathering showing large voids in two fibre bundles

consolidation, as the presence of some coplanar voids at the interface between two Twintex layers may suggest (Fig. 11).

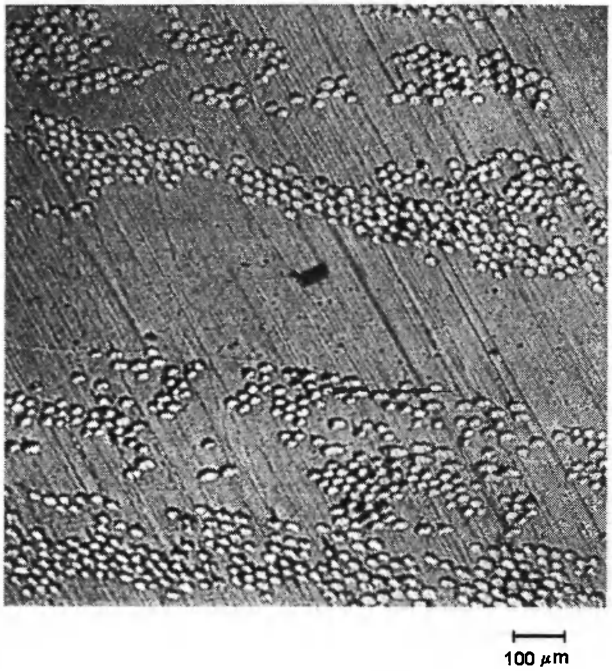

Fig.11: Micrograph of Twintex laminate showing a coplanar void at the interface between two layers

In spite of these limitations, jute/polyester laminates are capable of tolerating a high level of damage, including laminate curvature and delamination, before undergoing failure. In addition, microstructural analysis confirms that, although common problems (fibre bundle voids, air trapping) can be present in the manufacture of jute fibre reinforced composites, a number of parameters are also critical on E-glass reinforced composites moulding. Here some emphasis was placed on the oven-press transfer time in Twintex.

Coming back to jute reinforced laminates, the micrographs show significant variations in fibre dispersion, since regions richer in matrix than they should be, according to the fibre fraction, are often found. This can contribute to the scattering in mechanical and impact properties, also revealed by the experimental data. The high void content, exceeding 5% in jute fibre reinforced laminates, would also suggest some criticism about the RTM that was used to manufacture them. A possible improvement of the manufacturing procedure would most probably come about by using different moulding techniques, such as the vacuum infusion technique, which would be able to provide a much lower level of porosity in these laminates /34/.

Provided that manufacturing problems are addressed, as seems to have been the case in recent years, jute fibre reinforced composites can efficaciously replace – or integrate in hybrids – E-glass fibre laminates. In particular, there seem to be promising possibilities for this substitution in large-volume applications involving continuous load application for long time at low stresses. However, to confirm this possibility, a thorough investigation of the fatigue behaviour of these materials will also be required.

CONCLUSIONS

The possibility of using untreated jute fibre/polyester laminates to replace E-glass reinforced laminates in large volume applications was investigated. These materials show damage at relatively low load during impact tests, providing nevertheless a sufficient damage tolerance. In addition, the impact properties show a not inconsiderable degradation after weathering tests. Concerns were also expressed about RTM technology used to produce the laminates, that yielded a quite high porosity content, which is deemed to significantly affect mechanical properties and resistance to weathering. In spite of this, the results by jute fibre reinforced composites, yielded in particular from falling weight impact and interlaminar shear tests, are promising and would suggest improving the use of these laminates in isolation or in E-glass/jute hybrids.

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