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Laly A. Pothan, Sabu Thomas and N. R. Neelakantan

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Short Banana Fiber Reinforced Polyester Composites: Mechanical, Failure and Aging Characteristics

LALY A. POTHAN
Department of Chemistry
Bishop Moore College
Mavelikara, Kerala, India-689 101

SABU THOMAS*
School of Chemical Sciences
Mahatma Gandhi University
Priyadarshini Hills P.O.
Kottayam, Kerala, India-686 560

N. R. NEELAKANTAN
Chemical Engineering Department
High Polymer Engineering Division
Indian Institute of Technology
Madras, India-600 036

ABSTRACT: This paper describes the tensile, impact, flexural properties and aging behavior of short banana fiber reinforced polyester composites with special reference to the effect of fiber length and fiber content. Maximum tensile strength was observed at 30 mm fiber length while impact strength gave the maximum value for 40 mm fiber length. Incorporation of 40% untreated fibers gave a 20% increase in the tensile strength and a 341% increase in impact strength. On treatment with silane coupling agent, composites showed a 28% increase in tensile strength and a 13% increase in flexural strength. Aging studies showed a decrease in tensile strength of the composites. The experimental tensile strength values were compared with theoretical predictions according to Piggot equation. Scanning electron microscopy studies were carried out to understand the morphology of the fiber surface, fiber pullout and interface bonding. Water absorption studies showed an increase in water uptake with increase in fiber content. Finally, the properties of banana fiber reinforced polyester composites have been compared with other natural fiber reinforced composites.

KEY WORDS: banana fiber; polyester; coupling agent; aging.

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*Author to whom correspondence should be addressed.

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INTRODUCTION

LIGNOCELLULOSIC BASED NATURAL fibers are relatively inexpensive and these renewable resources which are abundantly available and underutilized have the potential to be fillers and reinforcements in polymers [1]. Studies have been carried out with other natural fibers like coir [2], sisal [3], pineapple leaf fiber [4], oil palm empty fruit bunch fiber [5], etc. Results of the above studies carried out in this laboratory by Thomas and coworkers have shown natural fiber to be an effective reinforcement in plastic. Studies have also been carried out on the effect of fiber treatment on various natural fibers to improve fiber matrix bonding [6]. Natural fibers are themselves cellulose reinforced materials and the cellulose content and microfibril angle determine the mechanical behavior of the fiber [7]. The high cellulose content (64%) and low microfibrillar angle (11°) of banana fiber indicate that it has potential as a reinforcing material [8]. Composites made out of banana/cotton hybrid fabric have been found to be useful in the preparation of low strength material [9]. It has been reported that addition of banana fiber to polymeric matrices can make composite products adequate for building application [10]. This study focuses on the effect of banana fiber on the mechanical properties of polyester composites. The influence of fiber loading and fiber length on the tensile, flexural and impact properties has been analyzed. Several studies have been reported based on the surface modification of fibers [11–16] to improve interfacial bonding between fiber and matrix. Effect of the coupling agent, vinyl triethoxy silane, on the mechanical properties of the composites has also been studied. The tensile and flexural failure surfaces of the samples have been examined by scanning electron microscopy to understand the nature of failure, fiber matrix adhesion, fiber breakage and pullout. Percentage decrease in tensile strength of samples subjected to aging has also been studied. Finally the properties of banana fiber reinforced polyester composites have been compared with other natural fiber reinforced thermoset composites.

EXPERIMENTAL

Banana fiber was obtained from Sheeba Fiber and Handicrafts, Poovancode, Tamil Nadu, India. The polyester used for the study was unsaturated polyester resin HSR 8131 (Sp. gr 1.12, viscosity 650 cps, gel time 25 min) obtained from M/s Bakelite Hylam Ltd., Hyderabad, India. Vinyl triethoxy silane was obtained from Merck, Germany. Methyl ethyl ketone peroxide and cobalt naphthanate were of commercial grade obtained from M/s Sharon Enterprises, Cochin, India. The characteristics of polyester and banana fiber are given in Tables 1 and 2.

The well separated fibers were cut into the desired length of 10, 20, 30 and 40 mm. The matrix was prepared by taking a definite amount of resin to which 0.9% (volume per cent) cobalt naphthanate and 1% (volume per cent) methyl ethyl ketone peroxide were added. Curing of laminates was done at room temperature for 24 h.Composites were prepared using treated and untreated fibers. Fiber treatment was done by immersing the chopped fibers in water/ethanol mixture in the ratio 40:60 containing different concentrations of silane (0.3, 0.6, 1 and 2%) for 1 1/2 h. The pH was maintained between 4 and 7 by adding acetic acid. The

Table 1. Typical properties of the liquid resin.

Appearance: A clear pale yellow liquid
Viscosity @25°C (cps) (Brookfield viscometer): 650
Specific gravity @25°C: 1.11

Typical properties of cured unreinforced resin (specimens cured for 24 h at room temperature followed by post-curing for 4 h at 80°C).

Tensile strength (psi): 9000
Flexural strength (psi): 16,000
Water absorption at 25°C (%), 28 days: 0.65

Table 2. Physical and mechanical properties of banana fiber.

Cellulose content: 63–64%
Hemicellulose: 19%
Lignin: 5%
Moisture content: 10–11%
Initial modulus: 20–51 MPa
Tensile strength: 520–750 MPa
Density: 1.35 g/cc

fibers were dried in air followed by drying in an oven at 70°C for 30 min. The tensile properties of samples were determined in accordance with ASTM D 638-76 at a cross head speed of 5 mm/min using Zwick model 1465. The tensile strength and modulus were determined from the stress strain curves. Five samples were tested in each set and the mean value was taken. Flexural strength of the specimen was done by three point bent tests as per ASTM D790-91 at a cross head speed of 4 mm/min. Charpy impact test on unnotched specimen was determined using a pendulum impact testing machine. Water absorption of composites was tested as per ASTM D570-81. Aging studies of the composite were carried out by subjecting the conditioned specimens to accelerated and natural aging.

RESULTS AND DISCUSSION

The performance of a composite is judged by its properties. The mechanical properties of short fiber reinforced composites which include the strength, modulus, mode of failure are all dependent on the properties of the banana fiber and polyester matrix and also on the fiber content and fiber orientation.

Tensile Properties

The tensile strength of the banana fiber is seen to vary from one variety to another and also from one locality to another [17]. The fibers have an initial modulus of 20–51 GN/m^2, tensile strength 520–750 MN/m^2 and extension at break 1.8–3.5%. The stress-strain curve of single banana fiber is given in Figure 1. The curve shows three distinct regions elastic, inelastic and crystalline. The initial portion, i.e., up to 3% elongation shows elastic behavior and after that it shows inelastic behavior. The increase in modulus at higher stress is due to the orientation of crystalline regions in the fiber.

Figure 2 delineates the effect of fiber loading on the tensile properties of the composite. At low fiber loading fibers act as flaws and the volume percent of fiber is not enough to impart high strength to plastic [18]. The tensile strength shows a linear increase after the initial decrease for 10% loading. The stress-strain curve of the composite as a function of fiber loading is given in Figure 3. The tensile stress is found to increase with fiber loading, the value being a maximum for 40% loading. At a loading of 30 and 40 percent, the stress-strain curves seem to overlap emphasizing the maximum allowable fiber content. There seems to be an increase of 159% in stress for a 40 weight percent composite compared to a 10 weight percent composite. However, compared to neat polyester the increase in stress is about 20%. Figure 4 delineates the effect of fiber content on tensile modulus. The tensile modulus is found to be maximum for 20% loading followed by a decrease at higher loading.

Figure 5 shows the effect of fiber length on the tensile strength of the composite. In a discontinuous fiber composite the stress along the fiber is not uniform. A certain fiber length called critical fiber length is required for the effective transfer of stress between fiber and matrix. From the figure it is clear that tensile strength gives a maximum value for 30 mm fiber. Tensile strength of the compos-

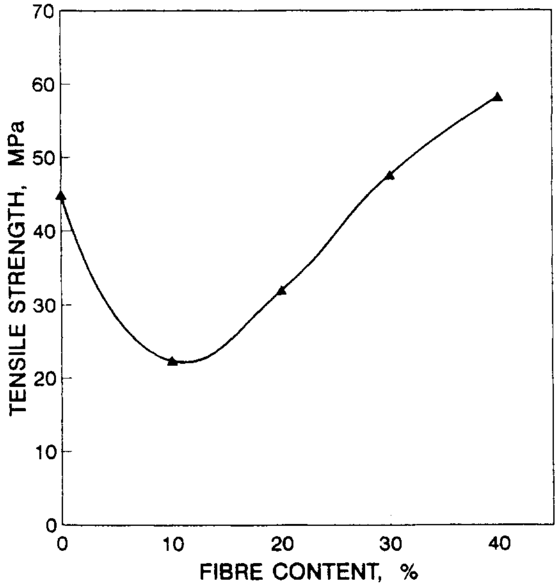

Figure 1. Stress-strain curve of banana fiber.

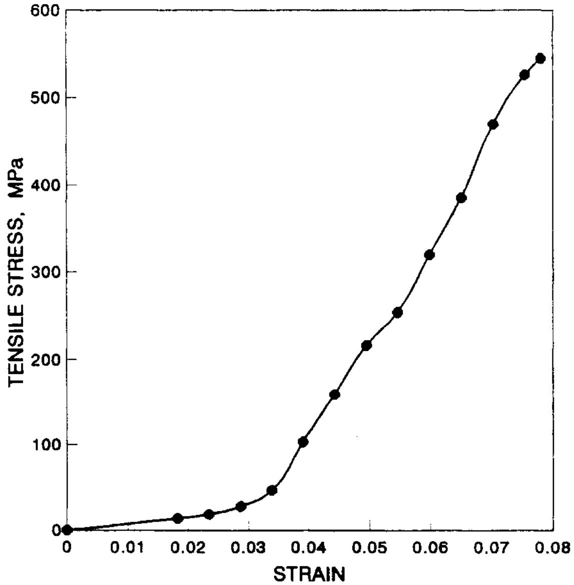

***Figure 2.** Effect of fiber content on the tensile strength of the composites (fiber length 20 mm).*

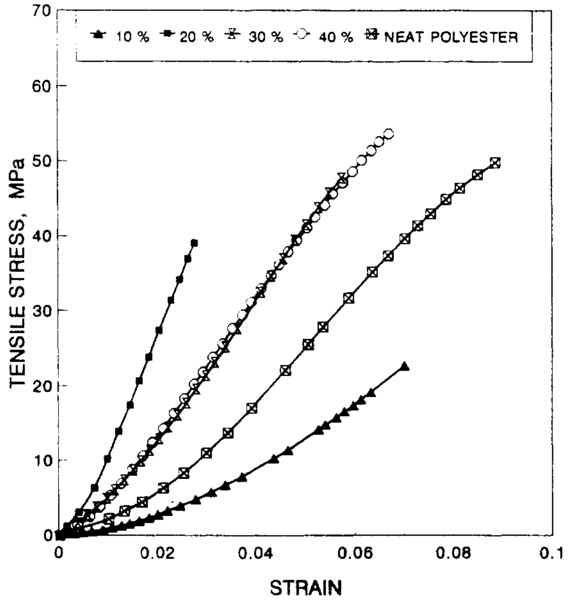

Figure 3. *Stress-strain curves of banana polyester composite at different fiber content under tension (fiber length 20 mm).*

ite shows a linear increase with fiber length. Curtis and Bader [19] found that the ends of fiber acted as notches and generated considerable stress concentrations which could initiate micro cracks. Tensile strength therefore is low for smaller fiber length. However, there is a decrease in tensile strength at 40 mm fiber length. At higher fiber lengths dispersion problems and fiber to fiber interactions can occur. Moreover, fiber curling will occur reducing the fiber length and thereby effective stress transfer.

Silane-coupling agents which are widely used on glass fiber to form stable covalent bonds to both the mineral surface and the resin are potentially suitable for use on cellulosic fibers [20]. Figure 6 shows the effect of silane concentration on the tensile strength of the composites. The increase in tensile strength is found to be 11% at 0.3% silane concentration while it is 28% at 0.6% concentration. At a higher concentration the improvement is only negligible. The silane coupling agent undergoes hydrolysis to form silanols which serves to bridge the interface. The silane by coreacting with the polymer modifies the morphology at the interface to improve stress transfer. This involves a tightening up of the polymer structure through increased crosslinking and increase in rigidity [21]. The mechanism of adhesion of the silane on to the fiber can be represented as follows.

$$CH_2{=}CH\text{-}Si(OC_2H_5)_3 + 3H_2O \longrightarrow \underset{\text{silanol}}{CH_2{=}CH\text{-}Si(OH)_3} + 3C_2H_5OH \quad (1)$$

$$\underset{\text{silanol}}{CH_2{=}CH\text{-}Si(OH)_3} + \underset{\text{from fiber}}{\text{Cellulose-OH}} \longrightarrow CH_2{=}CH\text{-}Si(OH)_2\text{-O Cellulose} \quad (2)$$

In the presence of moisture the silanol reacts with -OH groups attached to the glucose units of the cellulose molecule in the cell wall thereby bonding itself to the cell wall by further rejection of water. The tensile modulus also showed maximum value between 0.3 and 0.6% silane concentration (Figure 7).

The experimentally observed tensile strength values of short banana fiber reinforced polyester with different fiber loading have been compared with theoretical predictions. The Piggot equation according to which the strength of a composite is given by

$$T_c = T_f K_1 K_2 V_f + T_m(1\text{-}V_f) \quad (3)$$

where

T_c = composite strength
T_f = fiber strength
V_f = volume fraction of fibers
K_1 = fiber orientation factor
K_2 = fiber length factor ($l_c/21$)
l = length of the fiber

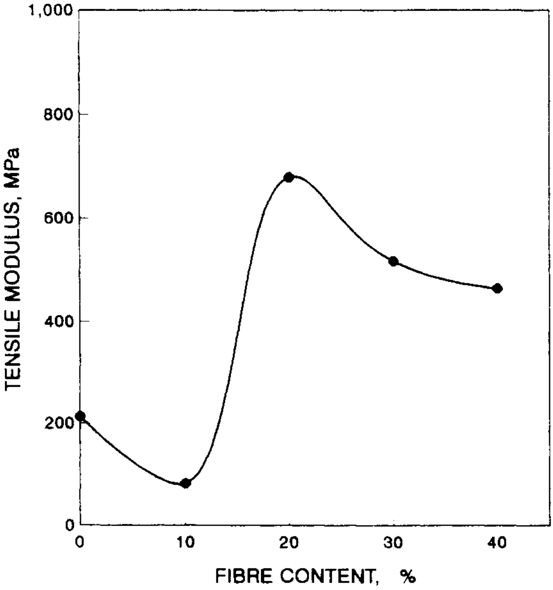

Figure 4. Effect of fiber content on the tensile modulus of the composites (fiber length 20 mm).

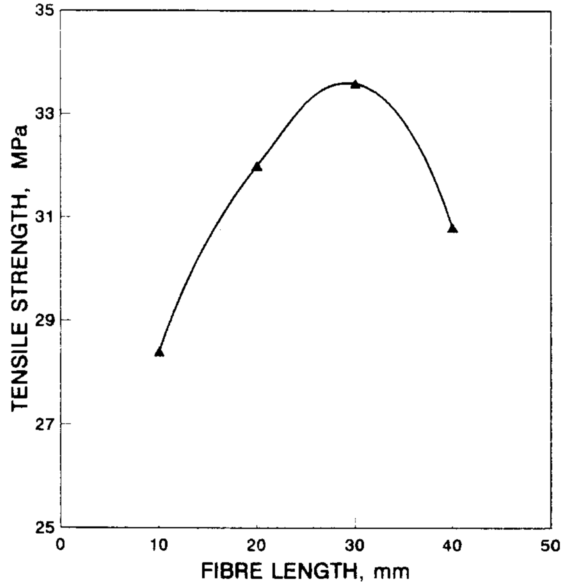

Figure 5. Effect of fiber length on the tensile strength of banana polyester composites (fiber content 20%).

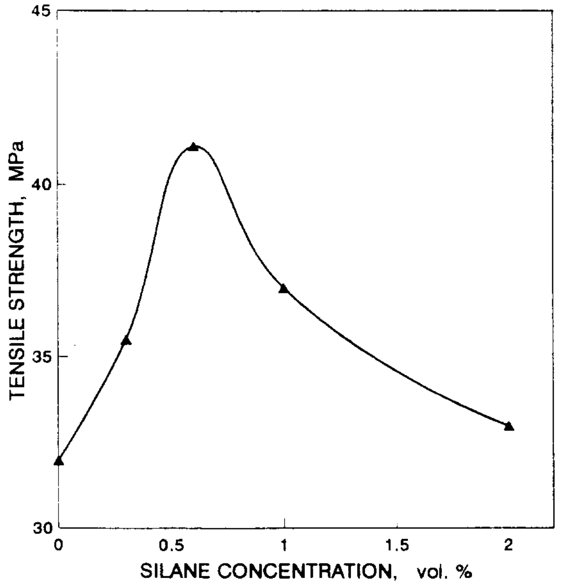

Figure 6. Effect of silane concentration on the tensile strength of banana-polyester composites (fiber length 20 mm; fiber content 20%).

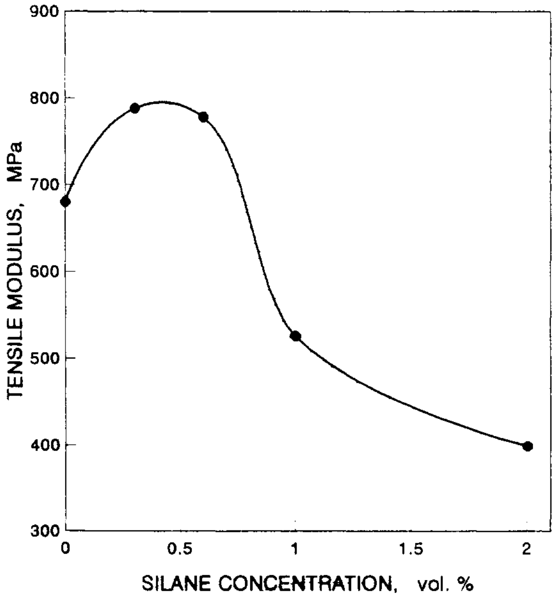

Figure 7. Effect of silane concentration on the tensile modulus of banana-polyester composites (fiber length 20 mm; fiber content 20%).

The values calculated using Piggot's equation showed agreement with the experimental values (Figure 8). However, deviation was found to be large at low fiber concentration.

Figures 9 and 10 are the SEM photomicrographs of untreated and silane treated banana fiber. The treated fiber has a rough surface topography. Development of a rough surface topography offers better fiber-matrix adhesion and an increase in mechanical properties. Figures 11 and 12 are the tensile fracture surface morphology of the untreated and silane treated banana polyester composite, respectively. The better fiber-matrix bonding can be seen from the polyester particles sticking to the fiber surface in the case of treated fibers (Figure 12). The clean fiber pull out regions in the case of untreated fibers show weak interfacial bonding (Figure 11).

Flexural Properties

Stress-strain characteristics of banana-polyester composites under flexure at different fiber loading are given in Figure 13. The flexural strength of the composite is found to be lower than that of neat polyester at lower fiber loading. Similar results have been observed by other workers. Zhu et al. [22] has reported that unlike other natural fiber composites flexural strength of banana fiber reinforced polyester composites is lower than that of neat polyester at low fiber loading. The

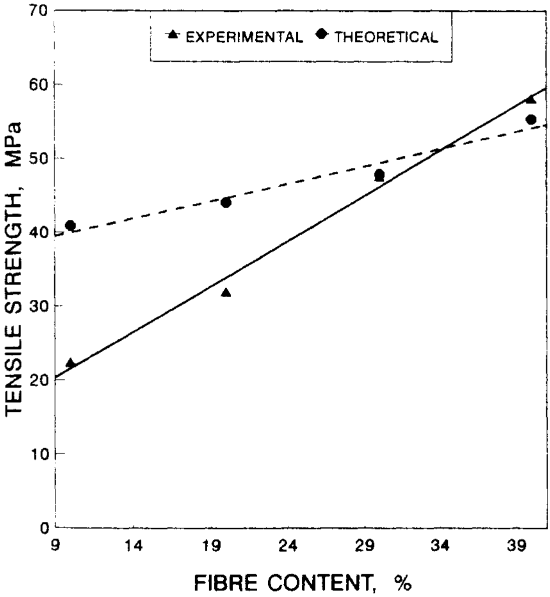

Figure 8. *Comparison of theoretical and experimental values of tensile strength at different fiber loading.*

Figure 9. *SEM photograph of banana fiber surface.*

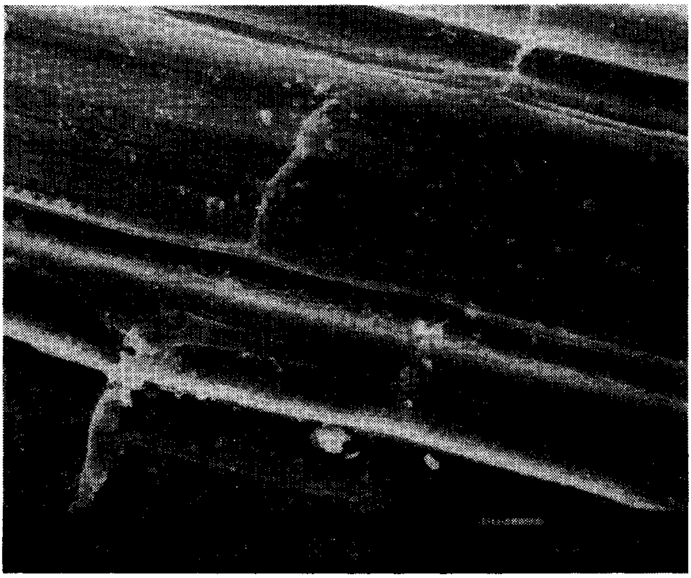

Figure 10. SEM photograph of the surface of silane treated banana fiber.

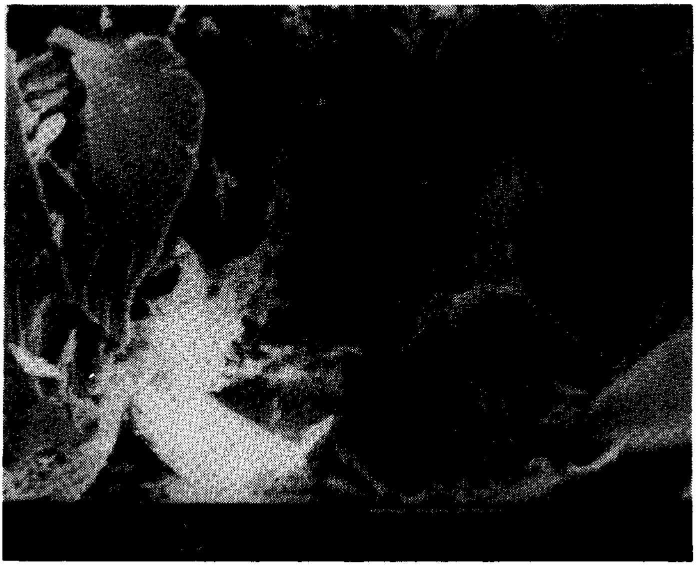

Figure 11. Tensile fracture surface of untreated banana fiber-polyester composites.

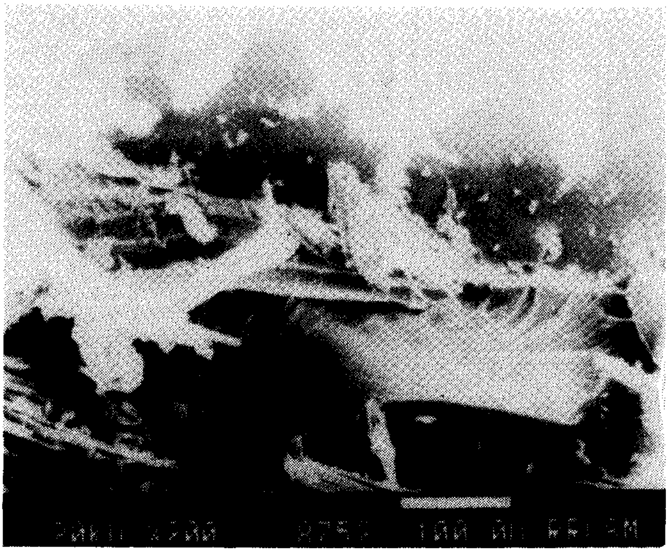

Figure 12. *Tensile fracture surface of treated banana fiber-polyester composites showing broken fiber and also adhering polyester particles.*

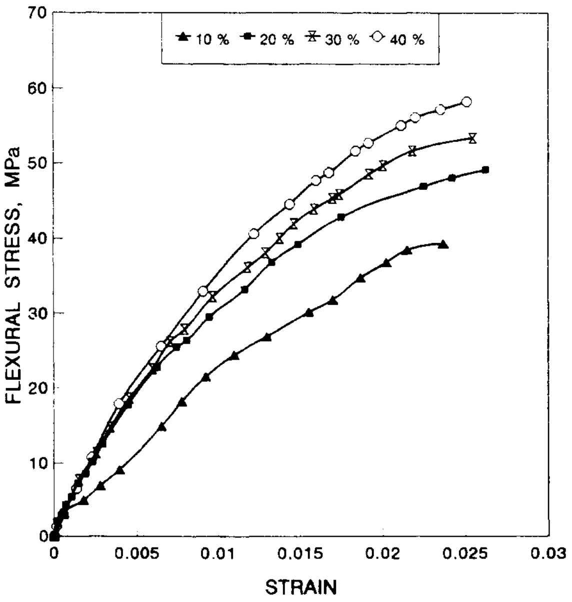

Figure 13. *Stress-strain curve of banana polyester composites under flexure at different fiber loading.*

flexural strength is found to be a maximum for 40% loading of fibers. For every 10% increase in fiber loading there is approximately an increase of about 13% in flexural strength. Figures 14 and 15 show the effect of fiber content on the flexural modulus and flexural strength. The flexural modulus is low for 10% loading but the modulus values increase appreciably when the fiber loading is increased to 20%. For 30% loading also the flexural modulus shows a comparatively higher value and the modulus does not show increasing trend after 30%.

Figure 16 shows the effect of fiber length on the flexural strength and flexural modulus at constant loading of 20%. The flexural strength and flexural modulus are found to be maximum when the fiber length is 20 mm.

The effect of silane concentration on the flexural strength and flexural modulus is given in Figure 17. Both flexural strength and flexural modulus give a high value at 1% silane concentration. The flexural strength of silane treated composites showed a 13% increase in strength. SEM photographs of the fracture surfaces of untreated and silane treated composites are given in Figures 18 and 19, respectively. Fracture surface of untreated fiber composite shows fiber pullout which is an indication of adhesion between fiber and matrix. Figure 19 shows fibrillation and also broken fibers in the case of treated fiber composites. This suggests improved fiber-matrix interaction.

Impact Properties

Impact strength of the samples were measured under varying fiber length and

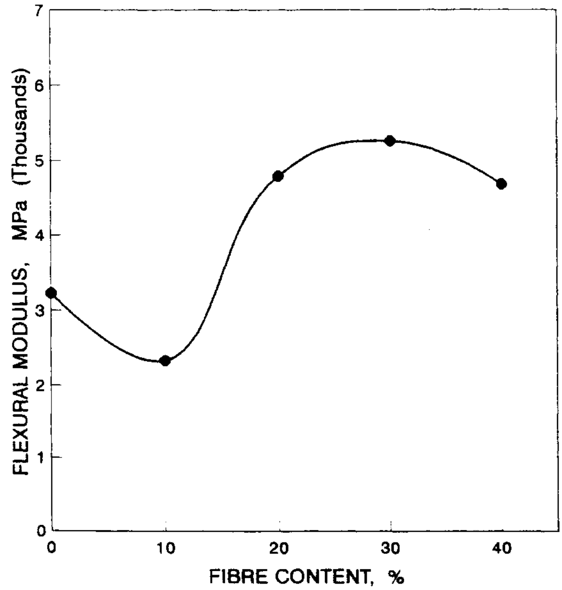

Figure 14. Variation of flexural modulus of banana-polyester at different fiber content (fiber length 20 mm).

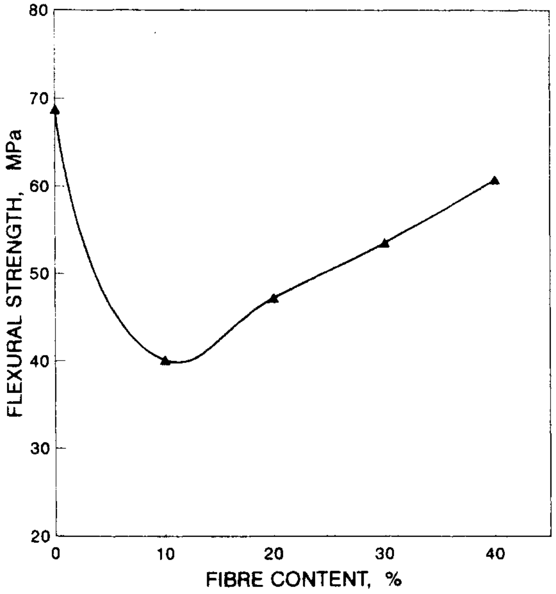

Figure 15. *Effect of fiber content on the flexural strength of composite (fibre length 20 mm).*

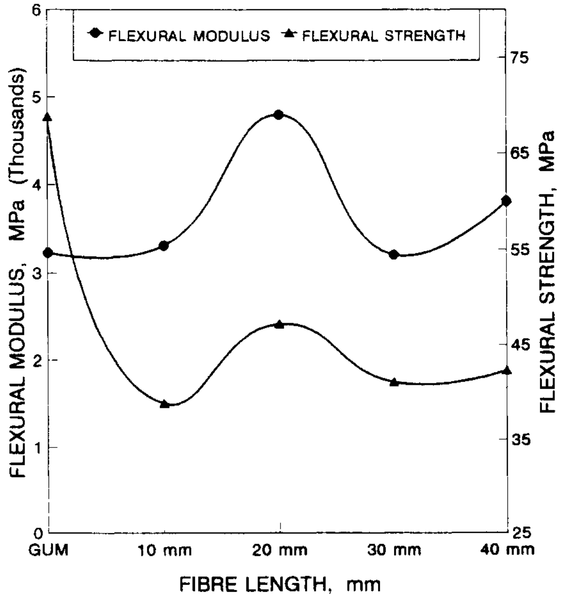

Figure 16. *Variation of flexural modulus and flexural strength with fiber length of banana-polyester composites (fiber content 20%).*

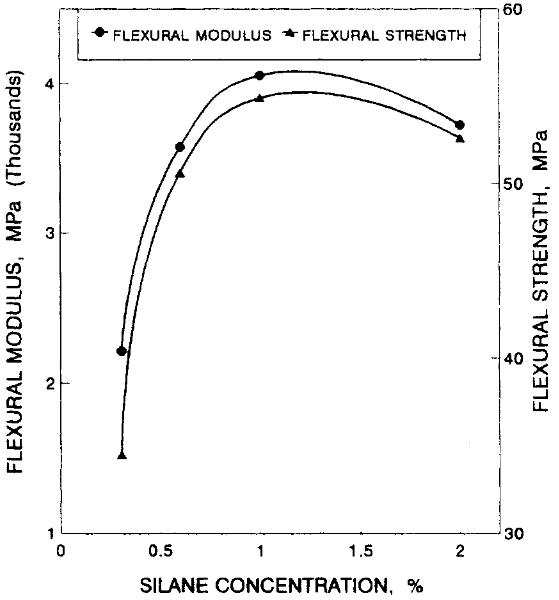

Figure 17. *Effect of silane concentration on the flexural strength and flexural modulus of banana-polyester composites (fiber length 20 mm; fiber content 20%).*

Figure 18. *Fracture surface of untreated banana fiber-composite under flexure.*

Figure 19. Fracture surface of treated banana fiber-composite under flexure.

fiber loading. Figures 20 and 21 show the effect of fiber loading and fiber length on the impact strength of the composites. For a given fiber length of 40 mm, the impact strength increases linearly with increasing fiber concentration. The percentage increase in impact strength is 177 for 20% fiber loading while the value changes to 270 and 341 for 30 and 40% loading. At a loading of 40% the impact strength at room temperature becomes maximum when the fiber length is 40 mm (Figure 21).

The high impact strength shown by composites with 40 mm length can be attributed to the extra energy dissipation mechanisms due to plastic deformation as shown in Figure 22 [23–25]. For shorter fiber length, the fiber being pulled out of the matrix is more likely than a plastic deformation. High impact strength for 40 mm fiber over the shorter fiber lengths can be explained as due to plastic deformation [24].

Water Absorption and Aging Studies

The slightest amount of water can significantly alter the key mechanical properties of natural fiber filled composites. The percentage increase in weight of the specimens after immersion in water for various time intervals (in days) is calculated to the nearest 0.01% as follows.

$$\text{Increase in wt\%} = \frac{\text{Net wt} - \text{Conditioned wt}}{\text{Conditioned wt}} \times 100$$

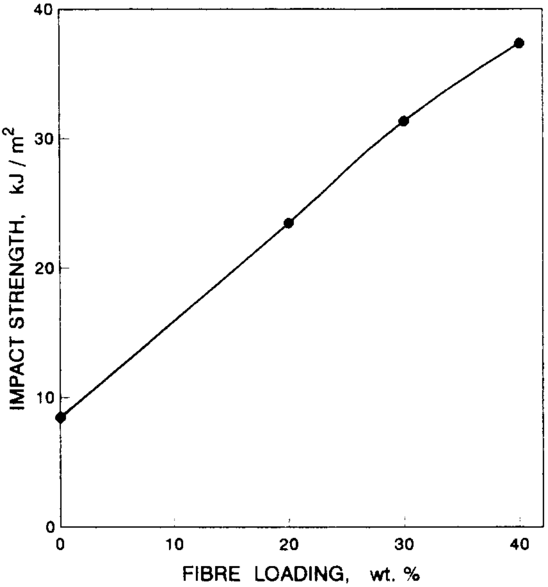

Figure 20. Effect of fiber loading on the impact strength of the composite (fiber length 40 mm).

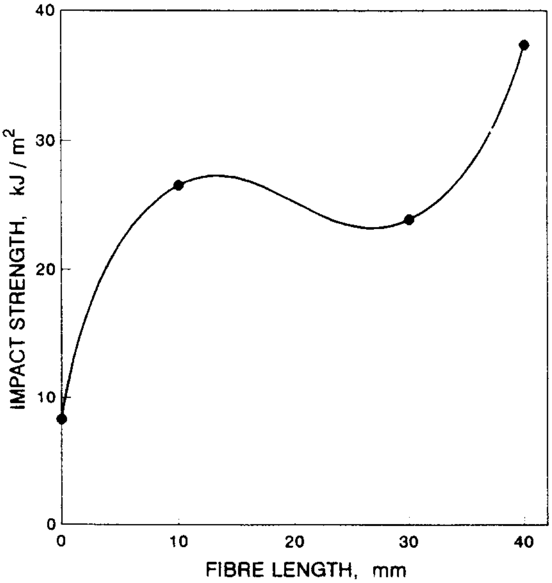

Figure 21. Effect of fiber length on the impact strength of the composite (fiber content 40%).

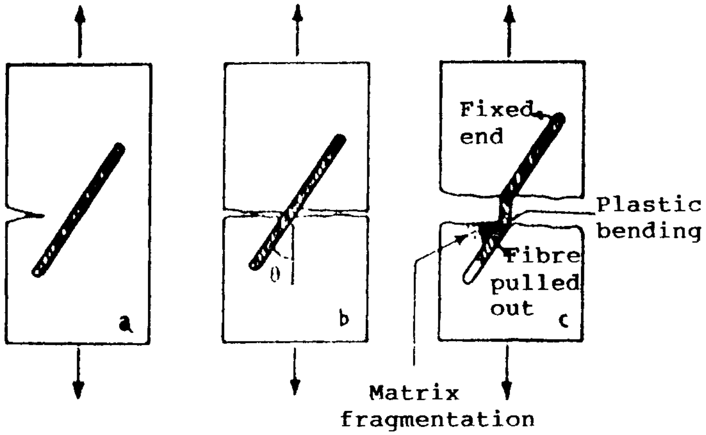

Figure 22. Model for plastic bending after Helfet and Harris[23] and Hing and Groves.[24]

Since the percentage of soluble matter lost during immersion in water is practically nil the increase in weight percent is equal to the percentage of water absorbed. The samples were soaked in water for about one month till the increase in weight almost leveled off. The percent absorption of water against time is shown graphically in Figure 23.

Water absorbed by the neat polyester was negligibly small, i.e., only 0.8% after a period of 35 days. The water uptake for samples with 10, 20 and 30% were found to increase regularly and leveled off at longer periods which is an indication of saturation. The leveling off period increases with the increasing concentration of fiber. The uptake is also due to the hydrophilic nature of cellulose and also due to the capillary action when fiber ends are exposed to water. The maximum water uptake was found to be for samples with 30 wt%, i.e., 29%.

Figure 24 shows the stress-strain curves of composite samples subjected to accelerated and natural aging. The stress is found to be maximum for the unaged sample. The stress of samples subjected to thermal aging is not much different from the unaged sample. While the unaged sample has shown a tensile strength of 903.16 MPa, the samples subjected to thermal aging has shown a value 845.5 MPa. The lowering of tensile strength is about 6%. Samples exposed to sun and rain continuously for six months have also shown only a 9% decrease in tensile strength. However, samples subjected to accelerated water aging have shown a 32% decrease in tensile strength. Other workers have also reported a decrease in mechanical properties of composites exposed to high humidity [26–28]. The water molecules act as a plasticizer by influencing the fibers, matrix and interface simultaneously and disturbing the mechanical integrity of the composite system [29]. Fiber-resin debonding may be initiated by the development of osmotic pressure pockets at the surface of fibers due to the leaching of water soluble substances from the fiber surface [30,31]. Also, initiators sometimes do not completely disappear but become converted into other substances which are capable of acting as osmotic solutes [32]. The degradation of composites may thus occur not only with the degradation of the individual constituents but also with the loss of interaction between them [29,33]. Table 3 shows the variation in tensile strength of the composites with aging. This study indicates that banana fiber reinforced polyester composite can withstand normal exposure to environment without any appreciable change in tensile strength and reconfirms it's utility as a substitute for timber in building purposes. The surface topology of banana fiber polyester composite shows wood like appearance. The composite has a smooth surface finish and resembles wood.

Comparison with Other Natural Fiber Reinforced Polyester Composites

In Table 4, the mechanical properties of banana polyester composites have been compared with other natural fiber composites. In fact, tensile, flexural and impact properties of banana fiber reinforced polyester composites have been compared with other natural fiber composites. Banana fiber composites have tensile and flexural strength comparable with other natural fiber composites while impact strength values are much higher than that of other composites.

CONCLUSIONS

Banana fiber has good potential as a reinforcing agent due to its high cellulose

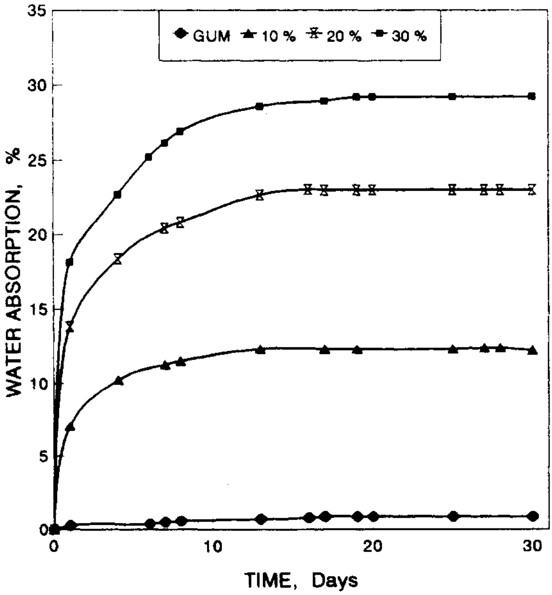

Figure 23. Effect of immersion time in water on the water absorbed (%) by banana-polyester composites.

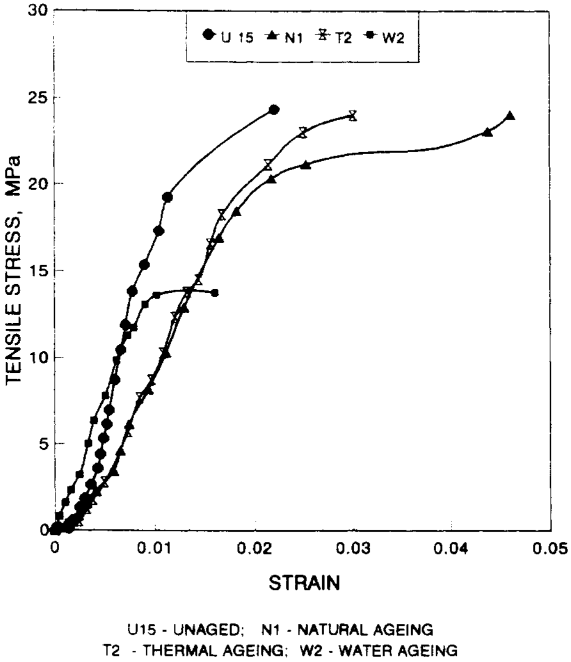

Figure 24. *Stress-strain curves of banana-polyester composites subjected to various ageing conditions.*

content and low microfibrilar angle. Banana fiber composites are promising as a substitute for timber in building industry. The influence of fiber length and loading on the mechanical and aging characteristics of the composite has been investigated. The stress-strain behavior in tension indicated that the addition of fiber makes the composite more ductile. The tensile strength of the composite was found to increase with increasing concentration of fiber, after an initial decrease in tensile stress for 10% loading. The initial decrease in tensile stress can be attributed to the volume fraction being not enough to impart high strength to the composite. In the present study, maximum tensile strength and tensile modulus were observed for 40% and 20% loading, respectively.

Table 3. Variation in tensile strength of composites with aging.

Sample Type	Tensile Strength (MPa)
Unaged	903.16
Thermally aged	845.50
Water aged	614.15
Naturally aged	821.90

Table 4. Properties of natural fiber polyester composites prepared by hand lay up (30%).

Composite	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJm^{-2})
Jute-polyester	—	66.25	14.67
Straw-polyester	—	47.00	2.6
Sisal-polyester	28	53.00	11.00
PALF-polyester	52.7	80.2	24.2
Banana-polyester	47.6	53.5	31.3
Coir-polyester (9 wt%)	18.61	31.15	3.910

Silane treatment has been found to increase the tensile strength of the composite by about 28%. A silane concentration of 0.6 volume percent used in this study has given the maximum improvement in tensile strength. SEM photographs of the tensile fracture surface of treated fiber composites showed improved adhesion between fiber and matrix. Theoretical predictions of tensile strength made according to Piggot's equation showed good agreement with experimental values.

In the case of flexural strength an increase in fiber content by about 10% has resulted in an increase of about 13%. The maximum value of flexural strength and flexural modulus was obtained for 40% loading. Impact strength of the composite showed a linear increase with fiber content. The improvement in impact strength at a fiber loading of 40% was found to be 341%.

Aging studies showed a decrease in tensile strength of about 6% for samples subjected to thermal aging, while it is 9% for samples kept exposed to sun and rain for six months. However, samples subjected to accelerated water aging showed a decrease of 32%. Water uptake of the composite was found to increase with fiber content and leveled off at longer periods. The leveling off period increases with increasing fiber concentration.

Comparison of the properties of banana fiber composites with other natural fiber composites has shown comparable tensile and flexural strength values but much higher impact strength values than other composites.

Banana fiber serves as an effective reinforcement in polyester composites. A fiber length of 30–40 mm and a fiber loading of 40% used in this study has given the best properties. These properties together with the inexpensive nature of the indigenous fiber make the composite attractive for industrial application. The surface topology of banana fiber polyester composite shows wood-like appearance. The composite has a smooth surface finish and resembles wood. The results suggest that banana fiber reinforced polyester composites have an edge over the conventional materials used in building industry.

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