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Natural fibres: can they replace glass in fibre reinforced plastics?

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Abstract

In this work, natural fibres (sisal, kenaf, hemp, jute and coir) reinforced polypropylene composites were processed by compression moulding using a film stacking method. The mechanical properties of the different natural fibre composites were tested and compared. A further comparison was made with the corresponding properties of glass mat reinforced polypropylene composites from the open literature. Kenaf, hemp and sisal composites showed comparable tensile strength and modulus results but in impact properties hemp appears to out-perform kenaf. The tensile modulus, impact strength and the ultimate tensile stress of kenaf reinforced polypropylene composites were found to increase with increasing fibre weight fraction. Coir fibre composites displayed the lowest mechanical properties, but their impact strength was higher than that of jute and kenaf composites. In most cases the specific properties of the natural fibre composites were found to compare favourably with those of glass.

Keywords: B. Mechanical properties; A. Glass fibres; Natural fibres; B. Interfacial strength

1. Introduction

In the past few decades, research and engineering interest has been shifting from monolithic materials to fibre-reinforced polymeric materials. These composite materials (notably aramid, carbon and glass fibre reinforced plastics) now dominate the aerospace, leisure, automotive, construction and sporting industries. Glass fibres are the most widely used to reinforce plastics due to their low cost (compared to aramid and carbon) and fairly good mechanical properties. However, these fibres have serious drawbacks as indicated in Table 1. The shortcomings have been highly exploited by proponents of natural fibre composites. Table 1 compares natural and glass fibres and clearly shows areas the former have distinct advantages over the latter. Carbon dioxide neutrality of natural fibres is particularly attractive. Burning of substances derived from fossil products (e.g. petroleum) releases enormous amounts of carbon dioxide into the atmosphere. This phenomenon is believed to be the root cause of the greenhouse effect and by extension the world's climatic changes [1].

Attempts have been made to use natural fibre composites in place of glass mostly in non-structural applications. So far a good number of automotive components previously made with glass fibre composites are now being manufactured using environmentally friendly composites [1,2].

Currently, plenty of research material is being generated on the potential of cellulose based fibres as reinforcement for plastics. All researchers who have worked in the area of natural fibres and their composites are agreed that these renewable (unlike traditional sources of energy, i.e., coal, oil and gas that are limited [1]), abundantly available materials have several bottlenecks: poor wettability, incompatibility with some polymeric matrices and high moisture absorption by the fibres [3].

The first and the most important problem is the fibre–matrix adhesion. The role of the matrix in a fibre reinforced composite is to transfer the load to the stiff fibres through shear stresses at the interface. This process requires a good bond between the polymeric matrix and the fibres. Poor adhesion at the interface means that the full capabilities of the composite cannot be exploited and leaves it vulnerable to environmental attacks that may weaken it, thus reducing its life span. Insufficient adhesion between hydrophobic polymers and hydrophilic fibres result in poor mechanical properties of the

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Table 1
Comparison between natural and glass fibres

	Natural fibres	Glass fibres
Density	Low	Twice that of natural fibres
Cost	Low	Low, but higher than NF
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	wide
CO_2 neutral	Yes	No
Abrasion to machines	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

natural fibre reinforced polymer composites. These properties may be improved by [4,5]: physical treatments (cold plasma treatment, corona treatment) and chemical treatment (maleic anhydride, organosilanes, isocyanates, sodium hydroxide, permanganate and peroxide).

Gassan et al. [6] improved the tensile, flexural strength and stiffness of Jute-Epoxy composites by treating the fibres with silane. Tripathy et al. [7] found that delignification by bleaching produces better interfacial bond between jute fibre and polyester matrix and hence better mechanical properties of the composites.

The absorption of steam by sisal, hemp and banana fibre /novolac resin composites was found to reduce after esterification of the –OH groups with maleic anhydride [8]. The tensile strength of the maleic anhydride treated fibre composites was found to be higher than that of untreated fibre composites.

Luo et al. [4] found an increase in the mechanical properties of "green" composites prepared from pineapple leaf fibres and poly(hydroxybutyrate-co-valerate) resin (a biodegradable polymer [9]) with the fibres in the longitudinal direction. However, the researchers report a negative effect of the fibres on the properties in the transverse direction.

Gauthier et al. [10] report that adhesion may be improved by using coupling agents like maleic anhydride to incorporate hydroxyl groups on the matrix through hydrophilization and consequently enhancing the wetting effect of the resin on the fibres. The hydroxyl groups then interact with –OH molecules on the lignocellulosic fibres via hydrogen bonding thus producing a stronger bond [5,10].

Second, the composite properties are influenced by the fibre properties. Natural fibre properties are highly variable and depends on conditions of growth. It is therefore very difficult to get the same mechanical properties after repeat testing. The fibre properties, such as dimensional instability, have been found to improve after treatment with chemicals such as maleic anhydride, acetic anhydride and silanes.

Though natural fibres' mechanical properties are much lower than those of glass fibres (Table 2 [11]), their specific properties, especially stiffness, are comparable to the stated values of glass fibres. Moreover, natural fibres are about 50% lighter than glass, and in general cheaper.

2. Experimental

2.1. Materials and methods

The kenaf and coir (coconut husk) fibres were purchased from JB fibres, UK, in loose form and the sisal from Teita Estate, Kenya. Polypropylene (Valtec HH-442 H) was supplied by Montell Polyolefins. The polypropylene used had a very high melt flow index (800 dg/min) which ensured proper wetting of the fibres. Polypropylene films were made in the laboratory from the supplied polypropylene pellets.

To prepare for composites processing, the polypropylene films were stacked between three layers of fibres spread as randomly as possible, except in the case of hemp and jute that were delivered in random mat form. Each layer of fibres was prepared by evenly spreading the fibres on a 30 cm × 30 cm wooden frame. The material was then wrapped in an aluminium foil. It was preheated in an oven at 140 °C for 20 min to reduce the moisture present and to encourage faster and uniform heating of the material. The composites were made by pressing the material between hot plates of a compression moulding press at 180 °C for 2 min at 5 bar pressure on the material. Cooling was done under the same pressure by placing the composite between the two cold plates of the press for 3 min. All the composites were processed at 40% fibre weight fraction. Kenaf fibre composites were additionally processed at 30 and 50% fibre weight fractions to investigate the effect of fibre content on the mechanical properties of the composites.

2.2. Mechanical testing

Tensile tests were performed using an Instron model 4505, in accordance with ASTM D638-77a standards. The displacement was measured with a 50 mm extensometer. The specimens were tested at a rate of 2 mm per minute. The elastic modulus, failure strain and tensile strength were calculated from the stress–strain curve. Flexural tests were performed on the same machine using the 3-point bending method as per ASTM D790-71 standard.

Impact tests were performed on an Instron charpy impact testing machine model PW5. The test method adopted was consistent to ASTM D256-78 method B. All the test specimens were un-notched. Impact loading was done with a 15 J-hammer. A total of ten samples were tested and the mean value of the absorbed energy taken. The impact strength (kJ/m^2) was calculated by

Table 2
Properties of natural fibres in relation to those of E-glass [11]

Properties	Fibres							
	E-glass	Hemp	Jute	Ramie	Coir	Sisal	Flax	Cotton
Density g/cm^3	2.55	1.48	1.46	1.5	1.25	1.33	1.4	1.51
Tensile strength (MPa)	2400	550–900	400–800	500	220	600–700	800–1500	400
E-Modulus (GPa)	73	70	10–30	44	6	38	60–80	12
Specific (E/d)	29	47	7–21	29	5	29	26–46	8
Elongation at failure (%)	3	1.6	1.8	2	15–25	2–3	1.2–1.6	3–10
Moisture absorption (%)	–	8	12	12–17	10	11	7	8–25

dividing the recorded absorbed impact energy with the cross-sectional area of the specimens.

3. Results and discussion

3.1. Tensile and flexural strengths

Fig. 1 shows the measured tensile strengths of the fibre/polypropylene composites. Hemp fibre composites displayed the highest (52 MPa) tensile strength while coir showed the lowest (about 10 MPa). The strengths of the kenaf, sisal and jute composites were approximately 30 MPa. At similar fibre volume fraction (about 30%), glass mat polypropylene composites showed a tensile strength of about 32 MPa [12], though higher values (88 MPa) at 22% fibre volume fraction have been reported (Table 3) [13].

The ultimate stress of any composite depends on several factors, chief among them being the properties of the reinforcement and matrix and the fibre volume fraction [14]. The fibre mechanical properties, such as initial modulus and ultimate tensile stress, are related not only to the chemical composition of the fibre but also to its internal structure. The low strength of coir compared to other natural fibres is due to its low cellulose content and reasonably high microfibrillar angle (i.e. angle between the fibre axis and the fibril of the fibre) [15].

The effect of the fibre weight fraction on the tensile strength of the composites can be seen in Fig. 2 [16]. As would be expected, an increase in the fibre weight fraction produces a corresponding increase in the tensile strength. A similarity between the flexural strength results of kenaf, coir and sisal composites can be observed in Fig. 3. Hemp composites showed the best flexural strength properties (54 MPa) and compares well

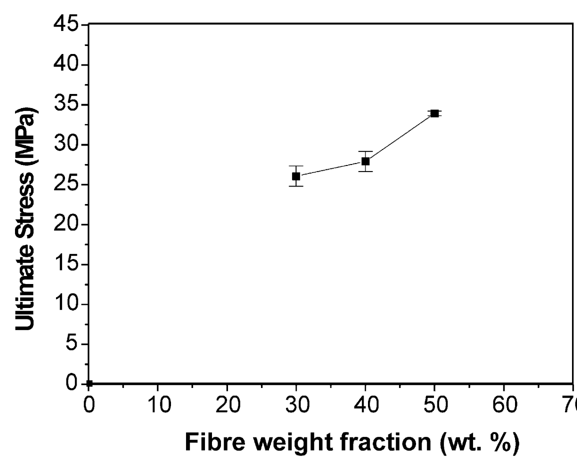

Fig. 2. Effect of fibre weight fraction on the tensile strength of KFRP composites [16].

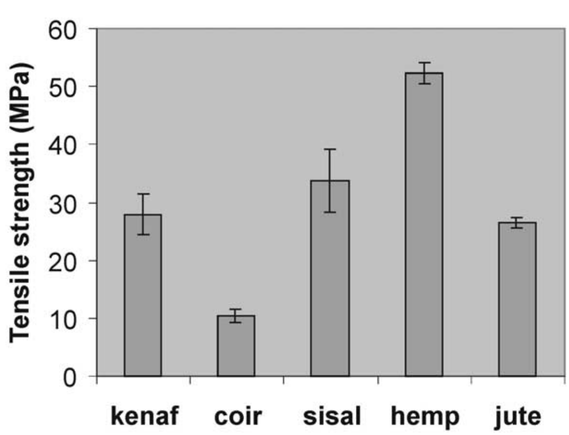

Fig. 1. Tensile strengths of fibre reinforced polypropylene composites.

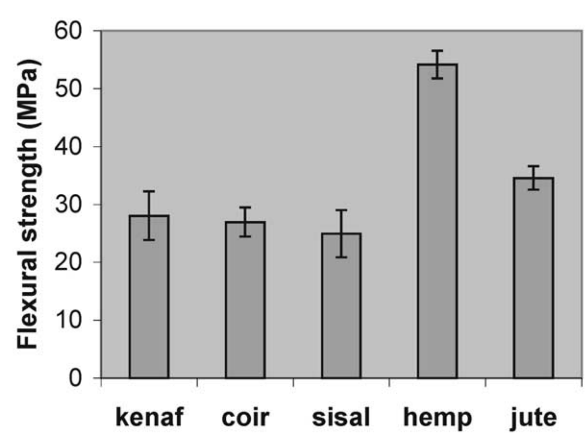

Fig. 3. Flexural strengths of fibre reinforced polypropylene composites.

with glass mat composites (60 MPa, [12]). However, the specific flexural strength (flexural strength divided by density) of hemp composites (36.5) was higher than that for glass mat composites (about 24).

3.2. Tensile and flexural moduli

Fig. 4 shows the measured tensile moduli of the natural fibre composites. The tensile modulus of the coir composites was very low (1.3 GPa) in contrast to hemp and kenaf composites which registered about 6.8 GPa, similar to glass mat composites (6.2 GPa) [13]. However, the specific moduli of hemp and kenaf composites was about 4.6, higher than the corresponding result (2.5) for glass mat composites. The relationship between tensile modulus of the kenaf composites with fibre weight fraction is demonstrated in Fig. 5. The results show an increase in the tensile modulus with increasing fibre weight fraction.

The flexural modulus results (Fig. 6) were comparatively lower than the corresponding tensile modulus ones. These two loading conditions exhibit different kinds of stresses in the specimen under test. Whereas the stresses in a tensile test are uniform throughout the specimen cross-section, the stresses in flexure vary from zero in the middle to maximum in the top and bottom surfaces [17].

The simple tension and flexure moduli measurements can hence differ significantly when the material is inhomogeneous and anisotropic. A flexural test is highly influenced by the properties of the specimen closest to the top and bottom surfaces, whereas a simple tension test reflects the average property through the thickness [17]. In a flexural test, the total bending deflection is a combination of a bending deflection and a shear deflection as shown in Eq. (1):

$$\delta_{\text{flex}} = \frac{Pl^3}{48EI} + \frac{Pl}{4G} \quad (1)$$

The shear contribution to the bending deflection is normally neglected [18] in the determination of the flexural modulus, resulting in a lower value than the tensile modulus.

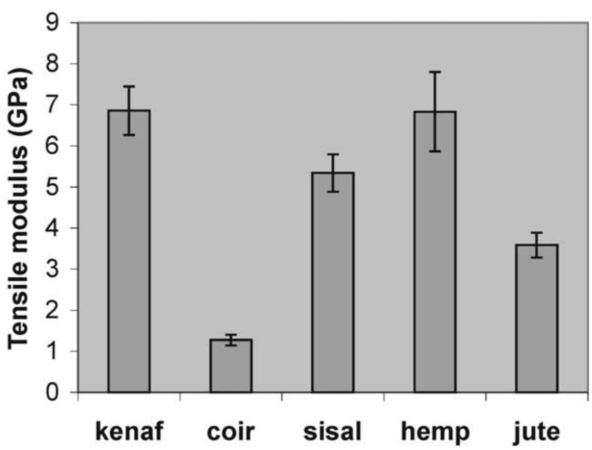

Fig. 4. Tensile modulus of fibre reinforced polypropylene composites.

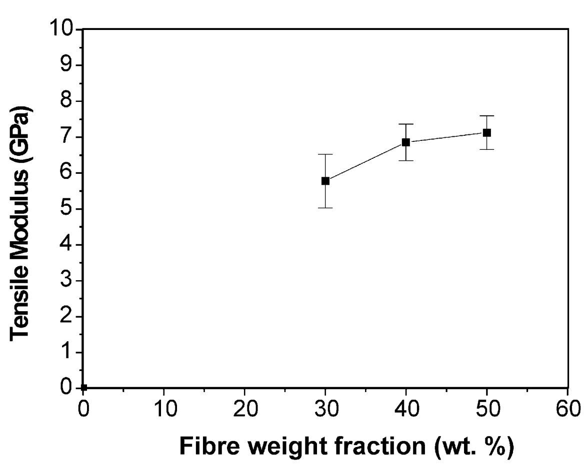

Fig. 5. Effect of fibre weight fraction on the tensile modulus of KFRP composites.

3.3. Charpy impact

Fig. 7 represents the charpy impact strength (energy absorbed/cross-sectional area) results of the composites. The natural fibre composites tested displayed low impact strengths (only hemp and sisal registered >25 kJ/m^2) compared to glass mat composites (54 kJ/m^2 [19]). However, in terms of specific impact strength

Table 3
Mechanical properties of glass fibre mat/polypropylene composites [12,13,19]

Tensile strength (Mpa)	E-Modulus (Gpa)	Flexural modulus (Gpa)	Flexural strength (Gpa)	Charpy impact strength (kJ/m^2)
88.6 ±7.8	6.2 ±0.14	4.38 ±0.38	60.0 ±5.5	54.12 ±10.40

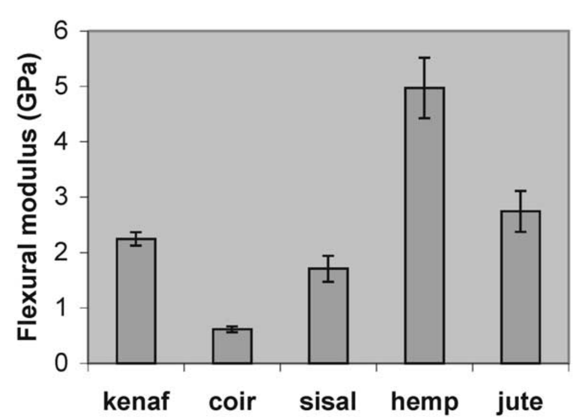

Fig. 6. Flexural modulus of fibre reinforced polypropylene composites.

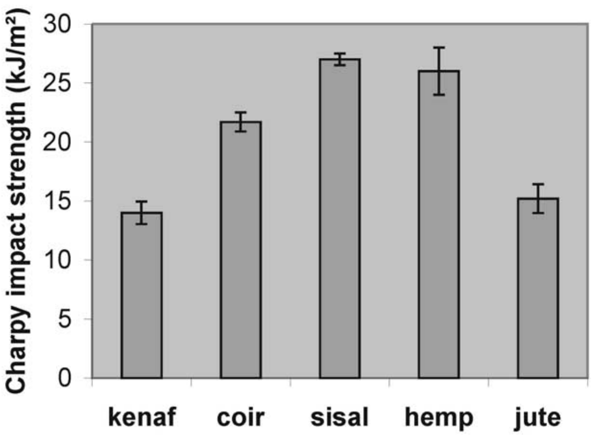

Fig. 7. Charpy impact strengths of fibre reinforced polypropylene composites.

properties (impact strength divided by density), natural fibre composites appear to compare well with glass mat composites. In spite of their low tensile and flexural properties, coir fibre composites demonstrate better impact properties than jute and kenaf composites. This is probably due to the high strain to failure (15–40% [20]) of the coir fibres. It is well known that the impact response of fibre composites is highly influenced by the interfacial bond strength, the matrix and fibre properties. Impact energy is dissipated by debonding, fibre and/or matrix fracture and fibre pull out. Fibre fracture dissipates less energy compared to fibre pull out. The former is common in composites with strong interfacial bond while the occurrence of the latter is a sign of a weak bond.

The effect of fibre weight fraction on the impact strength is indicated in Fig. 8. A moderate increase in impact strength is seen between 30 and 40% fibre weight fraction and a sharp increase from 40 to 50% fibre weight fraction. A larger serrated fracture surface was noted at 50% fibre weight fraction compared to the case at 30% fibre weight fraction of the composites, where the fracture surface was more or less flat. The serrated failure mode absorbs more energy than a sharp fracture. The failure mechanism was mainly by fibre pull out due to the weak interfacial strength between the coir fibres and the matrix. A good bond due to, for example, chemical treatments has been reported to reduce the impact strength [16,21,22].

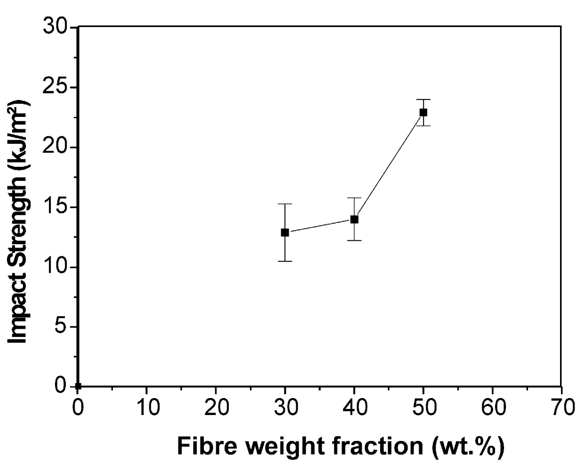

Fig. 8. Charpy impact strength of kenaf composites as a function of fibre weight fraction [16].

4. Conclusions

The mechanical properties of sisal, hemp, coir, kenaf and jute reinforced polypropylene composites have been investigated. The tensile strength and modulus increases with increasing fibre volume fraction. Among all the fibre composites tested, coir reinforced polypropylene composites registered the lowest mechanical properties whereas hemp composites showed the highest. However, coir composites displayed higher impact strength than jute and kenaf composites.

The mechanical properties of the natural fibre composites tested were found to compare favourably with the corresponding properties of glass mat polypropylene composites. The specific properties of the natural fibre composites were in some cases better than those of glass. This suggests that natural fibre composites have a potential to replace glass in many applications that do not require very high load bearing capabilities.

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