An Investigation of the Mechanical Properties of Sisal Fibre, Loofah Matt and Their Composites with Epoxy Resin

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ABSTRACT

The mechanical properties of sisal fibre, loofah matt, epoxy resin and their resulting composites were determined experimentally. The influence of volume fraction of the reinforcing fibres and matt on the mechanical properties of the composites was investigated. It was found that loofah matt reduces the mechanical properties of epoxy resin and as such loofah is not a suitable reinforcing material. Sisal fibre on the other hand does improve the mechanical properties of epoxy resin; the improvement being dependent on fibre volume fraction. This makes fibre reinforced composites useful practical materials. Based on the "effective reinforcement" and the advent of multiple matrix fracture, design limitations for the composites were set.

KEY WORDS

Sisal, loofah matt, epoxy resin, composites

1.0 INTRODUCTION

Sisal and loofah are two amongst a number of natural fibres that are found in Kenya. While sisal is cultivated commercially in large scale plantations loofah grows in the wild. Traditionally sisal is used in the making of rope, sacks, carpets, bags and cushioning upholstery, while loofah matt is used as washing sponges, pillowing material, filter material for oil presses and for scouring and cleaning machinery.

The leaves of sisal plant are decorticated to give sisal fibres of 1.2-1.5 metres in length, with diameters that decrease gradually from the base to the tip (Mutuli, 1979). The sisal fibre is composed of many hexagonal shaped cells, with a central cavity (lumen) of 2-15 μm in diameter and walls of 5 μm in thickness. The cell wall consist of crystallinic cellulose in the form of microfibrillar micelles of 0.60 μm thickness running on a spiral along the axial direction of the cell together with amorphous lignin. It is this cellulosic material that mainly gives the fibre strength (Bisanda, 1988; Lock, 1969; Mutuli, 1979).

Sisal fibre exhibits a linear stress versus strain curve, with brittle failure at fracture that is accompanied by longitudinal tearing (Mutuli, 1979). Bisanda (1988) observes that the initial stage in the failure of sisal fibre, is the separation of cells within the strands along the cellular boundaries. This is followed by shearing of the microfibrillar bands in the secondary layers of the cell walls. The strands eventually collapse to complete the fracture of the fibre.

Loofah matt is extracted from the mature fruit of the loofah plant. The mature fruit measures about 30-50 cm in length and 8-12 cm in diameter (Yamaguchi, 1983; Tindall, 1983; Hutchinson, 1964; Janick, 1986, Lind and Tallantire, 1975). The top tissue of the mature loofah fruit is removed to reveal a fibrous matrix of surface layers which occur in two mutually orthogonal directions, namely the axial or longitudinal direction and the circumferential or transverse direction. These surface layers are joined to the central fibrous core by a series of fibrous radial ribs.

Epoxy resins or ethoxylene resins are formed by three dimensional cross-linking of primary epoxy groups and hardener groups. Their composites with aramid fibre, carbon fibre and glass fibre find wide application as structural composites (Phillips, 1988; Arnold, 1969; Hull, 1990).

2.0 THEORY

Mutuli (1979) noted that the cross-sectional area of sisal fibre is very irregular and that it varies widely between individual fibres. He obtained an average cross-sectional area of 4.95 x 10^{-8} m^2, with a standard of 1.38 x 10^{-8} m^2, from a total of 80 specimens. In the present work, an average value of 7.44 x 10^{-8} m^2, with a standard deviation of 4.71 x 10^{-8} m^2 was obtained, from a total of 30 specimens. Bisanda (1988) observed that the experimental values of ultimate tensile strength (UTS) that are normally based on the average cross-sectional area, which is determined for the unloaded fibre, are in error. He noted that this was due to contraction of the cross-sectional area of the fibre, at which fracture occurs, during the process of failure.

The strength of sisal fibre varies as a function of the moisture content, testing speed, the position along the fibre from which the sisal test piece has been obtained and the method that is used to extract the fibre from the leaf (Bisanda, 1988; Mutuli, 1979). Mutuli (1979) obtained average values of UTS ranging from 336 with a standard deviation, s, equal to 124, 313 and 325 Mpa. for dry, moist and wet sisal fibres respectively, for crosshead speeds of 20 mm/min. The corresponding values for the Elastic Modulus were 15.46 (s = 5.86), 14.07 (s = 3.65) and 7.70 (s = 2.33) Gpa respectively. Bisanda (1988) obtained average values of UTS for the whole fibre of 643.9 (0.5 mm/min), 684.1 (5 mm/min) and 767.3 (50 mm/min) and 442.8 (0.5 mm/min), 463.9 (5 mm/min) and 448.5 (50 mm/min) Mpa. for the lowest 150 mm of the fibre. The equivalent values of Elastic Moduli were 15.42, 20.61 and 19.85 and 4.10, 5.31 Ind 3.51 Gpa respectively. Filho et al. (1990) obtained values of sisal fibre strength ranging between 470 - 535 Mpa, while Savastanojr (1990) obtained values of 458 Mpa and 15.2 Gpa for the fibre strength and Elastic Modulus respectively.

To determine the fibre volume fraction of a composite accurately, the void content must be known. Where accurate measurement of the void content is not possible, its minimum value can be estimated from the following computations after Maringa (1993):-

$$M_T = M_m + M_f \qquad \ldots\ldots\ldots\ldots \quad 1$$

where M_T, M_m and M_f denote the masses of the composite, reinforcing fibres and base matrix respectively. It can further be shown that the density ρ_m of the epoxy resin matrix is given by:

$$\rho_m = (M_T - M_f)/(\upsilon_T - \upsilon_o - \upsilon_f) \qquad \ldots\ldots\ldots\ldots \quad 2$$

where υ_T, υ_o and υ_f are the volume fractions of the composites, voids and fibre respectively. From equation (2) above, one can write

$$\rho_{mn} > (Mt - Mf)/(U_T - M_f/P_f) \qquad \ldots\ldots\ldots\ldots \quad 3$$

where ρ_{mn} stands for the minimum density of the epoxy resin matrix. This is the minimum density of the matrix that will give a void content of zero in equation (2) above. The most accurate value of the computed matrix minimum density for a series of test pieces, will be the one that gives a void volume fraction that is greater than or equal to zero for all the test pieces against which equation (3) above is applied. Equations (1), (2) and (3) above, are applied in determining the fibre volume fraction and the void content of the composite specimens that are used in the present work.

The reinforcing effect of loofah matt on epoxy resin will depend on the relative strength and strain to fracture of the two materials. The interfacial bond strength will also have a contribution. Therefore evaluation of the load carrying capacity of loofah matt and epoxy resin test pieces of equal cross-sectional area, will give a good measure of this effect. The following four possibilities arise in the theoretical analysis of the failure mode of loofah/epoxy composites:

i) Where the interfacial bond strength is insignificant, while the stress and strain to fracture of the loofah matt are more than the equivalent values for epoxy resin.

ii) Where the interfacial bond strength is insignificant, while the stress and strain to fracture of the loofah matt are less than the equivalent values for epoxy resin.

iii) Where the interfacial bond strength is significant while the stress and strain of the loofah matt are more than the equivalent values for epoxy resin.

iv) Where the interfacial bond strength is significant, while the stress and strain to fracture of the loofah matt are less that the equivalent values for epoxy resin.

The prevailing alternative can be identified by observing the behaviour of the composite as it is loaded to failure [Maringa (1993)].

The dependence of the mechanical properties of fibre reinforced composites on the fibre content can be approximated by constant gradient theoretical curves or by varying gradient Rule Of Mixtures (R.O.M.) curves (Holister and Thomas, 1966; Hull, 1990; Flinn and Trojan, 1990; Maringa, 1993). Depending on which one of these two approaches is adopted, the resulting stress versus strain curves are either single stage or two stage respectively.

The R.O.M. is based on a number of assumptions namely:

i) That both the matrix and the fibre behave elastically.

ii) That the bond between the matrix and the fibre is perfect, thus implying the absence of any strain discontinuity across the fibre/matrix interface.

iii) That the properties of the matrix do not vary with the distance away from the interface.

iv) That the fibres are arranged in regular repeating arrays (Hull, 1990).

The rule of mixture states that:

$$P_c = P_f\upsilon_f + P_m\upsilon_m \qquad \ldots\ldots\ldots\ldots \quad 4$$

where P_c, P_f and P_m stand for some mechanical parameter of the composite, reinforcing fibre and base matrix respectively.

The curves that are based on the R.O.M. are more accurate in that they identify both the minimum and critical fibre volume fractions, neither of which are identified by the curves that are based on the theoretical equations. The minimum fibre volume fraction is defined as the percentage of reinforcing fibre at which some mechanical property of the composite is a minimum. The critical fibre volume fraction is defined as the percentage of reinforcing fibre above which some mechanical property of the composite is more than that of the pure epoxy resin. Thus the critical fibre volume fraction is the minimum value that must be satisfied for "effective reinforcement" to be realised.

Fibre reinforced composites exhibit the phenomena of multiple fibre fracture or multiple matrix fracture under uniaxial tensile loading depending on whether the percent elongation of the reinforcing fibre is less than or greater than the percent elongation of the base matrix. For brittle fibres in ductile matrices, multiple fibre fracture will occur for all fibre volume fractions below a certain volume fraction of fibre. For ductile fibres in brittle matrices, multiple matrix fracture will occur for all fibre volume fractions above a certain volume fraction of fibre, (Aveston, Cooper and Kelly, 1971). The phenomena of multiple fracture introduces yet another stage in the stress versus strain curves of fibre reinforced composites. Therefore design specifications for liquid containers that are made of fibre reinforced composite materials, must take due account of the possible occurrence of this phenomena.

3.0 TESTING PROCEDURE

Sisal fibres of grade "U.G." from Taita Sisal Estate in Kenya, were randomly selected from a bulk of fibres, from which test pieces were cut from the butt-end, middle and apex portions of the fibre. Thirty test pieces each of 100 mm length were then selected randomly from among these. The fibres were weighed and the diameters of the heaviest, median and lightest fibres were determined at three different cross-sections, using a magnifying projector. The average diameter was used to determine the strength of the fibre. The fibres were tested in uniaxial tension according to Kenya Standard (KS) 08-268: 1983, which is similar to International Organization for Standardization (ISO) 2062. A crosshead testing speed of 10 mm/min was used for all sisal fibres.

In determining strength of sisal fibre, two different approaches are used. In one approach, the cross-sectional area of sisal fibre is determined using either a photographic microscope in conjunction with a planimeter or a magnifying projector, while in the other approach the cross-sectional area is determined by dividing the weight of the fibre with the fibre density. The latter method will give better estimates of the average cross-sectional area. Though both of these two methods give acceptable values of the average cross-sectional of sisal fibre, they both suffer limitations as is highlighted in the first paragraph of section 2.0.

By separating the central core and the ribs of the loofah matt, two sets of specimens of loofah were prepared for testing. The first set had its loading direction coincident with the orientation of the longitudinal fibres, while the other set had its loading direction coincident with the orientation of the transverse fibres. The dimensions for the two sets of test pieces were 200 mm long x 55 mm wide and 155 mm long x 50 mm. wide respectively. The test pieces were tested to determine the breaking load under uniaxial tension according to KS 08 -119: 1981, which is similar to ISO 5081. A crosshead testing speed of 10 mm/min was used in testing the loofah matt.

A thermosetting araldite GY257 and hardener HY850, in weight proportions of 5:3 respectively were used to produce the epoxy resin. The densities of both the araldite and the hardener at 25°C are given by the manufacturer as 1150 kg/m^3 and 1590 kg/m^3 respectively. Some of the epoxy resin was reinforced with sisal fibre and some with loofah matt to produce appropriate composite test pieces. The epoxy resin and composite test pieces were tested in uniaxial tension according to method 370E of BS 2782 part 3.

Inorder to produce the composite specimens, a thin layer of epoxy resin was first poured into the molding box. Following onto this a layer of fibre or matt, depending on the reinforcing material, was hand laid onto the liquid epoxy resin to completely cover it. The layer of fibre or matt was tapped lightly till it was thoroughly soaked with epoxy resin. After this another thin layer of epoxy resin was applied on top of the fibre or matt. This process was repeated until the mold box was filled. In laying the fibre, efforts were made to straighten them as much as was physically possible. The composite was then allowed time to breath in order to reduce the amount of included air, after which the mold box cover was placed on top of the molding box. This was then left to cure for twenty four hours. The type of araldite laminating resin that was used in the present work did not require either oven curing or postcuring, in accordance with the manufacturers specifications.

The sisal/epoxy composite and pure epoxy test pieces were 170 mm long x 25 mm wide x 5 mm thick. The elongation rate in the pure epoxy and sisal/epoxy composite test pieces varied from 1.35-1.5 mm/min before the occurrence of multiple matrix fracture, to 1.9 mm/min at low loads and 2.5 mm/min at high loads during multiple matrix fracture.

4.0 RESULTS

The minimum densities of epoxy resin and loofah matt were determined as 1299 kg/m^3 and 405 kg/m^3 respectively. The minimum density of loofah matt is the value that will give a void content of zero for the test piece with the lowest quantity of voids, based on the above value of the minimum density of epoxy resin.

Table 1 shows the relationship between the physical characteristics and the mechanical properties of sisal fibre, for the range of specimens that were tested.

The average values of percent elongation strength and Elastic Modulus for sisal fibre are given at Table 2, for the range of specimens that were tested.

The load versus elongation curves for loofah matt were found to be serrated during both the increase and decrease of load. The longitudinal test pieces necked at many positions simultaneously, with eventual separation occurring at one of the necked positions. Failure occurred by the initial breakage of the longitudinal fibres. The transverse fibres then realigned towards the longitudinal direction before eventually breaking.

The effect of loofah matt volume fraction on the strength and Elastic Modulus of loofah/epoxy composites is shown in figures 1 and 2 respectively. Figures 3 and 4 show the effect of sisal fibre volume fraction on similar mechanical properties for sisal/epoxy composites respectively.

Different values that were obtained by other researchers have been included in Table 2 for comparison purposes.

The mechanical properties of loofah matt are given in Tables 3 and 4.

Table 1. Statistical relationship between the physical characteristics and the mechanical properties of sisal fibre - average values

Parameter	Average	s	a	b	r
Fibre length (mm)	216	10	208	531	0.11
Fibre weight (g)	0.0134	0.0020	-	-	
Fibre texture no. (g/km)	62.10	9.40	2.01	4494.58	0.95
Strain x 10^{-2}	2.60	0.32	2.05	40.71	0.25
Breaking load (N)	20.23	6.18	17.02	2779.31	0.90
Breaking load (g)	2023	618	1702	277931	0.90
Breaking length (km)	32.09	5.50	5.71	1968.44	0.72
Breaking strength (MN/m^2)	275.77	90.96	249.52	39201.08	0.87
Elastic Modulus (GN/m^2)	10.55	3.13	-7.93	1379.12	0.89

Table 2. Statistical mechanical properties of sisal fibre (average values)

Parameter	Present results	Mutuli (1979)	Nutman*	Nutman (modified results)*
Breaking strength (MN/m^2)	276 (s = 91)	347 (s = 118)	557 ± 34	279 ± 17
Elastic Modulus (GN/m^2)	10.55 (s=3.13)	14.26 (s = 3.14)	26.47 ± 0.057	13.28 ± 0.029
% Elongation	2.6 (s = 0.32)	4.0		

*Values after Nutman as reported by Lock (1969).

Table 3. The statistical mechanical properties of loofah matt in the longitudinal direction average values

Parameter	Average	s	a	b	r
Specimen weight (g)	2.9434	0.9398			
Specimen equivalent tex. no. (g/km)	14718	4699	0.51	5000	1.00
Breaking load (N)	147.40	125.42	-122.0	-91.81	0.70
Breaking load (g)	14740	12542	-12222	-9181	0.70
Breaking length (km)	0.93	0.51	0.18	0.26	0.48

(Specimen length = 200 mm   Specimen area = 0.011 m^2)

Table 4. Statistical mechanical properties of loofah fibre in the transverse direction - average values

Parameter	Average	s	a	b	r
Specimen weight (g)	2.0912	0.4109	-		
Specimen equivalent tex. no. (g/km)	13491	2651	-0.44	6452	1.00
Breaking load (N)	99.00	17.40	58.64	19.30	0.46
Breaking load (g)	9900	1740	5864	1930	0.46
Breaking length (km)	0.75	0.16	1.16	-0.20	-0.52

(Specimen length = 155 mm   Specimen area = 0.078 m^2)

5.0 Discussion

The density of the epoxy resin that has been used in the present work, assuming no chemical reaction, would be 1283 kg/m^3. However, epoxy resins are formed in a chemical process, which involves cross-linking of atomic bonds. This process gives rise to small contractions in the order of 1%. Therefore the figure of epoxy resin minimum density of 1299kg/m^3 that has been obtained in the present work is a good estimate of the correct value.

The data in Tables 3 and 4 indicate that loofah fibre is stronger in the longitudinal direction than in the transverse direction. The tables also show that the linear regression correlation coefficient for the weight against the breaking length of loofah matt is low. The correlation coefficient is positive in the longitudinal direction and negative in the transverse direction. These two factors imply that the increase in weight of loofah matt pieces of the same dimensions, is mainly due to a weight increase of the longitudinal fibres.

Bisanda (1988) observed that the experimentally determined load versus elongation curves for sisal fibre exhibits a drop in gradient just before fracture. This behaviour he noted, precluded failure of sisal fibre by instantaneous fracture. Though the gradient of the load versus percent elongation curve did vary slightly, the Elastic Modulus of the sisal fibre test pieces was determined by assuming a constant averaged curve gradient. As was the case in the results that were obtained by Mutuli (1979), the present results did not show the expected final stage plastic formation.

The value of the breaking length of sisal fibre that was obtained in the present work using 30 fibres per test was 32.09 km, s - 5.50 km. This compares favourably with values that were determined by Nutman as reported by Lock (1969) for East African sisal (31-48, average 42) km. Nutman used a data base of 1000 fibres per test and assumed that the density of sisal fibre was equal to the density of cellulose, which is equal to 1500 kg/m^3. By using the correct value of 750 kg/m^3, for the density of sisal fibre, the values in the third row of Table 2 change to the values that are given in the fourth row of the same table. The breaking length of sisal fibre refers to the continuous length of fibre that will break on its own weight. The choice between one set of results and the other in Table 2 can only be based on the size of the data base, assuming the same level of accuracy. In this respect the values after Mutuli (1979) will be adopted here for use in evaluating the reinforcing effects of sisal fibre on epoxy resin, noting that the same grade of sisal fibre from the same estate was used in his work and in the present work. The density of sisal fibre is taken here as 750 kg/m^3 based on the work of Digby and Smith as reported by Mutuli (1979).

The addition of reinforcing fibres or matt on a matrix affects the void content by way of air entrapment on the one hand and the displacement and bursting of air bubbles on the other hand. The results obtained in the present work show that the latter two effects have a greater significance than the first effect.

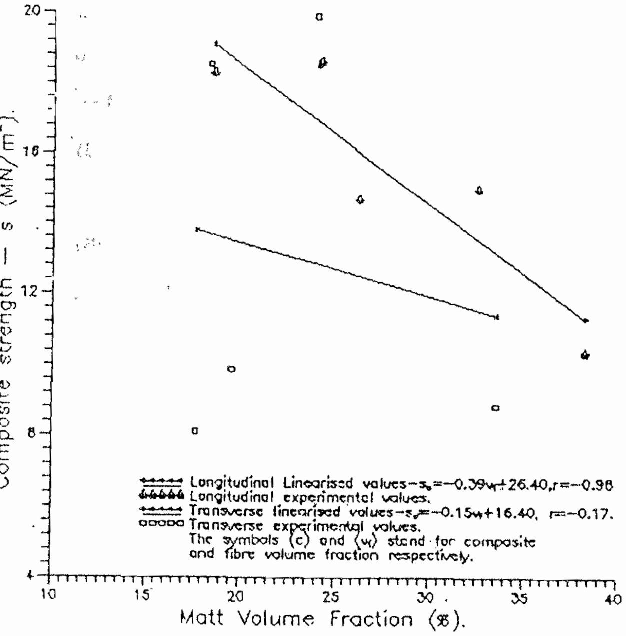

Fig. 1. The effect of loofah matt volume fraction on the strength of loofah/epoxy composites

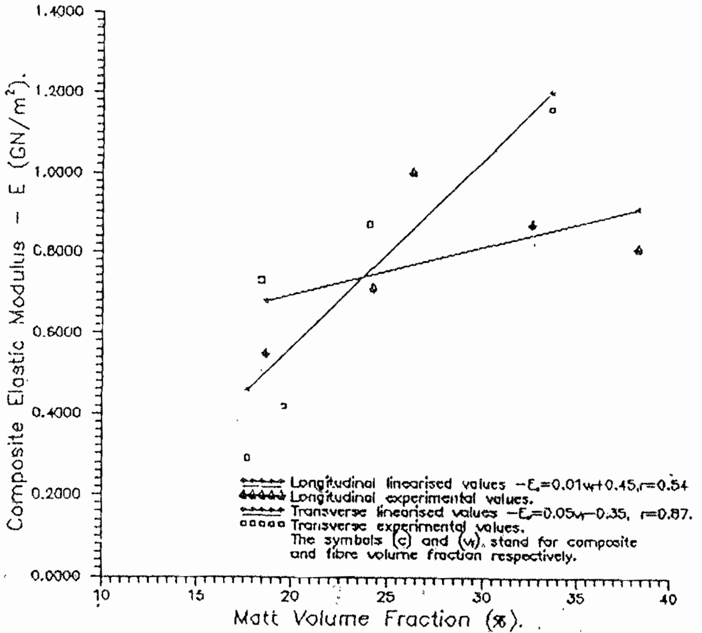

Fig. 2. The effect of loofah matt volume fraction on the Elastic Modulus of loofah/epoxy composites

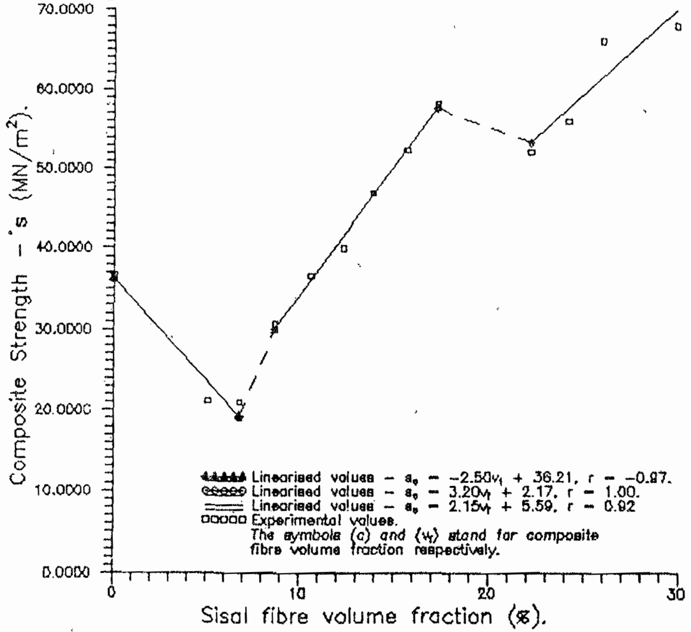

Fig. 3. The effect of sisal fibre volume fraction on the strength of sisal/epoxy composites

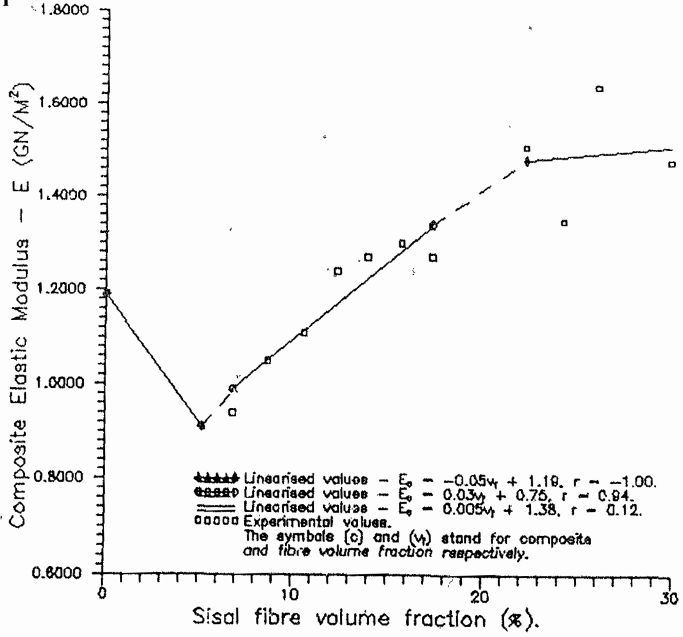

Fig. 4. The effect of sisal fibre volume fraction on the Elastic Modulus of sisal/epoxy composites

The linearised curves of loofah/epoxy composites that are shown in Fig.1 have negative gradients. Multiple Matrix Fracture (M.M.F.) did not occur and no cases of fractured fibre within the matrix were noted. All the fracture surfaces were irregular, with fracture in certain cases occurring along the transverse fibres. The fracture surfaces had protruding fibres especially in the transversely reinforced test pieces. This implies that the failure mode of loofah/epoxy composites can best be described by the failure mode, where the interfacial bond strength is significant and the stress and strain to failure of loofah matt are less than the equivalent values for epoxy resin.

The curve of loofah/epoxy composites that is shown in Fig.1 exhibits a drop of strength with increasing loofah matt volume fraction. That loofah matt reduces the strength of epoxy resin is also supported by the results in Table 5. Figure 2, however, shows that the Elastic Modulus of loofah/epoxy composites increases with increasing matt volume fraction. Therefore the rate of reduction of the composite strength with increasing loofah matt volume fraction, is lower than that of the composite percent elongation.

Table 5. Load carrying capacity of loofah/epoxy composites

	Load carrying capacity (N)						
Cross-sectional	Loofah				Epoxy	Composite	
area (mm)^2	longitudinal.		transverse.		Resin	Long.	Trans
	(1)	(2)	(1)	(2)			
(50 x 5)	148	295	99	198	9198	4985	5215
(50 x 10)	-	-	-	-	18396	9970	10430

Where (1) and (2) stand for one and two layers of loofah matt respectively. Loofah matt has an exact width of 55 mm in the longitudinal and transverse directions respectively.

The curves in Figs 3 and 4 clearly show both the minimum and critical fibre volume fraction. Depending on the accuracy of performing tests on sisal/epoxy resin composites, one or more of the regimes that are shown in these curves may be missed out. This gives rise to the following three possibilities:

i) Case a - for fibre volume fractions that are greater than the minimum fibre volume fraction, where only the data within M.M.F. zone is obtained. The limiting design fibre fraction will specify composites with higher values of strength and percent elongation and lower values of Elastic Modulus than the actual values that were set from the full data range. M.M.F is implied over the full fibre volume fraction range above the minimum fibre volume fraction.

ii) Case b - data within the M.M.F. zone is not obtained. Consequently the limiting design fibre volume fraction will specify composites with lower value of strength percent elongation and Elastic Modulus than the actual values that are set from the full data range. M.M.F. is not detected.

iii) Case c - data is obtained within the full range but no distinction is made between the

M.M.F. zone and the preceding zone. The resulting curves in this case will not show a minimum point for percent elongation. The curves will give values of critical fibre volume fraction for the composite strength and Elastic Modulus that are less than the actual values based on the case where a distinction between the M.M.F. zone and the preceeding zone is made.

The present work identifies both the critical and minimum fibre volume fractions as well as the M.M.F. phenomena, for sisal epoxy resin composites. This then gives rise to a three stage sisal/epoxy composite curve, as opposed to the two stage curves of the works that has been referenced here on sisal based composites.

6.0 CONCLUSIONS

i) The minimum density of epoxy resin is 1299 kg/m^3.

ii) The minimum density of loofah matt is 405 kg/m^3.

iii) Linear correlation between the weight and the mechanical properties of loofah matt is poor.

iv) The strength of loofah matt is higher in the longitudinal direction than in the transverse direction.

v) Loofah matt reduces the mechanical properties of epoxy resin and is therefore unsuitable as a reinforcing material in this respect.

vi) The mechanical properties of sisal fibres can be represented by an equation of the following form: $y = a + bw$ where y and w stand for some mechanical property and the weight of sisal fibre respectively and a and b are linear correlation constants.

vii) Sisal fibre does give a definite improvement in the mechanical properties of epoxy resin. This improvement is dependent on the volume fraction of reinforcing fibres.

viii) The values of the minimum and critical fibre volume fractions differ for the percent elongation, strength and Elastic Modulus of sisal/epoxy composites. They are 5.8%, 6.0% and 4.9% respectively.

ix) The curves of the present work generally agree with those that are based on the R.O.M. Therefore design specifications for sisal/epoxy composites must be referenced to a specific fibre volume fraction. The specified fibre volume fraction must in all cases be greater than the critical fibre volume fraction for the reinforcement to be effective.

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