

Bamboo Fiber Reinforced Polypropylene Composites and Their Mechanical, Thermal, and Morphological Properties

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ABSTRACT: Short bamboo fiber reinforced polypropylene composites were prepared by incorporation of various loadings of chemically modified bamboo fibers. Maleic anhydride grafted polypropylene (MA-g-PP) was used as compatibilizer to improve fiber–matrix adhesion. The effects of bamboo fiber loading and modification of the resin on the physical, mechanical, thermal, and morphological properties of the bamboo reinforced modified PP composites were studied. Scanning electron microscopy studies of the composites were carried out on the interface

and fractured surfaces. Thermogravimetric analysis and IR spectroscopy were also carried out. At 50% volume fraction of the extracted bamboo fiber in the composites, considerable increase in mechanical properties like impact, flexural, tensile, and thermal behavior like heat deflection temperature were observed. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 119: 1619–1626, 2011

Key words: composites; mechanical properties; morphology; polypropylene (PP); thermal properties

INTRODUCTION

Natural fibers from renewable resources such as pineapple, banana, bamboo, henequen, sisal, jute, wood and saw dust, coconut (coir), rice husk, and wheat straw are being extensively studied as reinforcing agents in different polymer matrices. Natural fibers are ligno-cellulosic in nature, and unlike glass, carbon fibers, and mineral fillers, when used as reinforcing agents they impart certain benefits such as low density, high specific strength, modulus, and relative nonabrasiveness without any health hazards to the composites. All the ligno-cellulosic based natural fibers consist of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. The microfibrils run all along the length of the fiber and have a complex layered structure made up of thin primary wall encircling a thicker secondary wall similar to single wood fiber.

Bamboo is one of the world's best known natural engineering materials and perhaps it is also one of the most under-utilized natural resources available abundantly in Southeast Asian countries. India is home to almost 45% of the world's bamboo forests.¹ Bamboo is a key element in not only maintaining the ecological balance but also in sustaining the socio-economic status of society.

Short bamboo fibers were selected in the present study as reinforcement materials in polypropylene

(PP) matrix for the following reasons. First, bamboo has the fastest growth rate among the various types of renewable natural fibers. Second, the cellulose fibers in bamboo are aligned along the length of the bamboo providing maximum tensile strength, flexural strength, and rigidity in that direction.² Attributes like 60% cellulose, considerably high percentage (32%) of lignin and 2–10° microfibril angle³ are responsible for making bamboo a preferred reinforcing agent. The mechanical properties of bamboo fiber reinforced plastics are comparable to other commonly used composites such as glass fiber reinforced plastics.⁴ Finally, even though bamboo is abundantly available in most of the tropical countries it has not been exploited to its potential as a reinforcing agent. Strangely, this is true in spite of the fact that bamboo has commonly been used in the tropical countries as a structural material in building huts, scaffoldings, etc. making it a potential reinforcing material. Some of the typical properties of bamboo fiber are presented in Table I.³

While analyzing the effect of a silane coupling agent, on curing characteristics and mechanical properties of bamboo fiber filled natural rubber composites, Ismail et al.⁵ concluded that presence of silanes improve the adhesion between fiber and rubber matrix and enhances the tensile strength, tear strength, hardness, and tensile modulus. Again while studying the mechanical properties and curing characteristics of bamboo fiber reinforced natural rubber characteristics, as a function of fiber loading and bonding agents, Ismail et al.⁶ reported that hardness and tensile modulus increases in presence

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TABLE I
Physical, Chemical, and Mechanical Properties of Bamboo Fiber

Natural fiber	Diameter (μm)	Density (kg/m^3)	Moisture raw/extracted (%)	Cellulose (%)	Lignin (%)	Microfibriller angle ($^\circ$)	Young's modulus (GPa)	Tensile strength (MPa)	Failure strain (%)
Bamboo	88–125	800	9/4	60	32	2–10	359	441	13

of bonding agents and increasing loading of bamboo fiber. Thwe and Liao⁷ fabricated short bamboo fiber reinforced PP composites (BFRP) and short bamboo-glass fiber reinforced PP hybrid composites (BGRP) and found that using maleic anhydride PP (MA-g-PP) compatibilizer resulted in enhanced mechanical properties for both BFRP and BGRP with mechanical properties of BGRP having an edge over BFRP. Again, Thwe and Liao⁸ carried out durability studies on BFRP and BGRP by subjecting them to hygrothermal ageing and cyclic tensile load and found that the use of MA-g-PP as a coupling agent in both the composite systems suppressed the moisture absorption and tensile strength degradation.

Okubo et al.⁹ carried out the development of bamboo based PP composites using steam explosion method and studied their mechanical properties. The steam explosion technique was found to be more effective method to extract bamboo fibers compared to the composites using fibers that are mechanically extracted. The tensile strength and modulus of the PP based composites using steam exploded fibers increased about 15 and 30%, respectively, due to well impregnation and the reduction of number of voids compared to those of fibers that were mechanically extracted. Chen et al.¹⁰ prepared another type of BFRP composites using MA-g-PP compatibilizer and studied their mechanical properties. It was observed that the mechanical properties of the composites increased significantly when 24% MA-g-PP (with 0.5% maleic anhydride content) was used in the composite formulation. The tensile strength was increased from 32 MPa to 36 MPa and the tensile modulus was increased from 5 to 6 GPa.

It is thus observed from the literature^{4–10} that investigations carried out so far, have shown significant improvement in tensile, impact and moisture absorption characteristics of BFRP composites using MA-g-PP as compatibilizer. Little or no information is available on the flexural properties and those related to thermal transitions such as HDT of the developed composites with varying fiber volume percentages. In the present work, Bamboo fiber–PP composites were fabricated using the conventional hot press method after extracting the bamboo fibers with steam explosion technique in the presence of MA-g-PP as compatibilizer. The compatibility between the bamboo fiber surface and the PP matrix was caused by esterification of the anhydride groups of MA-g-PP with the hydroxyl groups of the bamboo fiber.

Physico-mechanical properties such as water absorption, impact, tensile, flexural, and properties related to thermal transition such as HDT properties of the composites at different volume fractions of fiber loading both with and without MA-g-PP coupling agent were compared. Morphological observations were carried out with scanning electron microscopy (SEM).

EXPERIMENTAL

Materials

The Bamboo used in this study was of the species *Bambusa Balcoa* obtained from Dimapur, Nagaland (India). PP, Injection grade (Repol, H110MA) was obtained from Reliance Industries Limited, Jamnagar, Gujarat, India. Other chemicals viz., ethanol, hydrochloric acid, benzene, NaOH, xylene, isopropanol, benzoyl peroxide, maleic anhydride, etc, were obtained from S.d.Fine Chemicals, Mumbai.

Resin modification

PP was grafted with maleic anhydride by grafting process as reported by Kasandariya et al.¹¹ and Hujuri et al.¹² resulting in MA-g-PP. Fifty gram of PP was dissolved in 500 mL of xylene at 100°C. 4 g of Maleic acid dissolved in a minimum quantity of isopropyl alcohol and 0.4 g of benzoyl peroxide were then added to the solution of PP in xylene and continuously stirred. The resulting solution was then heated to 100°C for 7 h. Methanol was then added to obtain a white precipitate of MA-g-PP. This whitish powder like material was dried in vacuum oven at 60°C for 24 h. The fourier transform infrared (FTIR) spectra of the material confirmed the presence of carbonyl group attached to PP in MA-g-PP. This was used as a compatibilizer during blending of fiber and resin. The extent of grafting was estimated by calculating the acid number of the MA-g-PP compound as per ASTM D 7389. The acid number of MA-g-PP was found to be 41 and the MA content in MA-g-PP was estimated to be 0.036 moles per 100 g of MA-g-PP.

Fiber extraction

Bamboo fibers were extracted using a semi pilot scale extraction technique. The cylindrical bamboo culms excluding the node portions were cut into smaller chips of 1–1.5 cm length and about 10 mm in width. The culms weighing around 15 kg were

put into a digester (capacity-100 L, make-Universal Engineers, UP, India) charged with 20% alkali mixture of sodium hydroxide and sodium sulfide and digestion was carried out at a temperature of 160°C and pressure of 7.5 kg/cm² for 1 h. The pulp was then washed with acidified (dil. HCl) water until they showed no alkalinity reaction. They were then washed with cold distilled water, and squeezed using hydroextractor. The pulp was then dried in an oven at 105°C for 72 h. The pulp was finally put into a high speed blender and grinded into short bamboo fibers. The yield of bamboo fiber was 42% on weight basis. Ground bamboo fibers of sizes 1–6 mm were obtained using sieves with equivalent aperture size. Fiber diameters taken in this study were in the range of 90–125 µm determined microscopically.

Preparation of biocomposite

The required amount of bamboo fiber and PP to be mixed for each volume fraction of the fibers was calculated before composite fabrication. For this, at first density of the bamboo fiber was found out according to ASTM D-792. Then, the required amount of fiber and the polymer for different fiber volume fractions viz., 30, 40, 50, and 60% were weighed giving an allowance for flash in the sheet mould of the compression moulding press.

The melt mixing of the bamboo fibers and PP were carried out in a Two Roll Open Mill (make Pyrotech Engineers, Delhi), heated with rows of cartridge heaters. The temperature of the front and the back rollers were maintained at 140 and 160°C, respectively. Composites were prepared with extracted fibers without any compatibilizing agent and with MA-g-PP compatibilizer incorporated at 5% level into PP. After uniform mixing of the fibers and the polymer matrix, the resultant fiber-polymer matrix mix was scraped out from the roller without allowing it to harden and immediately pressed into 205 × 205 × 3.5 mm sheet mould in a Compression Moulding Press (make-SANTEC, Delhi) by applying a pressure of 25 tons. The material was kept at a contact temperature of 160°C for 5 min. After giving a sufficient time for cooling of the composite sheet to attain ambient room temperature, it was taken out and edges were trimmed. Two polyester sheets were put above and beneath the mould platens to facilitate better surface finish of the moulded composite sheets.

Characterization techniques

Sem analysis

The surface topography of the bamboo fiber-PP composite interface and fractured impact surfaces both with and without MA-g-PP were scanned with

the aid of a variable pressure digital scanning electron microscope (model LEO 435 VP) at the scanning electron microscope center of all India Institute of Medical Sciences (AIIMS), New Delhi.

Spectral analysis

Raw and extracted bamboo fibers after drying were pulverized and compressed in KBr to form pellets. Pure PP and MA-g-PP granules were made into thin film in slide under heated condition. The fourier transform infrared (FTIR-ATR) spectra of the raw and extracted (treated) bamboo fiber samples and pure PP and MA-g-PP were recorded in a FTIR (ATR) (model: FTLA 2000–100).

Physicomechanical properties

In the earlier studies by the authors^{12–14} investigations on physicomechanical properties were carried out on untreated natural fiber-PP composites with and without compatibilizers and treated natural fiber-PP composites with and without compatibilizers. The fibers used were pine apple leaf fiber and banana fiber. In this study, as the bamboo fibers were extracted with 20% alkali mixture of sodium hydroxide and sodium sulfide, no separate fiber modification (alkali treatment) after extraction was required and accordingly the physicomechanical properties of only the extracted fiber (chemically treated ones) with and without compatibilizer were studied and are reported here.

Water absorption

Water absorption was determined following ASTM D 570–98 (Reaffirmed 2005). For each test, three test specimens in the form of bar of dimension 76.2 × 25.4 × 3 mm were cut from composite sheets. The specimens were then dried in an oven at 60°C for 24 h, cooled in a desiccator, and immediately weighed (conditioned weight, w_1) to the nearest 0.001 g. The specimens were then immersed in a container of distilled water at room temperature ($23 \pm 1^\circ\text{C}$). After removal from the water the test specimens were carefully dried using absorbent paper and then weighed (wet weight, w_2) to the nearest 0.001 g immediately. The percentage increase in weight during water immersion was calculated as, increase in weight, $\% = (w_2 - w_1)/w_1 \times 100$.

Tensile strength and modulus

For each tensile test, five replicate dumbbell shaped test specimens from bamboo fiber-PP composites both with and without MA-g-PP of dimension 165 mm as the overall length, 13 mm as the width of the

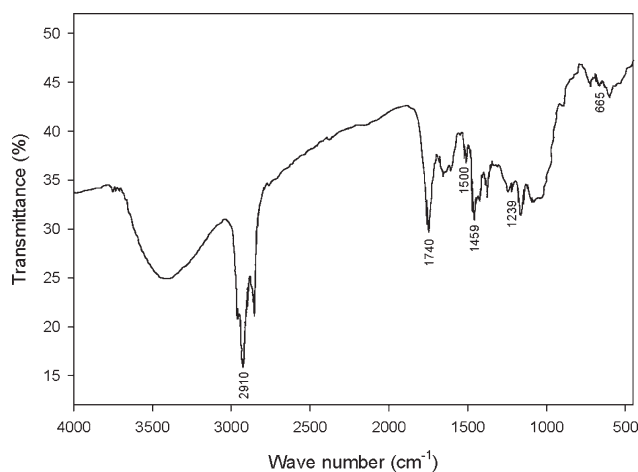


Figure 1 FTIR spectra of raw (untreated) bamboo fiber (% T versus wavenumber).

narrow section, 3 mm thickness, and 50 mm gauge length as per ASTM D 638 (Type I) were prepared. The tests were carried out using Universal testing machine (UTM), H 50 K-S supplied by Tinius Olsen, England. Load range of 10 kN, and crosshead speed of 5 mm/min was used for carrying out the test. From the experimental data obtained, the average data as well as corresponding maximum standard deviation were calculated.

Flexural strength and modulus

Flexural tests under three point bending were carried out on similar composite samples of bamboo fiber + PP without MA-g-PP and bamboo fiber + PP + MA-g-PP having dimension $80 \times 12.7 \times 3$ mm using the same UTM, as per IS 13,360 (Part 5/Sec 7): 1996, at a load range of 500 N and crosshead speed of 1.0 mm/min. For each test, five replicate test specimens were taken and from the experimental data obtained, the average data as well as corresponding maximum standard deviation were calculated.

Impact strength

Notched izod impact test on specimens having dimensions $63.5 \times 12.7 \times 3$ mm was carried out using a Ceast Impactometer (code 6545/000) as per ASTM D-256 with a notch angle 45° and depth of 2.54 mm. For each test, five replicate test specimens were taken and from the experimental data obtained, the average data as well as corresponding maximum standard deviation were calculated.

Thermal properties

Heat deflection temperature (HDT) was determined on composite samples of bamboo fiber with and without MA-g-PP, using the HDT/Vicat Softening

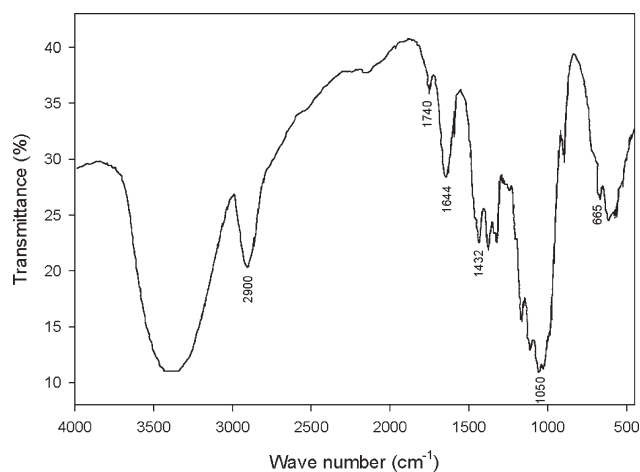


Figure 2 FTIR spectra of treated (extracted) bamboo fiber (% T versus wavenumber).

Temperature apparatus (make- Toyo Seiki Seisaku Sho, Japan) as per ASTM D 648-07, with span value 100 mm (Method B) and 1.82 MPa flexural loads. The test sample in the form of a bar of rectangular cross section having dimensions $127 \times 13 \times 3$ mm was tested in the edgewise position. The temperature of the heat transfer medium when the test specimen deflected 0.25 mm was recorded as the distortion temperature. For each test, two replicate test specimens were taken and from the experimental data obtained, the average data as well as corresponding maximum standard deviation were calculated.

RESULTS AND DISCUSSION

Characterization of the fiber and the resin

Shin et al.¹⁵ while carrying out studies on mechanical properties and microstructure of bamboo epoxy composites observed that the ultra-structure of the bamboo fiber consists of alternating broad and narrow

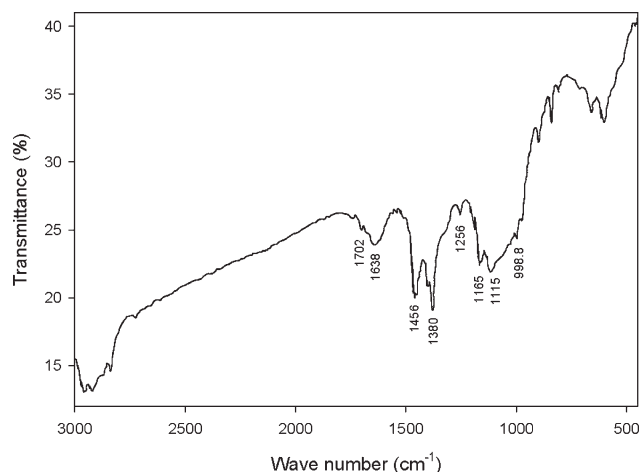


Figure 3 FTIR spectra of treated (extracted) bamboo fiber + MA-g-PP (% T versus wavenumber).

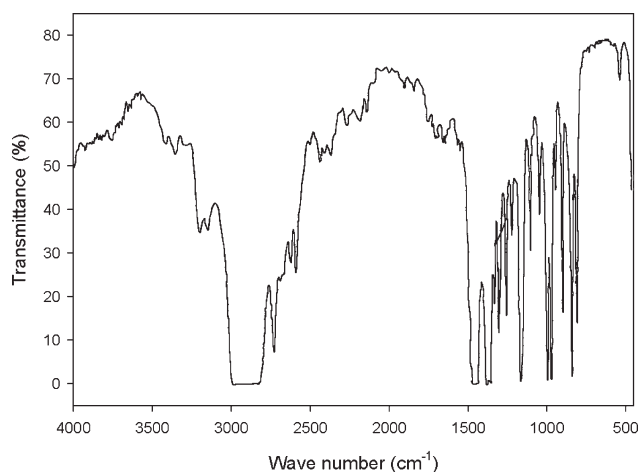


Figure 4 FTIR spectra of PP (% T versus wavenumber).

lamellae with different fibrillar orientation with each layer being made up of lignin, pentosan, and cellulose compound. The cellulose fibrils are embedded in the lignin-polyose matrix by hydrogen bonding.

FTIR peaks of the raw bamboo fibers (Fig. 1) show CH stretch at 2910 cm^{-1} . The carbonyl peak at 1740 cm^{-1} which is prominent in raw fiber (Fig. 1) is much reduced in the extracted one (Fig. 2). The peak at 1740 cm^{-1} which is attributed to the C=O stretching of the acetyl groups of hemi-cellulose¹⁶ is reduced due to its partial removal from the fiber surface. The lignin peak at 1459 cm^{-1} present in the raw bamboo fiber is not present in the extracted one due to its removal from fiber surface. COOH bending peaks at 665 cm^{-1} and C–O stretch at 1060 cm^{-1} is more prominent in the extracted fibers probably due to oxidation of some of the CH₂OH groups during fiber extraction. FTIR studies (Fig. 3) on treated bamboo fiber + MA-g-PP shows the presence of $\nu\text{-C(=O)-O}$ stretch in the region 1256 cm^{-1} and ρCH_3 bending at 1165 cm^{-1} which

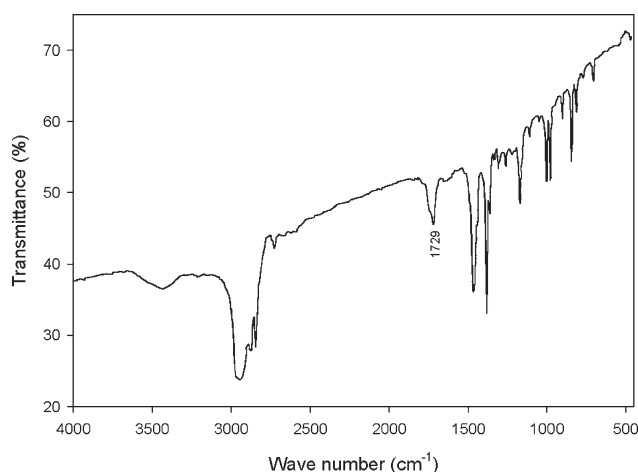


Figure 5 FTIR spectra of MA-g-PP (% T versus wavenumber).

TABLE II
Water Absorption (%) of Bamboo-PP Composites at Varying Fiber Volume %

Fiber (vol %)	Water absorption (%)	
	Extracted fiber + PP	Extracted fiber + PP + MA-g-PP
0	0.09	0.09
30	2.07	1.02
40	3.28	1.18
50	3.54	1.30
60	3.76	1.45

clearly indicates the birth of ester bond.¹⁷ FTIR spectra of PP and MA-g-PP are shown in Figures 4 and 5, respectively. The absorption peak at about 1729 cm^{-1} in MA-g-PP is characteristic of the carbonyl group of the anhydride that is absent in virgin PP.

SEM micrographs of PP and MA-g-PP carried out in our earlier studies¹² showed considerable amount of grafted polymer in the polymer backbone of MA-g-PP.

Thermogravimetric analysis thermograms carried out in our earlier studies^{12–14} had shown a marginal improvement in thermal behavior of the fibers after alkali treatment. A change in the degradation pattern of the composites was also noticed after fiber incorporation along with slight improvement in their thermal stabilities.

Effect of surface modification and compatibilizer on the physicomechanical and thermal properties of the composites

The variation in physical and mechanical strength as a function of fiber volume percent is represented in Tables II–V. Water absorption capacities in extracted fiber composites with and without compatibilizer enhances with increase in fiber volume loadings (Table II). This is quite obvious because of the presence of hydroxyl and other polar groups in various constituents of natural fibers. Water absorption is comparatively less in composites of extracted fiber (Table II) with compatibilizer. The reason for this

TABLE III
Impact Strength of Bamboo-PP Composites at Varying Fiber Volume %

Fiber (vol %)	Impact strength (J/m)	
	Extracted fiber + PP	Extracted fiber + PP + MA-g-PP
0	26.54 ± 0.15	26.54 ± 0.15
30	26.62 ± 0.28	29.58 ± 0.37
40	26.86 ± 0.35	33.21 ± 0.41
50	27.32 ± 0.48	36.32 ± 0.38
60	27.54 ± 0.15	38.92 ± 0.29

TABLE IV
Flexural Properties of Bamboo-PP Composites at Varying Fiber Volume %

Fiber (vol %)	Extracted fiber + PP		Extracted fiber + PP + MA-g-PP	
	Flexural strength (MPa)	Flexural modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)
0	38.00 ± 0.30	1650 ± 3	38.00 ± 0.30	1650 ± 3
30	45.49 ± 0.88	2077 ± 4	56.73 ± 0.49	2929 ± 5
40	46.60 ± 0.52	2432 ± 7	58.82 ± 0.45	3572 ± 8
50	49.56 ± 0.64	2867 ± 4	68.85 ± 0.33	4127 ± 5
60	48.86 ± 0.74	3307 ± 8	61.77 ± 0.58	3906 ± 6

behavior is that, at first by the action of alkali⁹ a substantial portion of uronic acid, a constituent of hemicellulose and other polar groups are removed causing reduction in moisture absorption. Secondly, incorporation of MA-g-PP imparts hydrophobicity to the fibers due to esterification of the anhydride groups of MA-g-PP with the hydroxyl groups of natural fiber. Thwe and Liao⁸ reported that PP-MA-g-PP matrix reduces water uptake in BFRP due to the improved interfacial adhesion that reduces water accumulation in the interfacial voids and prevents water from entering the bamboo fiber.

It is also observed that the mechanical properties such as impact strength (Table III); flexural strength and flexural modulus (Table IV); and tensile strength and tensile modulus (Table V) of the extracted bamboo fiber-PP composites with and without compatibilizer increases with the increase in fiber loading from 30 to 50% and then the values either tries to saturate or decrease at 60% fiber loading. The increase was more in composites with MA-g-PP compatibilizer as the maleic anhydride binds with bamboo fiber resulting in an improved interfacial adhesion between the matrix and the fiber.^{8,18} The overall performance of any fiber-reinforced polymer composite depends to a large extent upon the fiber-matrix interface, which in turn is governed by the surface topography of the fiber and by the chemical compatibility of fiber surface and resin properties. Maleic anhydride binds with bamboo fiber resulting in an improved interfacial adhesion between the matrix and the fiber. This improved interfacial adhesion allows a more efficient transfer of stress along the fiber/matrix interface. The linear increase with

increase in fiber volume is due to availability of more fiber for increased stress transfer. The maleic anhydride group of MA-g-PP covalently links with the hydroxyl groups of the fibers forming an ester linkage, while the nonpolar part (PP) of MA-g-PP becomes compatible with the virgin matrix, lowers the surface energies of the fibers, increases their wettability and dispersion within the matrix.¹⁹ The decrease in mechanical properties at higher volume fractions of fiber loadings is due to the increase in fiber-fiber interactions, the fibers not being perfectly aligned with matrix, and poor dispersion of fibers in the matrix. Moreover, higher void content (which might be due to the presence of moisture in trace amounts), and low interfacial strength resulted in a lower efficiency of load transfer with increasing fiber loading.¹² The marginal increase in tensile strength of the composites without compatibilizer may be attributed to the shorter bamboo fiber lengths (1–6 mm) which are not able to absorb completely the tensile stress transfer from the matrix.

Thus, the composites prepared with 5% MA-g-PP concentration at an optimum 50% fiber volume % (fiber size 1–6 mm) had about 37% increase in impact strength, about 81% increase in the flexural strength, about 150% increase in the flexural modulus, about 105% increase in the tensile strength and about 191% increase in tensile modulus as is evident from the experimental data in Tables III–V, respectively.

The variations in HDT as a function of fiber volume percent in extracted bamboo fiber composites with and without MA-g-PP compatibilizer are represented in Table VI. It is observed that the HDT of the bamboo fiber-PP composites without MA-g-PP

TABLE V
Tensile Properties of Bamboo-PP Composites at Varying Fiber Volume %

Fiber (vol %)	Extracted fiber + PP		Extracted fiber + PP + MA-g-PP	
	Tensile strength (MPa)	Tensile modulus (MPa)	Tensile strength (MPa)	Tensile modulus (MPa)
0	24.50 ± 0.21	560 ± 4	24.50 ± 0.21	560 ± 4
30	25.80 ± 0.37	1357 ± 9	37.37 ± 0.47	1370 ± 6
40	26.27 ± 0.28	1776 ± 8	42.84 ± 0.36	1527 ± 8
50	28.95 ± 0.34	1721 ± 10	50.26 ± 0.39	1633 ± 11
60	25.50 ± 0.45	1643 ± 12	46.45 ± 0.42	1586 ± 8

TABLE VI
Heat Deflection Temperature (HDT) of Bamboo-PP Composite at 1.8 MPa and Span Value of 100 mm

Fiber (vol %)	HDT (°C)	
	Extracted fiber + PP	Extracted fiber + PP + MA-g-PP
0	72	72
30	87	95
40	97	104
50	105	110
60	110	119

shows linear increase with the increase in fiber volume percent from 30% to 60%. On the other hand, the HDT of the fiber composites with MA-g-PP compatibilizer also shows linear increase with the increase in fiber volume percent from 30 to 60% but in much higher magnitudes. Compared to the HDT of virgin PP, the HDT of the fiber composites with MA-g-PP compatibilizer shows increase by 23 to 47°C with increase in fiber volume percent from 30 to 60%. In bamboo fiber composites without compatibilizer the increase in the HDT with increase in fiber volume % is due to increase in restricted mobility of the polymer chains in the amorphous phase which is further augmented in presence of fiber composites with MA-g-PP compatibilizer because of enhanced interfacial strength. Similar observation was also reported in our earlier study.¹³

Morphology of the interface

SEM analysis of the fiber-polymer interface was carried out [Fig. 6(a,b)] for 50 vol % bamboo fiber composites with and without compatibilizers. The bamboo fiber-PP composite without compatibilizer shows [Fig. 6(a)] fibers bunched together, with many gaps in between while dispersion is marginally bet-

ter and relatively more uniform in the bamboo fiber-PP composite with compatibilizer [Fig. 6(b)].

Morphology of the fractured surface

The morphology of the impact test fractured surfaces of the fiber-PP interface was observed under the SEM for 50 vol % bamboo fiber composites with and without compatibilizers and presented in Figure 7(a,b). In Figure 7(a), where compatibilizer was not used, relatively, poor fiber-matrix adhesion was seen, whereas in Figure 7(b), improved fiber matrix adhesion is visible in the composites with compatibilizer. In some portion of the fractured surfaces as seen in Figure 7(b), the bamboo fibers are still embedded in the matrix whereas in Figure 7(a), the bamboo fibers are seen to be detached from the matrix and poor adhesion has left many gaps after pull out of fibers.

CONCLUSION

The physical, mechanical, and thermal behavior of the short BFRP composites at varying fiber volume percent has been studied. The properties of the extracted bamboo fiber+PP with and without compatibilizer, MA-g-PP are compared. The composites prepared with 5% MA-g-PP concentration at an optimum 50% fiber volume % had 37% increase in impact strength, 81% increase in the flexural strength, 150% increase in the flexural modulus, 105% increase in the tensile strength, and 191% increase in the tensile modulus. The HDT of the chemically treated fiber composites with MA-g-PP compatibilizer showed increase by 23 to 38°C (when compared to virgin PP) with increase in fiber volume from 30 to 50%. Thus, 50% bamboo fiber volume fraction with 1–6 mm fiber length and 90–125 µm fiber diameters coupled with MA-g-PP

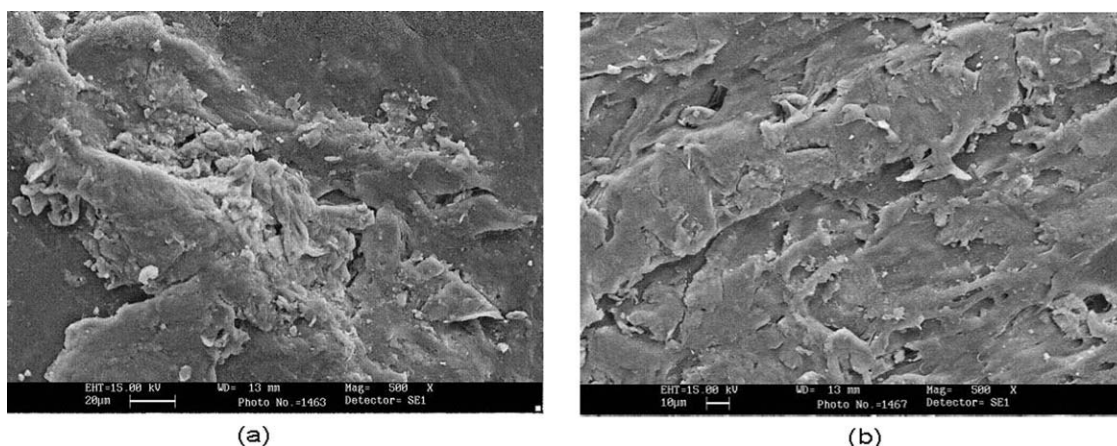


Figure 6 SEM micrograph of bamboo fiber-Polypropylene interface, (a) without MA-g-PP and (b) with MA-g-PP for 50% volume fraction of bamboo fiber.

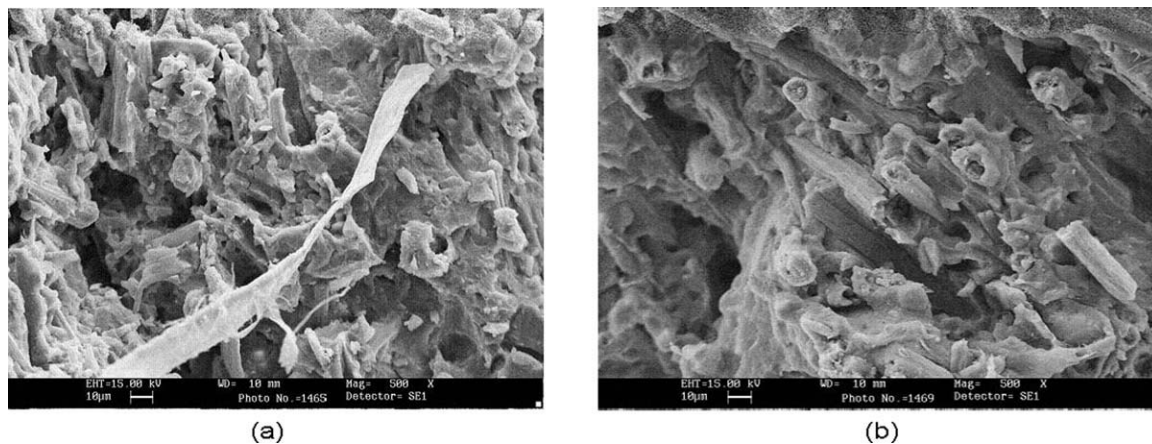


Figure 7 SEM micrograph of fractured surfaces of impact specimen of composites, (a) without MA-g-PP and (b) with MA-g-PP for 50% volume fraction of bamboo fiber.

compatibilizer is the recommended composition, where the mechanical properties are at maximum and the thermal stability is also quite high.

As all plant-based natural fibers have similarity in structure i.e., they are all lignocellulosic, consisting of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose, this study can provide some firsthand information for other possible natural fiber reinforced thermoplastic composites. Natural fibers other than bamboo with similar cellulose and lignin compositions and lower microfibrillar angles are also expected to exhibit similar improvements in mechanical and thermal properties in their reinforced thermoplastic composites.

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References

1. Bakshi, R. "The Hindu" online edition. July 02, 2000.
2. Lakkad, X.; Patel, J. M. *Fib Sci Technol* 1980, 14, 319.
3. Jain, S.; Kumar, R.; Jindal, U. C. *J Mater Sci* 1992, 27, 4598.
4. Jindal, U. C. *J Compos Matt* 1986, 20, 19.
5. Ismail, H.; Edyham, M. R.; Rirjosentono, B. *Polym Test* 2002, 21, 139.
6. Ismail, H.; Shuhelmy, S.; Edyham, M. R. *Europ Polym J* 2002, 38, 39.
7. Thwe, M. M.; Liao, K. *Compos: Part A* 2002, 33, 43.
8. Thwe, M. M.; Liao, K. *Compos Sci Technol* 2003, 63, 375.
9. Okubo, K.; Fujii, T.; Yamamoto, Y. *Compos: Part A* 2004, 35, 377.
10. Chen, X.; Guo, Q.; Mi, Y. *J Appl Polym Sci* 1998, 69, 1891.
11. Kasandariya, A. B.; Desai, A. B.; Shah, A.; John, N.; Patel, H. A. *Popular Plast Packaging* 2004, 9, 91.
12. Hujuri, U.; Chattopadhyay, S. K.; Ghoshal, A.; Uppaluri, R. *J Appl Polym Sci* 2008, 107, 1507.
13. Chattopadhyay, S. K.; Khandal, R. K.; Ghoshal, A.; Uppaluri, R. *J Appl Polym Sci* 2009, 113, 6.
14. Chattopadhyay, S. K.; Khandal, R. K.; Ghoshal, A.; Uppaluri, R. *J Appl Polym Sci* 2010, 117, 3.
15. Shin, F. G.; Xian, X. J.; Zheng, W. P.; Yipp, M. W. *J Mat Sci* 1989, 24, 3483.
16. Satyanaryana, K. G.; Sukumaran, K.; Mukherjee, P. S.; Pavithran, C.; Pillai, S. G. K. *Cem Concr Compos* 1990, 2, 117.
17. Verleye, G. A. L.; Roeges, N. P. G.; Moor, M. O. D. *Easy identification of plastics and rubbers*. Rapra Tech Ltd.; Shawsburg, U.K.; 2001; p 41.
18. Yuan, I.; Zhang, Y.; Zhang, X. *J Appl Polym Sci* 1999, 71, 333.
19. Dale, E. W.; O'dell, J. L. *J Appl Polym Sci* 1999, 73, 2493.