ELSEVIER

Polymer Testing 18 (1999) 181–198

POLYMER TESTING

Material Properties

The performance of cotton–kapok fabric–polyester composites

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Received 18 December 1997; accepted 6 March 1998

Abstract

Cotton–kapok fabric, at a ratio of 2:3, has been incorporated with unsaturated polyester resin in various fibre volume fractions. The fabric was also treated with 5% sodium hydroxide with the aim of improving fibre–matrix adhesion. A simple manual lay up technique was used in fabricating the composites. A hand operated hydraulic electrically heated press was used and the composites were cured at 100°C for 60 min and post cured overnight in the oven at 80°C. Mechanical properties such as tensile strength, tensile modulus, impact strength, and flexural properties of composites not subjected to weathering conditions and weathered composites have been evaluated. Composites with untreated fibres had higher fibre volume fractions than composites prepared using treated fibres. The tensile strength of composites with untreated fibres was higher than that of composites prepared using treated fibres but had, on average, higher tensile modulus than composites manufactured using untreated fibres. The impact strength decreased with increase in fibre volume fractions for both composites, with or without alkali treated fibres. Reductions in flexural strength and moduli were observed with weathered composites. The specific strength of the composites was comparable to that of other vegetable fibre reinforced resins.

1. Introduction

Natural fibres are attracting more attention as reinforcements to thermoset and thermoplastic matrices. The increasing demand for these cellulose materials as fillers in a wide variety of matr-

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0142-9418/99/$ - see front matter
PII: S0142-9418(98)00017-8

ices is essentially because of their desirable properties such as low cost, renewal, biodegradability and high specific properties compared with conventional matrix fillers, like glass and carbon fibres, which are expensive and not renewable, besides being environmentally undesirable. A large variety of natural fibres is available in Tanzania (Table 1). Most of these fibres have not been optimally utilised, except cotton and sisal fibres which are the country's main cash crops. At present, nearly all the fibres are utilised for conventional applications, for instance, for the production of yarns, ropes, mats, apparel and upholstery, etc. However, in recent times, many of these conventional uses of natural fibres are threatened by plastics and synthetic fibres like glass and nylon fibres. This has generated the need to develop new uses for natural fibres [1,2].

The application of natural fibres as reinforcement to polymeric matrices has been extensively researched and it is now possible to produce plastic composites using natural fibres for applications such as roofing, panelling, food grain silos and low cost housing units. Natural fibre reinforced composites are now being seen as the most appropriate and cost effective building materials [3].

A research programme was initiated at the University of Dar es Salaam to determine the application of cotton–kapok fabric [4] as reinforcing material in unsaturated polyester resin. The fabric was mercerised in slack form with 5% sodium hydroxide. The aim was to improve the fibre's wetting ability by extracting the non-cellulose substances, mainly wax and pectin. The extraction of these non-cellulose substances reveals the microfibrillar character of rough parallel ridges which adds to the fibre–matrix frictional forces, enhancing fibre–matrix adhesion. Mercerisation without tension allows total conversion of cellulose I to cellulose II, increases the strength uniformity along the fibre length and improves accessibility of reactive sites to binding chemicals [5].

The cotton–kapok fabric–polyester composites have been manufactured using untreated and treated fabric. Some of the composites with treated fabric have been subjected to accelerated

Table 1
Natural fibres available in Tanzania and the annual production (tonnes)

Fibre	Production ('000)	Possible production ('000)	Price (US $/kg)
Cotton	126	200	2.00
Sisal	30.5	200	0.74
Kapok	0.02	0.8	0.20
Wood	Abundant	–	–
Coir	2.31	–	0.85
Rice husk	221	–	–
Rice straw	2574	–	–
Wheat straw	213.5	–	–
Bagasse	385.4	–	–
Elephant grass	Abundant	–	–
Groundnut hull	Feasible	–	–
Coffee hull	10.4	–	–
Banana	Abundant	–	0.1
Cashew nut shell	24.6		
Bamboo	Abundant	–	–

Note: The price of glass fibre is about US $2.50/kg.

weathering conditions. This paper reports on the mechanical and thermal properties of cotton–kapok fabric–polyester composites and fibres.

2. Experimental procedure

2.1. Materials

Cotton–kapok fabric was manufactured at Morogoro Canvas Mill, Tanzania [4]. The fabric had a weave construction of 7 × 7 warp/weft, area density of 97.23 g/m^2 and breaking strength of 180 N/50 mm. The unsaturated polyester was obtained from Hankel Plastics Ltd, Dar es Salaam, Tanzania. No specifications of the polyester matrix were given by the supplier.

A 30 mm^2 hand operated electrically heated hydraulic press was used for compression moulding and a mould with internal measurement of 250 × 60 × 60 mm (length, width, and height, respectively) was used to manufacture the composites. It had vents as exit pathways for the excess expelled resin during compression. The mould was made of mild steel plates.

2.2. Methods

2.2.1. Scanning electron microscope (SEM) analysis

A Philips SEM 501 scanning electron microscope was used to study the fibres and the tensile fracture surface of the composite samples. Prior to the analysis, the samples were metallised with Au/Pd alloy, by means of Polaron sputtering apparatus. The equipment was set to make a coating of 18.2 nm thickness.

2.2.2. Dynamic mechanical thermal analysis (DMTA)

Dynamic mechanical measurement was carried out by means of a dynamic thermal analyser (DMTA MK III Polymer labs) operating in a single cantilever bending mode at a frequency of 1 Hz. The samples, in the form of small bars 15 × 5 × 5 mm^3 in size, were investigated in the temperature range from 20 to 200°C.

2.2.3. Differential scanning calorimeter (DSC) analysis

A Mettler type differential scanning calorimeter was used. It was set to operate between 0 and 300°C. This range of temperature was considered sufficient to record the thermal characteristics of the fibres and composites. Samples of fibres and composites weighing between 5 and 10 mg were enclosed in an aluminium container and sealed. The container was then punctured with a needle to allow volatile substances to escape. The equipment was operated in a nitrogen environment.

2.2.4. Surface treatment of fibres

The surface treatment of fibres was performed in fabric form. The fabric was first soaked in commercial petrol for 4 h at room temperature. It was then washed in distilled water, rinsed and left to dry indoors for 24 h. The dried fabric was soaked in a hot solution of 5% sodium hydroxide for 2 h, after which it was thoroughly rinsed in distilled water and left to dry indoors for 24 h.

2.2.5. Moulding of composites

A convenient gel time for the unsaturated polyester was determined using a timer and observing the gel time of polyester when mixed with a hardener and thoroughly stirred. Ample time was allowed between preparation of the resin–fabric mixture and placing the soaked fabric in the mould for compression before complete gelling of the resin, otherwise complete compression to the desired composite thickness would be impeded.

Cotton–kapok fabric pieces were accurately weighed and soaked in polyester resin which had been mixed with a hardener. Excess resin was squeezed before moulding. A mould release agent was smeared onto the mould surfaces to facilitate the removal of the composites. A set of resin soaked fabric layers was then placed into an open-ended mould. A maximum of 40 min was sufficient to enable the laying of resin soaked fabric layers before hot curing started. A plunger was immediately fitted and a pressure of about 30 MPa was applied for 60 min. The composites were then removed from the mould and post cured in the oven at 80°C.

2.2.6. Weather degradation test

A simple accelerated test was performed by immersing the composite sample into boiling water for 2 h as per ASTM D 570-77. Flexural properties of the composites were then determined.

2.2.7. Tensile properties

The tensile testing of rectangular plain specimens was carried out using a Zwick tensile testing machine type 1141 in accordance with ASTM D 3039. The specimens were pre-conditioned to remove excess water and placed in the desiccator maintained at room temperature with a relative humidity of $50 \pm 5\%$.

Samples were tested at a cross-head speed of 5 mm/min and break time of 20 s. The tensile strength, modulus and elongation at break of the composite were calculated from the load–elongation curve. At least five specimens were tested for each set of samples and the mean and standard deviation values were reported.

2.2.8. Impact strength

Charpy-type impact tests were performed using a pendulum impact testing machine on samples of $7 \times 3.29\ mm^2$. The specimens were not notched because introducing a notch at right angles to the plane of the fabric layers would involve cutting through one or more layers. Impact loads were applied at right angles to the fabric. This orientation was chosen to represent lateral impact to a laminate panel in commercial use. The tests were carried out in accordance with ASTM D 256-92; five specimens were tested for each composite. No impact test was performed on weathered composites.

2.2.9. Flexural (bending) properties

Flexural properties were determined on weathered and non-weathered composites. ASTM D 790 method 1–Procedure A was used. The strain was maintained at 1.3 mm/min and a span-to-depth (thickness) ratio of not more than 8 was applied.

3. Results and discussion

3.1. Tensile properties

In this work, specimens taken from the middle part of the samples showed higher breaking load than those taken from other parts which gave a general decreasing trend of tensile properties with increase in the fibre volume fraction. Figs. 1 and 2 show examples of the selected load–elongation curves of the test pieces taken from the middle and peripheral parts of the samples. However, for consistency in the results, the middle test pieces were omitted from the calculations to obtain average values. The points of inflection in the curves indicate the failure of critically stressed fabric layers as a result of the lower fracture strain of fibres to the resin matrix.

It is possible that differences in the breaking load between the middle specimen and those taken from other parts of the samples are the result of the uneven distribution of the curing temperature during the hot compression period. This implies that the peripheral parts of the composites were under low curing temperatures, and that the post curing process did not compensate for this anomaly.

It should also be noted that the specimens were produced with no thickness control. It therefore follows that specimens with the highest fibre volume fraction were thicker than those with low fibre content. Naturally, the load required to fracture a thicker specimen is higher, although the calculated stress may actually be lower, as is the case in most of the specimens tested in this work (Tables 2 and 3).

It is believed that the drop in the mechanical properties (Fig. 3a and b) is likely to have been caused by a possible increase in void content with increasing fibre volume fraction. In addition

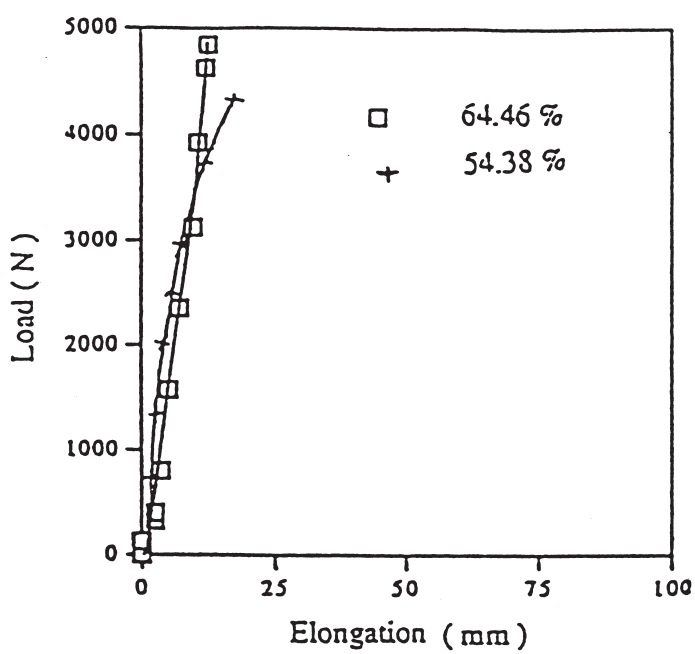


Fig. 1. Load–elongation curves of untreated fabric in the cotton–kapok fabric–polyester composite.

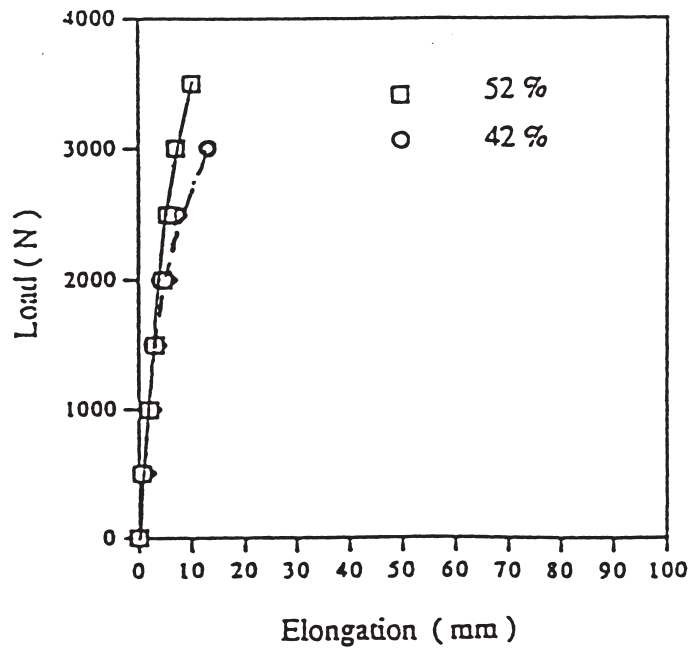


Fig. 2. Load–elongation curves of treated fabric in the cotton–kapok fabric–polyester composite.

Table 2
Mechanical properties of untreated cotton–kapok fabric–polyester composite

Fibre volume fraction (%)	Composite density (kg/m^3)	Tensile strength (MPa)	Tensile modulus (MPa)	Impact strength (kJ/m^2)
58	1231	57.49	739.37	103.96
59	1149	57.05	695.17	109.61
60	1171	55.70	884.34	110.53
62	1152	54.71	819.98	85.11
64	1159	54.40	665.08	77.27
65	1143	53.25	769.38	72.79

to this phenomenon, sodium hydroxide may have textured the fibres to the extent that it affected the mechanical properties of composites [6]. Ramaswamy et al. [7] obtained similar effects of sodium hydroxide when used in retting kenaf stalks. However, reducing the NaOH concentration to less than 1% is reported to have a minimal effect on the loss of the strength of cellulose materials [6].

Table 4 shows that the tensile strength of glass fibre–polyester composite is about 14 times that of cotton–kapok fabric–polyester composites, and that the specific energy is about seven times higher. However, the price of glass is 15 times that of kapok fibre and five times the price of cotton–kapok fabric at a 3:2 ratio, respectively.

The SEM thermograph (Fig. 4a) shows highly convoluted cotton fibres. Cross sections of the

Table 3
Mechanical properties of treated cotton–kapok fabric–polyester composites

Fibre volume fraction (%)	Tensile strength (MPa)	Tensile modulus (MPa)	Impact strength (kJ/m^2)
42.89	52.87	1635.24	119.25
44.76	44.76	858.48	–
46.62	41.70	1023.57	–
47.41	40.07	775.75	120.75
47.47	46.34	810.86	107.82
48.80	43.14	801.74	100.48
52.04	40.96	691.22	98.00

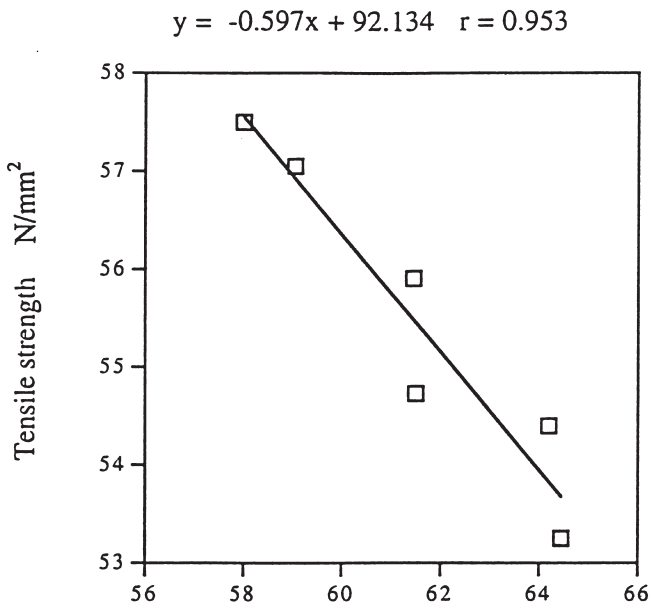
Table 4
Comparison of some natural fibre–polyester composites with glass fibre–polyester composites

Composite	Composite density (kg/m^3)	Fibre volume fraction (%)	Tensile strength (MPa)	Tensile modulus (MPa)	Impact strength (kJ/m^2)	Specific energy (kJ/kg)
Cotton–kapok–polyester	1171	60	55.70	884.34	110.53	47
Straw fibre–polyester	804	50	47.00	5600	–	58
Glass fibre–polyester	1930	50	750	38 000	60	338

fibre have a bean shaped structure with collapsed lumen. A longitudinal view of kapok fibres in Fig. 4c shows smooth cylindrical surfaces, while a cross section (Fig. 4d) reveals a wide open lumen with thin walls of about 2.5 μm. The width of the lumen is 16 μm.

The fracture surface of the matrix shows features of very brittle materials. Fig. 5a shows a severe surface action of the sodium hydroxide on the cotton fibre. The surfaces of the kapok fibre still have a smooth texture not very different from the untreated kapok fibres and show a good interface with the matrix. Delamination at the cotton–kapok fabric–matrix interface is due to the release of water on the surface of the fibres.

The shape of the DMTA thermogram of cotton–kapok fabric–polyester composite (Fig. 6) shows the presence of absorbed water in the composites and a glass transition temperature (T_g) of the matrix at approximately 84°C. DSC analysis on the individual fibres (Fig. 7a and b) gives similar thermogram characteristics with regard to the presence of water, and heat of fusion of about 163 J/g and 222 J/g for cotton and kapok fibres, respectively. Water present in the composite originates largely from the fibres and/or fabric, implying that the fabric and the composites were not effectively pre-conditioned before testing or that the time between removing the samples from the conditioning chambers and testing allowed the absorption of water, enough to affect the



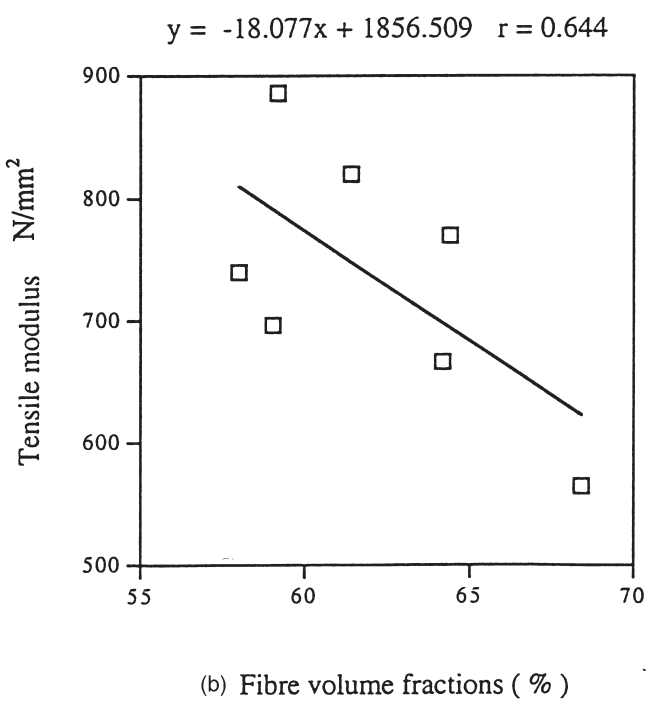
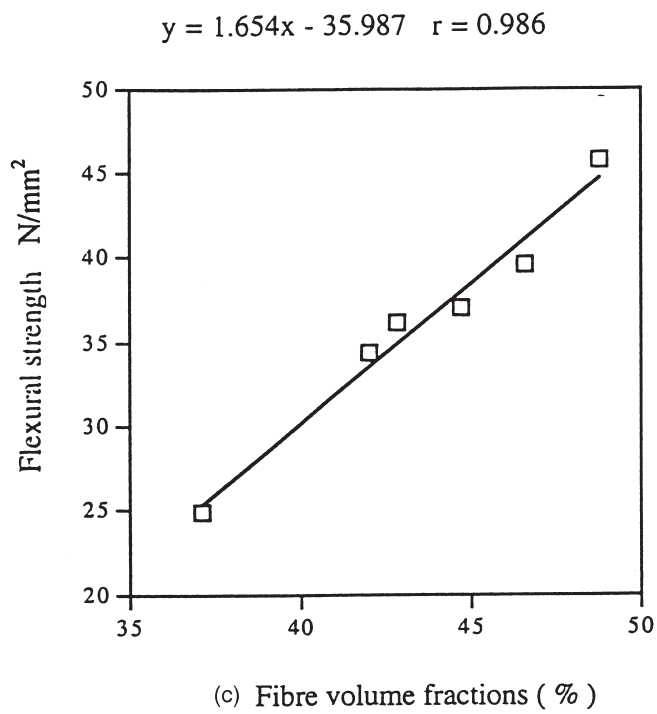


Fig. 3. (a) Tensile strength and (b) tensile modulus of untreated fabric of cotton–kapok fabric–polyester composites. (c) Flexural strength and (d) flexural modulus of composites subjected to accelerated weathering conditions.



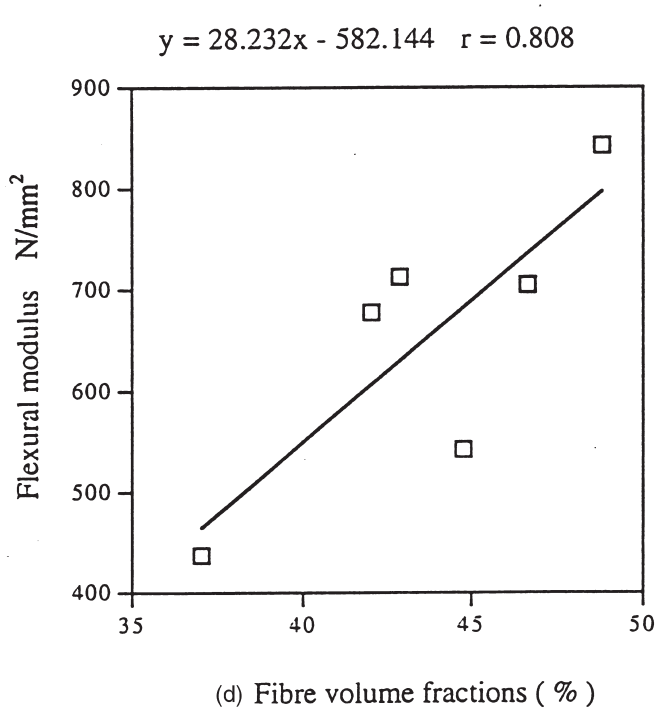
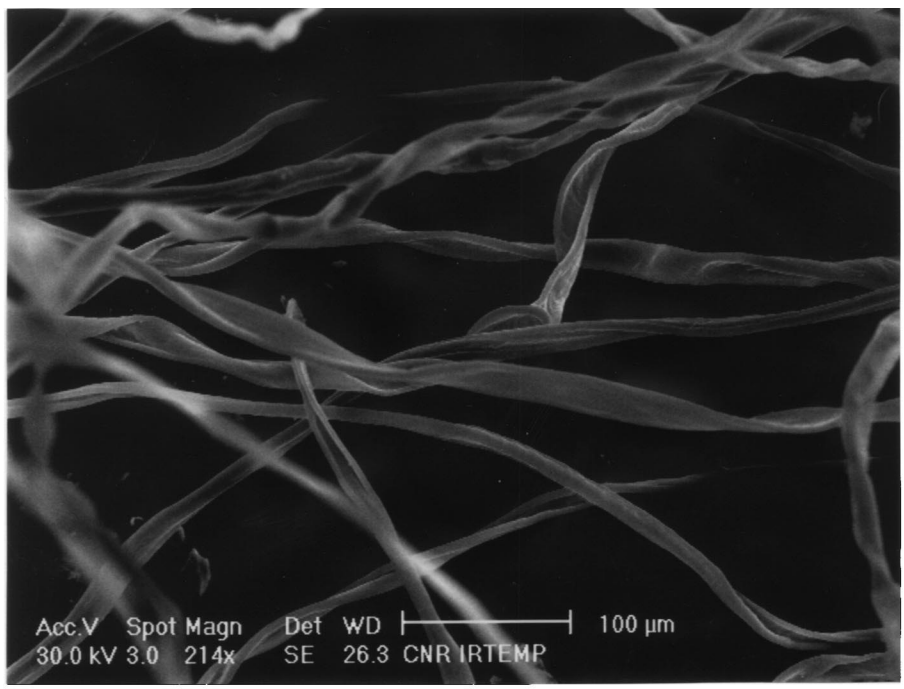
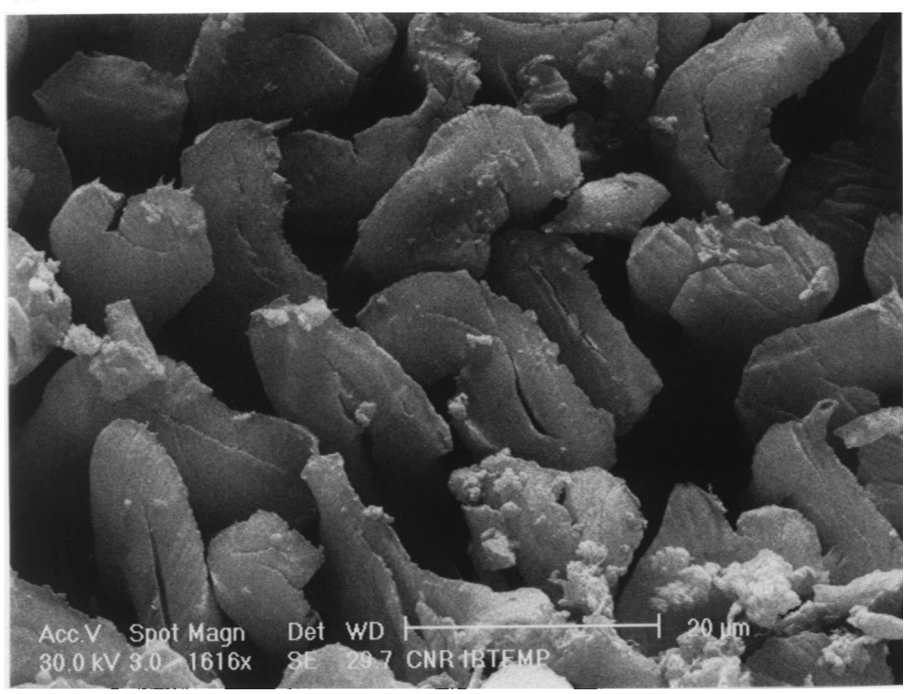


Fig. 3. Continued.

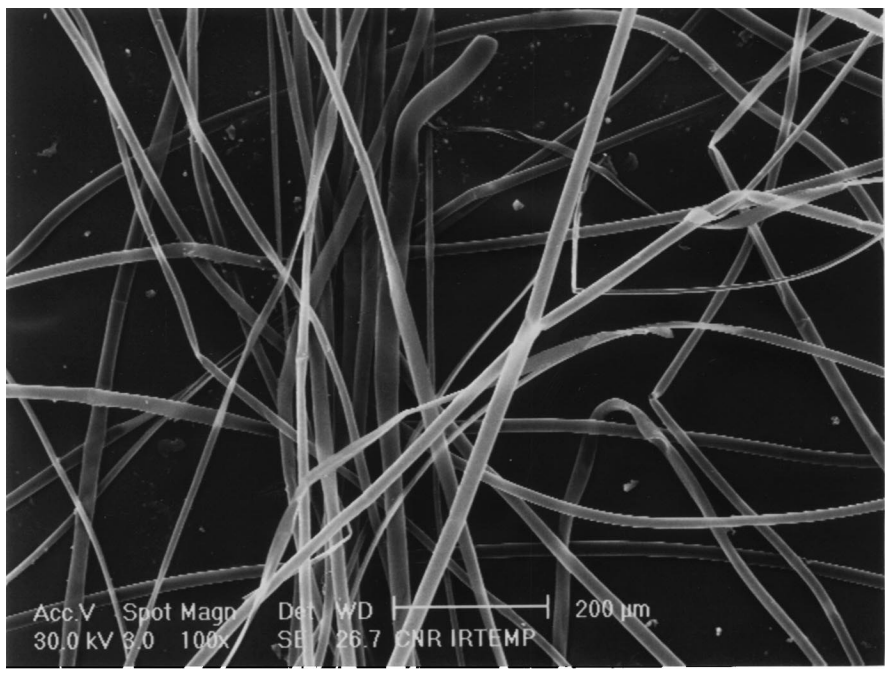


(a)

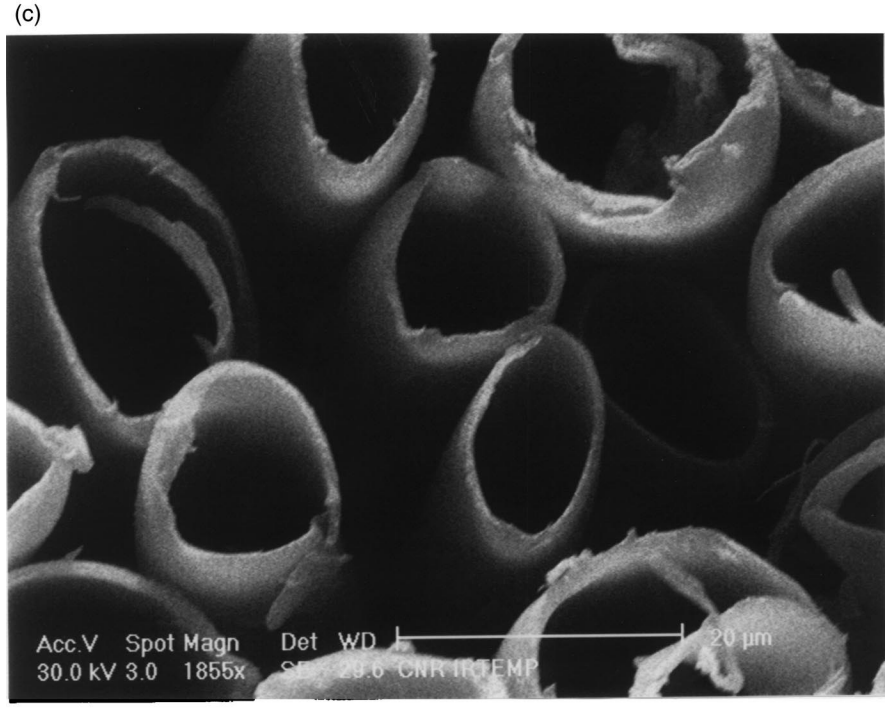


(b)

Fig. 4. SEM micrographs of (a) longitudinal view of cotton fibres, (b) cross sectional view of cotton fibres, (c) longitudinal view of kapok fibres and (d) cross sectional view of kapok fibres.

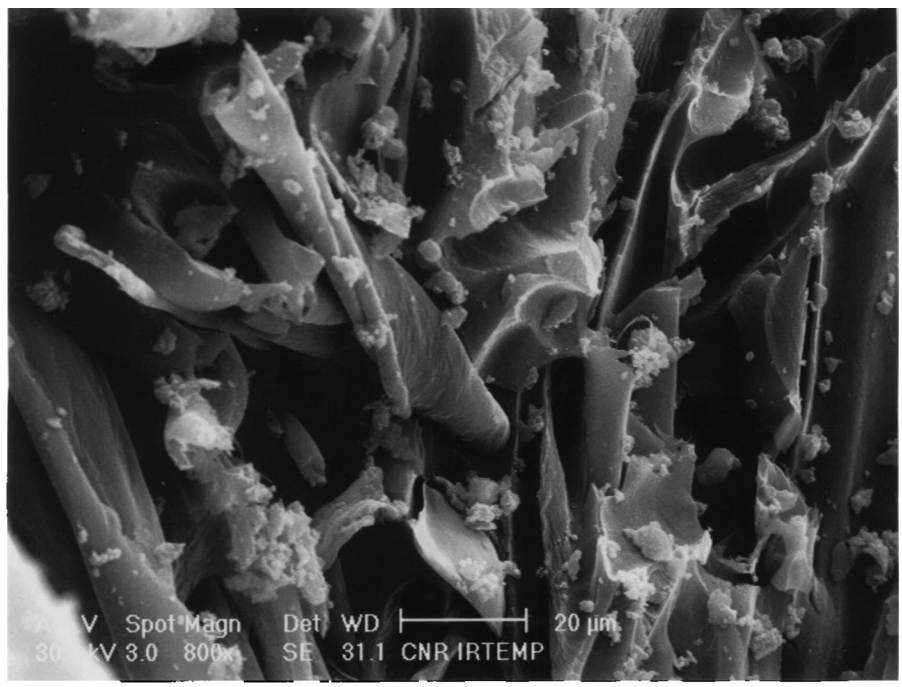


(c)

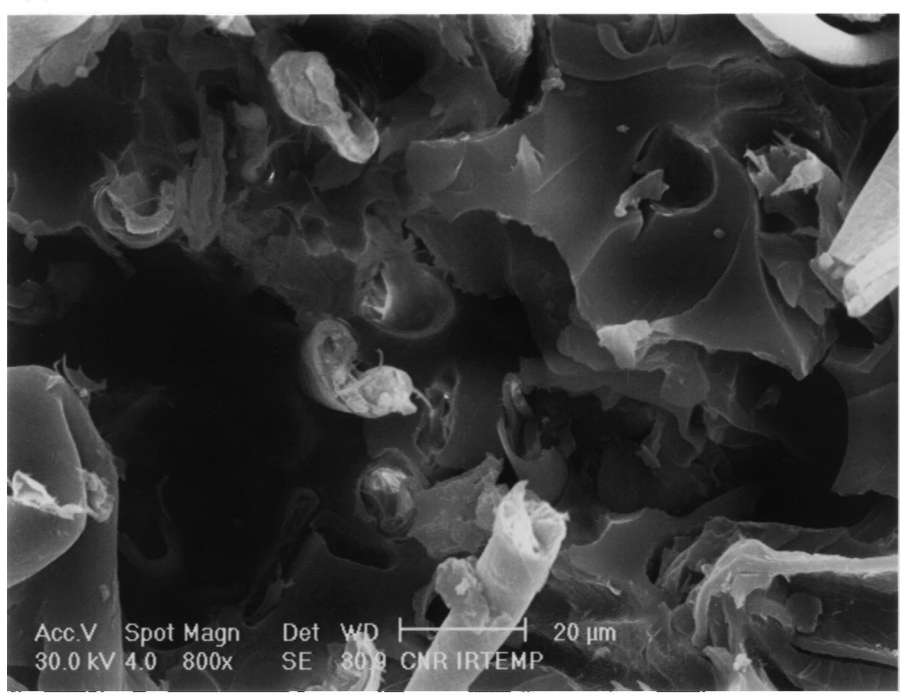


(d)

Fig. 4. Continued.



(a)



(b)

Fig. 5. SEM micrographs of the tensile fracture surface of polyester–cotton–kapok fabric composite.

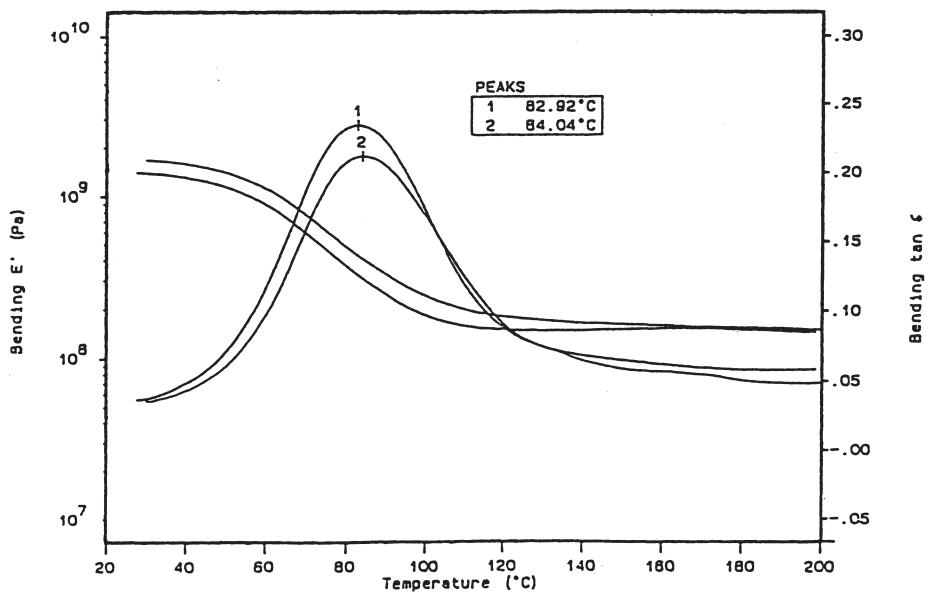


Fig. 6. DMTA thermogram of cotton–kapok fabric polyester composite (1–42.05% and 2–61.46%).

mechanical properties. However, observations on the thermogram (Fig. 8) indicate that the composite was well cured. The sample could possibly have originated either from the middle part of the specimen, samples were subjected to accelerated weather conditions or the time between composite production and the thermal calorimetry tests was long enough to allow complete cure. The presence of water in the composites tends to develop plasticity in the material, thus lowering its mechanical properties. Also, high moisture content leads to poor wetting ability with the resin and weak interfacial bonding between the fibres and the relatively hydrophobic polyester matrix [8,9].

The curve of storage modulus (E^{I}) and loss modulus (tan δ) of the treated and untreated composites as a function of temperature is given in Fig. 6. From analysis of the curves it can be deduced that the modulus E^{I} is higher at higher fibre volume fraction, which in this case appears to be the composites with the untreated fabric.

In both cases the storage modulus, E^{I}, decreases as samples go through the matrix–glass transition temperature. However, the glass transition temperature seems to be unaffected by the filler material. The slight difference in the T_{g} values is probably caused by higher fibre volume fractions and good curing and therefore less molecular segmental movements. No dynamic mechanical thermal analyses were performed on the neat matrix.

3.2. Impact strength

Fig. 9 shows the impact strength of untreated and treated fibre in cotton–kapok–polyester composites. In both cases, the impact strength decreases as the fibre volume fraction is increased. Similar observations have been reported by Berlin et al. [10], and Hancox [11] when testing the impact strength of carbon fibre reinforced composites using an Izod impact strength tester. The

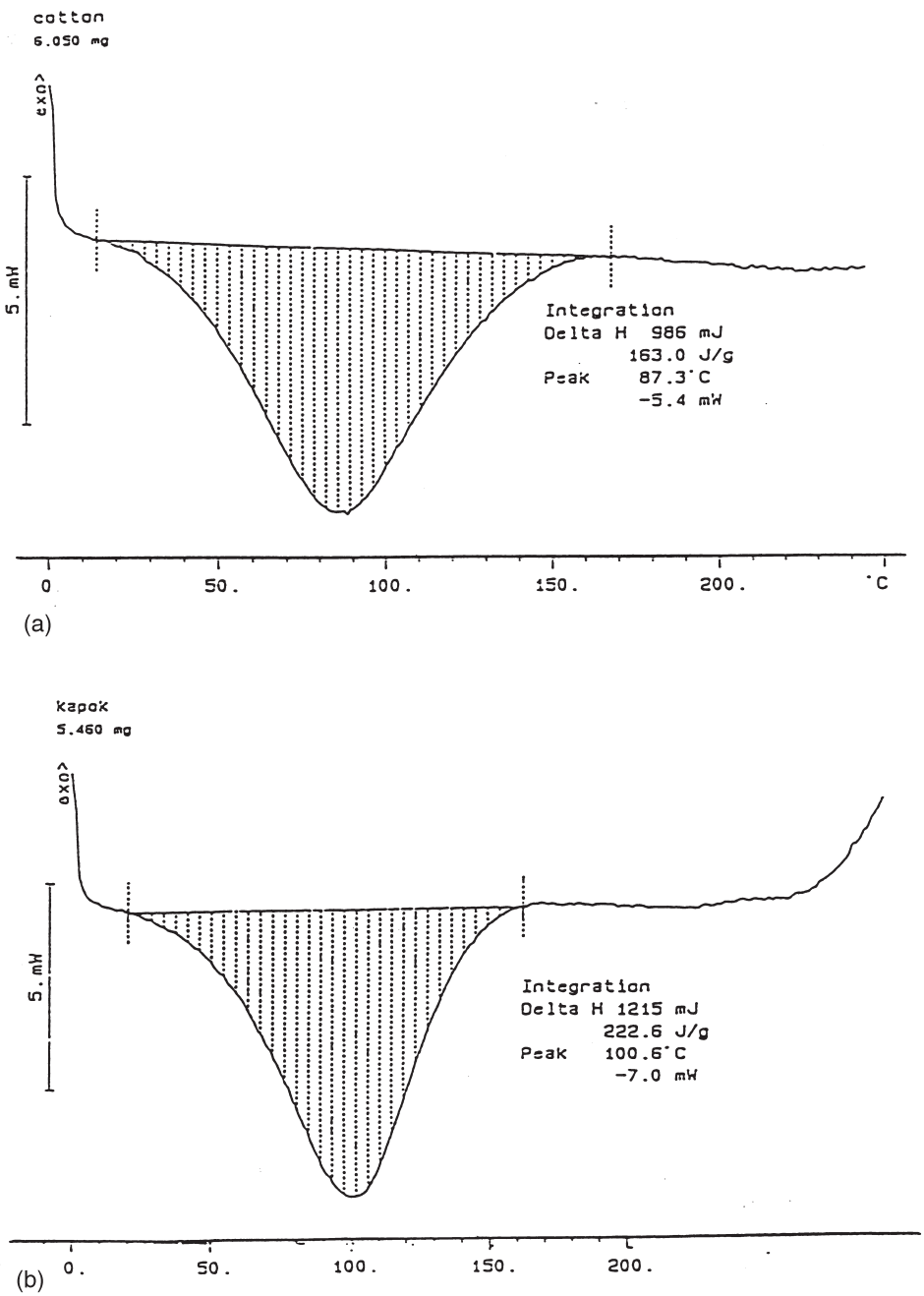


Fig. 7. DSC thermogram of (a) cotton fibre and (b) kapok fibre.

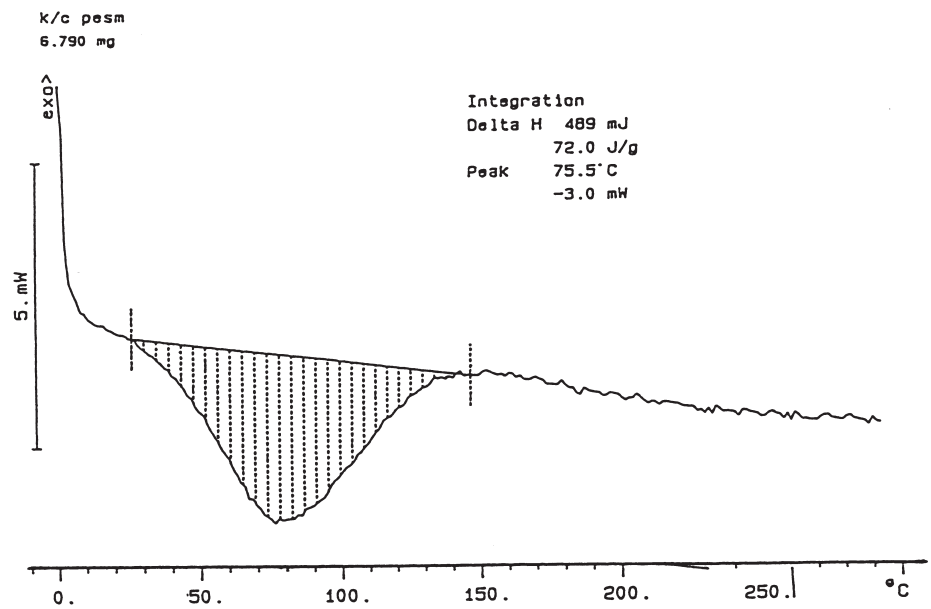


Fig. 8. DSC thermogram of cotton–kapok fabric–polyester composite.

reduction of the amount of matrix as the fibre volume fraction is increased contributes to the decrease in impact strength as the matrix is greatly responsible for the absorption of the impact energy.

3.3. Flexural strength

There was an increase in the flexural strength and modulus of the cotton–kapok–polyester composites subjected to accelerated weathering conditions as the fibre volume fraction increased (see Fig. 3c and d, and Table 5). This was possibly due to continued cross-linking of the polyester resin during the accelerated weathering process. However, this conflicts with the DSC results (Fig. 8), where the matrix appears to have been well cured, suggesting that another fibre–matrix phenomenon was responsible for the increase in the flexural properties. Incidentally, accelerated weathering did not result in uniform curing of the composite samples as elucidated by the graphic impression of the load–deflection response to bending for the middle and peripheral test specimen (Fig. 10), whereby the middle specimen required more load to break. Similar load variations were observed with samples subjected to tensile loading.

4. Conclusion

Cotton–kapok fabric–polyester composites provide a new class of materials that have demonstrated industrial potential. Increase in flexural strength and modulus as the fibre volume fraction is increased is an indication of a promising composite material in commercial use as design applications frequently involve a bending rather than tensile mode [12].

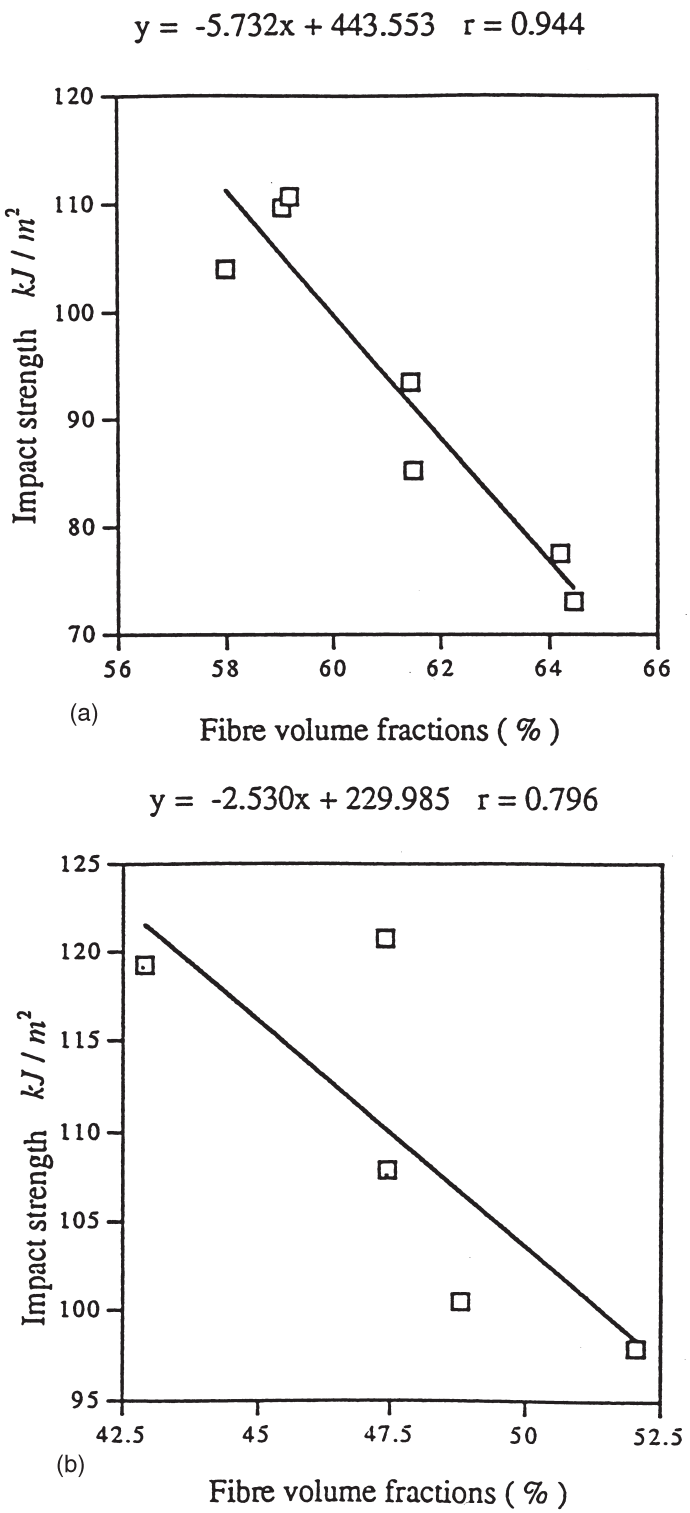


Fig. 9. Impact strength of (a) untreated and (b) treated fabric–polyester composites.

Table 5
Flexural properties of treated cotton–kapok fabric–polyester composites

Fibre volume fraction (%)	No weather treatment		Accelerating weathering	
	Flexural strength (MPa)	Flexural modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)
37.06	–	–	24.91	435.30
42.05	55.34	698.70	34.40	676.10
42.85	–	–	36.07	711.50
44.76	–	–	37.01	542.30
46.62	52.40	708.90	39.55	702.80
47.41	54.96	801.60	–	–
47.47	48.15	715.70	–	–
48.80	–	507.00	45.77	841.50
52.04	44.32	526.60	–	–

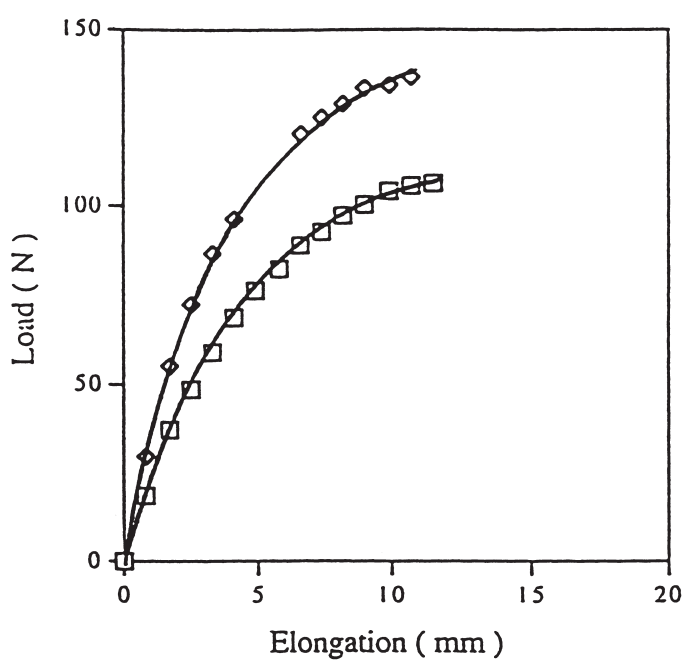


Fig. 10. Three-point bend graphs.

Moreover, it can be deduced from Table 1 that the low price of cotton–kapok fabric compared with glass fibre and the relatively good cotton–kapok fabric–polyester composite tensile and specific strength and flexural properties, imply that the new composite material may be preferred in applications such as low cost grain silos, school buildings, and housing units for low income and rural settlements.

However, the presence of free water in the cellulose cavities and water bonded by the amorphous regions has adverse effects on the mechanical properties of the composites. It is therefore important that the absorbed water is completely removed and that the hydroxyl groups on the cell wall are replaced by reactive chemicals, thus reducing the hydroscopic characteristic of the lignocellulose materials.

Extreme care must be taken when bleaching and/or mercerising cellulose with sodium hydroxide as when it is used in large quantities it tends to texturise the cellulose structure, thus affecting its mechanical properties. It is strongly recommended that the use of sodium hydroxide on plant fibres be avoided. The application of fibre volume fractions of less than 30% should be assessed for its effect on the mechanical properties of cotton–kapok fabric–polyester composites.

Accelerated weathering temperatures (~ 100°C) do not seem to have a degrading effect on the composite; perhaps a longer period of accelerated weathering will facilitate the fabric–matrix degradation. This is expected with polyester, which is known to degrade at temperatures above 200°C.

Further research is needed to develop the application of kapok fibre and blends as reinforcement for polymeric resins. Its positive results will revamp the commercial value of the crop with the added advantage for the environment, and improve rural incomes where kapok is grown.

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