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Fabrication, Mechanical Characterization and Interfacial Properties of Bamboo and E-glass Fiber Reinforced Polypropylene-based Composites

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Abstract: Bamboo and E-glass fiber-reinforced polypropylene (PP) based composites (50 wt% fiber) were fabricated by compression molding. Tensile strength (TS), bending strength (BS), tensile modulus (TM), bending modulus (BM) and Elongation at break (%) of the bamboo fiber reinforced PP composite was found to be 62 MPa, 78 MPa, 4.96 GPa, 5.76 GPa, and 5.0%, respectively. Then, E-glass fiber-reinforced PP-based composites (50 wt% fiber) were also fabricated using the same methods and after that, the mechanical properties of the composites were evaluated. The TS, BS, TM, BM and Eb% of the E-glass fiber reinforced PP based composites were found to be 86 MPa, 88 MPa, 7.0 GPa, 12 GPa, and 16%, respectively. It was revealed that E-glass fiber reinforced based composites had higher TS, BS, TM, and BM compared to bamboo fiber reinforced-based composites. At ambient conditions, degradation tests of the bamboo/PP composite were performed in soil and it took 24 weeks which showed that after degradation mechanical properties of the bamboo fiber retained its original mechanical properties. After the flexural test, fracture sides of the E-glass/PP and bamboo/PP composites were investigated using scanning electron microscope (SEM) and the results revealed that bamboo-fiber reinforced based composites matrix adhesion less than the E-glass fiber reinforced based composites.

Keywords: Polypropylene, Bamboo Fiber, E-glass Fibers, Mechanical Properties, Interfacial Properties, Composites

1. Introduction

In the last century, synthetic fiber reinforced based polymer composites gained huge attention and its composites are used as a replacement of conventional structural materials such as wood, metals, and reinforced concrete. Synthetic fiber-based composite materials have some advantages such as high stiffness, more durable, ease of installation, good processability, relatively good resistance to environmental agents and fatigue, etc. A good number of matrices and fibers with a wide range of properties are being used for processing composites [1–3]. Nowadays, synthetic fibers are used as a reinforcing agent. Among all of the synthetic fibers nylon, modacrylic, olefin, polyester, carbon, aramids, glass fiber, rayon, acrylic, are the most common synthetic fibers which are used as a reinforcing agent and also used to manufacture composite materials. Natural cellulose-based fibers also use as a reinforcing agent such as, sisal, okra, pineapple leaf fiber, bamboo fiber, banana fiber, kenaf, hemp, coir, ramie, etc. are being used in composite manufacturing [4–5]. Among all the synthetic fibers, glass fibers are now most widely used fibers which are dominant over other synthetic fibers due to their low cost and comparatively better physico-mechanical properties. During the textile process, several thin strands of silica-based or other formulations of glass are extruded into many fibers with appropriate small diameters and using those fibers glass fibers are produced. Since ancient times, this technique of heating and drawing glass into fibers has been known to produce glass fibers. In 1936, for the first time, glass fiber was started to use commercially for several applications such as

automobile application, aerospace, civil engineering application, etc. The most commonly used glass fiber is E-glass ($54.3SiO_2$–$15.2Al_2O_3$–$17.2CaO$–$4.7MgO$–$8.0BO$–$0.6Na_2O$). E-Glass is a low alkali glass which mainly contains SiO_2 54 wt%, Al_2O_3 14 wt%, CaO + MgO 22 wt%, B_2O_3 10 wt%, and Na_2O + K_2O less than 2wt%. Some other materials may also be found at impurity levels [6-7]. E-glass has good insulation properties and can maintain these properties up to 815°C. E-glass fibers are often preferred as reinforcement in a polymer matrix due to their higher strain to failure, low cost, high compressive strength, better impact resistance, good fatigue life and good corrosion resistance in most common environments. End uses for regular fiberglass are mats, insulation, reinforcement, sound absorption, heat-resistant fabrics, high stiffness, high production rates, relatively low density, corrosion-resistant fabrics, non-flammable, resistance to heat, good chemical resistance, relatively insensitive to moisture, able to maintain strength properties, good electrical insulation and high strength fabrics [8, 9].

Last few decades, natural fibers are getting more attention all over the world because of its biodegradability, availability, and low cost, low density, multi-functionality, low abrasion, high toughness, good thermal properties, acceptable specific strength properties, etc. because of its properties natural fiber replace synthetic materials in applications such as boat hulls, bathtubs, and archery bows [10]. Moreover, natural fibers are eco-friendly fiber. Nowadays, people are more concerned about the environment so they show much interest in natural materials to produce 'green' products which are biodegradable and eco-friendly as well. Because of its environmentally friendly character, natural fibers are started to use in different sectors such as automotive, aeronautic and building industries [11]. Several studies have been already done on natural fiber-reinforced structures. The advantages of natural fiber-reinforced polymer composites are lower energy consumption, toughness, when compared with synthetic-based reinforced composites natural fibers manufacturing processes are relatively safer than others, and low cost of natural fibers compared to synthetic fibers [12-14]. For this, natural fibers can be used as an alternative of synthetic fibers which can be used to reduce the cost of the composites. In this research study, bamboo fibers are used which is one kind of natural fibers. Bamboo fibers are generally called 'natural glass fiber' which are used to create various living facilities and tools. Bamboo fibers are cellulosic fibers which are produced from bamboo plants. Bamboo plants are mostly found in tropical countries. It is considered as a composite material which consists of cellulose fibers embedded in a lignin matrix. Bamboo fiber consists of cellulose (73.8%), hemicellulose (12.5%), lignin (10.1%), pectin (0.4%), and aqueous extract (3.2%) [15-18].

After cotton, silk, linen, wool, bamboo fiber is the fifth-largest natural fiber. Bamboo fiber has good air permeability, non-abrasive nature, sound absorption, low cost, low weight, strong wear resistance, water absorption, and environmentally friendly green fiber and water. Bamboo fiber contains anti-bacterial substances, it contains many amino acids, UV resistance quality, therefore, it is known as 'natural green and economic fiber' and it is 100% biodegradable natural fiber [19]. Because of its good mechanical and physical properties, the bamboo fiber-reinforced composite structures become more popular among the people, researchers, and scientists as well as all over the world [20]. Several studies have been done on bamboo fiber reinforced polymer-based composites especially fiber reinforced thermoplastic polymers (polypropylene, polyethylene, polylactic acid, and polybutylene succinate) and fiber reinforced thermosetting resins (polyvinyl chloride, polyester, novolac, epoxy resins). In recent years researchers have focused on biodegradable composites which are made out of natural fibers and bio-resins. In this present studies, bamboo fiber and polypropylene was used [21-23].

In this research study, as a matrix material, polypropylene (PP) was used because of its excellent characteristics PP was used for composite fabrication. During manufacturing composites, PP behaves like thermoplastic engineering polymer. Because of its several imperative and useful properties such as high heat-distortion, high impact strength, transparency, dimensional stability, flame resistance, filling, reinforcing and bending properties PP is now widely used polymer in many applications. When PP mixed with natural fibers, it creates a natural synthetic polymer composite [24-25]. In this case, the quantity of the polymer-fiber interface is very important because it controls the mechanical properties of the resulting composites. Using the single-fiber fragmentation test, the interfacial properties of fiber-reinforced composites can be measured. Several scientists use this method to determine the interfacial properties of the fiber reinforced polymer composites [26-30].

The scanning electron microscope (SEM) also studied to get some information about the strength of fiber-matrix interactions and fiber surfaces. Using SEM analysis, interfacial adhesion or extensive interfacial failure surface of the composites can be seen. In this research study, fracture surface and interfacial bonding between bamboo fiber and polypropylene (PP) matrix can be shown by SEM analysis. Additionally, interfacial bonding and fracture surface of the E-glass fiber/PP can be analyzed using SEM methods [31].

The present investigation involves measuring the mechanical properties of the matrix (PP) and the composites (bamboo/PP and E-glass fibers/PP). The mechanical properties of bamboo fiber/PP composites were compared over the E-glass fiber/PP composites. Scanning electron microscope (SEM) was used to see the fracture surface of the composites of the bamboo fiber/PP and E-glass fiber/PP based composites. The ultimate aim of the present research works as to compare the mechanical and interfacial properties between bamboo/PP and E-glass fibers/PP composites.

2. Methodology

2.1. Materials

PP granules manufactured by Cosmoplene Polyolefin

Company Ltd, Singapore, were collected for this experiment. Figure 1 shows the Molecular structure of poly-propylene (PP). Bamboo fiber was collected from Sylhet Division of Bangladesh. Figure 2 shows the image of bamboo fiber. E-glass fiber (woven roving) was collected from Saint-Gobain Vetrotex India Ltd which was used in this experiment. Figure 3 shows the images of E-glass fiber (a) Mat and (b) roll.

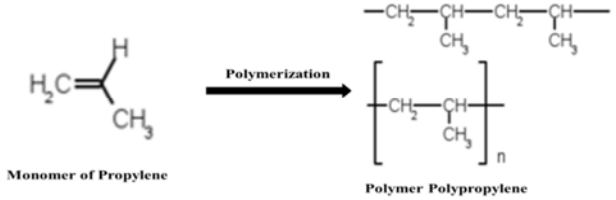

Figure 1. *Molecular structure of poly-propylene (PP).*

Figure 2. *Images of the Bamboo Fiber.*

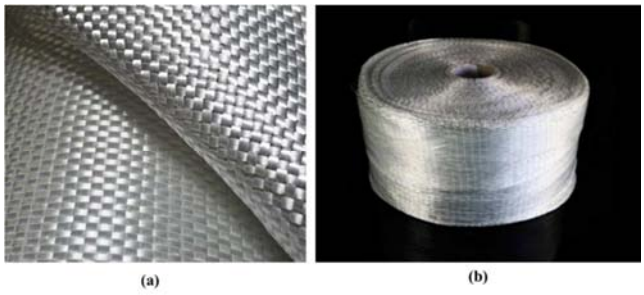

Figure 3. *Digital images of E-glass fiber (a) mat and (b) roll.*

2.2. Methods

2.2.1. Fabrication of Composites

For making one PP sheet, granules of PP (about 6 g) were placed between two steel plates and placed into the heat press (Carver, INC, USA Model 3856). Steel plates were pressed at 5 bar consolidation pressure at 220°C for 1 min. After that, at room temperature, the plates were cooled for 5-7min for another compression molding machine of the same model. The resulting PP sheets ware cut into desired size (12cm × 12cm) for composite fabrication. Then, bamboo reinforced composites were manufactured by using PP sheet on both sides. For making bamboo/PP based composites four layers of bamboo fabrics between five sheets of PP were used. The sandwich then placed into the two steel plates and heated at 180^0C for 5 min using 5 bar pressure. The fiber weight fraction for bamboo was calculated to be about 50%. E-glass/PP composites were also fabricated using similar methods in the same heat press. The fiber weight fraction for E-glass fiber PP based composite was calculated to be about 50%.

2.2.2. Testing of Samples

(i) Determination of Mechanical Properties of the Composites

The tensile properties such as tensile strength (TS), tensile modulus (TM), elongation at break percentage (Eb%) and bending properties such as bending strength (BS), bending modulus (BM) of the prepared composites were evaluated by using the Hounsfield series S testing machine (UK) with a cross-head speed of 1 mm/s at Institute of Radiation and Polymer Technology Laboratory, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh and the test specimens were prepared according to ASTM-D638-01 standard. Impact strength (IS) of the composites were measured using the Impact tester machine (model: HT-8041B IZOD, Serial no.: 7406) pendulum type, Germany and test specimens were prepared according to ASTM-D256 method. Hardness was determined by HPE Shore-A Hardness Tester (model 60578, Germany). Using a band saw, text specimens were cut into their required dimension. The dimensions of the test specimen were (ISO 14125): 60 mm × 15 mm × 2 mm.

(ii) Water Absorption (Water uptake tests)

Water absorption was done at 25^0C room temperature. This test was carried out in de-ionized water. Water uptake of bamboo fibers were done at room temperature and placed composites into static glass beakers containing 100 ml of deionized water. The size of the specimens was 20 mm× 10 mm× 2 mm. At 105°C, the samples were taken out from the de-ionized water and wiped by tissue paper and then dried for 6 h and after that weighed the composites [24-29]. Water absorption was calculated using the following formula:

$$W_g = \frac{W_a - W_o}{W_0} \times 100,$$

where, W_g is the water absorption (%), W_a denoted the mass of the samples after water treatment, and W_o indicated the mass of the specimens before immersion in the water.

(iii) Soil Degradation Tests of the Composites

Composite samples were buried in the soil (having at least 25% moisture) for different periods of time. After a certain period, samples were withdrawn carefully, washed with distilled water, and dried at 105°C for 6h, kept at room temperature (25°C) for 24h, and then measured for their mechanical properties.

(iv) Scanning Electron Microscopic Analysis

Bamboo fibers and E-glass fibers were examined by Philips scanning electron microscope (SEM) at an accelerating voltage of 10 kV. SEM specimens were sputter

coated with gold. After bending tests, fracture surfaces of the composites were also observed using SEM.

(v) Interfacial Properties of the Composites

Single fiber composite of each sample was prepared for one single filament of fiber (bamboo fiber and E-glass fiber) between two sheets of PP. Then sandwich placed between two steel plates and after that heat pressed (Carver, USA) at 180^0C for 1 min at 5 bar pressure and the plates were cooled in a separate press (Carver, USA) using 5 bar pressure at room temperature. The thickness of the specimen was 0.40 mm. The single fiber composite specimens size were 25 mm × 5 mm × 0.40 mm. Then those specimens were loaded on the Universal Testing Machine (Hounsfield series, UK) and after loading it showed repeated breakage of the fiber. For this test, 25 mm gauge length and 0.25 mm/min crosshead speed were used. During the test, a Hitachi microscope was attached to a monitor and using this microscope the whole experiment was monitored. After the end of the experiment, digital images of the breakage of the fibers were taken and these images were taken from the video graphic printer. Fiber fragment length at the saturation point was measured in this experiment. To reach the saturation level, the number of fragments over the 25mm gauge length at each load level (using 2N increments) was counted [28, 30]. The critical length (l_c) was then measured using this formula: $l_c = 4/3l_f$, where l_f is the average fragment length; l_f was calculated as the monitored length 25mm which was divided by the number of breaks observed within that length of the experimental fragment length distribution. The number of fragments had to be counted and after that, using the number of fragments critical length had been calculated. Using tensile testing filaments (the international standard BS ISO 11566), fiber tensile properties were obtained. During the experiment, a single fiber was placed on the paper frame with a gauge length of 25 mm and then sample was gripped in the tensile machine. The paper section were cut down before starting the test. During the test, 1 mm/min crosshead was used. Using Kelly–Tyson and Drzal equations, the IFSS of the composites was calculated. This formula $\tau_i = d \times \frac{\sigma_f}{2} \times l_c$ was used to calculate IFSS and this formula was formulated by Kelly and Tyson. In the above formula, d indicated the fiber diameter, σ_f denoted the single-fiber TS at the critical fragment length l_c [29, 32].

3. Result and Discussion

3.1. Water Uptake of Bamboo Fiber

Water uptake of bamboo fibers was measured by soaking the bamboo fiber in a static glass beaker contained deionized water at 25°C room temperature for 60 min. The results were presented in Figure 4. It was found that bamboo absorbs water in a typical manner. Initially, bamboo fiber absorbed water less rapidly and became static after 60 min. For instance, after 1 min of immersion bamboo fiber absorbed 16% water, but 38% and 58% mass gain evidenced after 10 and 60 min, respectively. From this investigation, it was clear that, bamboo fiber absorbed water more slowly. Bamboo fiber contains 42–49% cellulose, 26–27% pentosan, 25–26% lignin, 3–6% ethanol toluene extractives, and 1–2% ashes. This higher amount of lignin in bamboo fiber makes it less hydrophilic and slow down the water uptake process [11, 16-18].

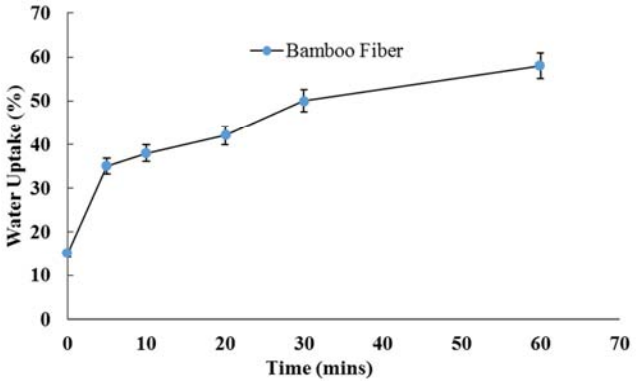

Figure 4. *Water uptake of the 50% bamboo fiber against different soaking period.*

3.2. Degradation Test of Bamboo Fiber in Aqueous Medium

Six weeks of degradation (mass loss) of bamboo fiber was performed in deionized water at room temperature (25°C), and the results are depicted in Figure 5. It was found that, bamboo fiber lost 3.0% of mass after 1 week of immersion in water but 15% and 24% mass losses were found in 3 and 6 weeks, respectively. On the contrary, bamboo fiber lost 2.5% of mass after 1 week of immersion in water but 14.0% and 23.5% losses of mass were found in 3 and 6 weeks, respectively. Because of hydrophilic nature, bamboo fiber takes time to degrade it into the aqueous medium [1, 12].

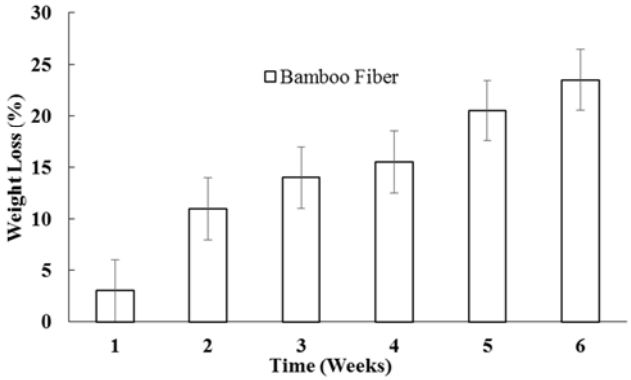

Figure 5. *Degradation of bamboo fiber in the aqueous medium at room temperature (25°C).*

3.3. Investigation of Mechanical Properties of the Composites

The mechanical properties such as tensile and bending properties of the PP sheet, bamboo fiber/PP and E-glass/PP, composites were evaluated, and the values given in Table 1 and Table 2. It was found that tensile strength (TS), tensile

modulus (TM), elongation at break (%), bending strength (BS), and bending modulus (BM), impact strength (IS) and hardness (Shore-A) of the PP sheet were found to be 22 MPa, 0.63 GPa, 398%, 28 MPa, 1.98 GPa, 4.47 kJ/m^2 and 95 (Shore-A) respectively. Bamboo fiber/PP based composites made of 50% fiber significantly improved the mechanical properties (TS, TM, Eb%, BS, BM and IS). TS, TM, BS, and BM for the bamboo fiber/PP composite were found 62 MPa, 4.96 GPa, 5%, 78 MPa, 5.76 GPa and 20 kJ/m^2 respectively. Bamboo composites gained 181.82% increase in TS and 178.57% increase in BS over that of the matrix PP. It was also found that TM, BM and IS improved by 687.31% and 190.91%, 347.43% respectively than that of the matrix material PP. On the other hand, percentage elongation at break (Eb%) was reduced drastically because of low Eb% of the fibers compared to PP. From this investigation, it was clear that bamboo fiber/PP based composites gained huge mechanical properties over the matrix material and thus indicated good fiber matrix adhesion. From Table 1 and Table 2, it was very clear that bamboo composite possessed a significant improvement in TS, BS, TM, and BM compared to the matrix PP. TS, TM, Eb (%), BS, BM and IS of E-glass fiber/PP composite were found 86 MPa, 7 GPa, 88 MPa, 12.0 GPa, and 37 kJ/m^2 respectively. It was revealed that the E-glass fiber/PP composites were found to have 290.91% and 214.29% improvements in TS and BS over the matrix PP. TM, BM and IS also improved and they increased by 1011.11%, 506.06%, and 727.74%, respectively, over the matrix material PP. The increased mechanical properties were attributed due to the reinforcement of the E-glass fiber with the matrix PP. E-glass fiber/PP based composites showed significantly higher TS, BS, TM, and BM over the bamboo/PP based composites. It was revealed that the E-glass fiber/PP composites were found to have 38.71% and 41.13% improvement of TS and TM over the bamboo composites. It was also reported that BS, BM, Eb% and IS also improved by 12.82, 108.33%, 220% and 85% than that of the bamboo/PP composites. Hardness (Shore A) of the E-glass composites was also better than that of the bamboo/PP composites.

Table 1. *Tensile and bending properties of PP sheet and the composites.*

Material	Tensile and bending properties				
	Tensile properties			Bending properties	
	Strength (MPa)	Modulus (GPa)	Elongation at Break (%)	Strength (MPa)	Modulus (GPa)
PP	22	0.63	398	28	1.98
Bamboo/PP composite	62	4.96	5	78	5.76
E-glass/PP composite	86	7	16	88	12.0

Table 2. *Impact strength of the PP sheet and the composites.*

Material	Impact Strength (kJ/m^2)	Hardness (Shore-A)
PP	4.47	95
Bamboo/ PP composite	20	96
E-glass/PP composite	37	97

3.4. Comparative Studies of the Degradation Tests of the Composites in Aqueous Medium

Degradation tests of the composites (bamboo fiber/PP and E-glass fiber/PP) were performed in soil at ambient conditions for up to 25 weeks. TS and BS values were plotted against degradation time as shown in Figure 6 and Figure 7. It was found that for bamboo/PP composites, both TS and BS decreased slowly with time but for E-glass/PP, a very slow decrease was observed. After 24 weeks of soil degradation, bamboo composites lost almost 37.77% and 30% TS and BS, respectively. On the other hand, E-glass fiber/PP composites lost 7.5% and 7.31% of TS and BS, respectively. Similarly, TM and BM also decreased over soil degradation time and the results were depicted in Figure 8 and Figure 9. It was found that, bamboo fiber/PP composites lost 24% and 20% of TM and BM, respectively, during soil degradation test. After 24 weeks of soil degradation, E-glass fiber/PP composites lost almost 4.47% and 9.09% of TM and BM, respectively. From this investigation, it was evident that E-glass fiber/PP composites retained much of their original mechanical properties than the bamboo fiber/PP based composites during soil degradation. Bamboo is a natural biodegradable fiber and it contains higher percentage of lignin and this fiber being cellulose based, it absorbs water within a couple of minutes indicating its strong hydrophilic character. Cellulose has a strong tendency to degrade when buried in soil [33-34]. During soil-degradation tests, water penetrated from the cutting edges of the composites in bamboo-based samples and degradation of cellulose occurred in bamboo; as a result, the mechanical properties of the composites decreased significantly. Whereas E-glass fiber/PP based composite shows hydrophobic characteristics which repel water thus retaining much of their integrity during exposure to the soil.

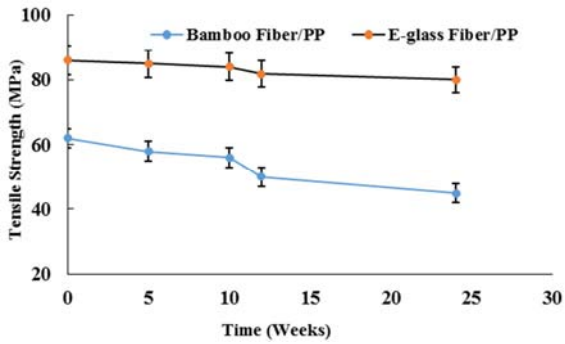

Figure 6. *Degradation of TS of the composites during soil degradation tests.*

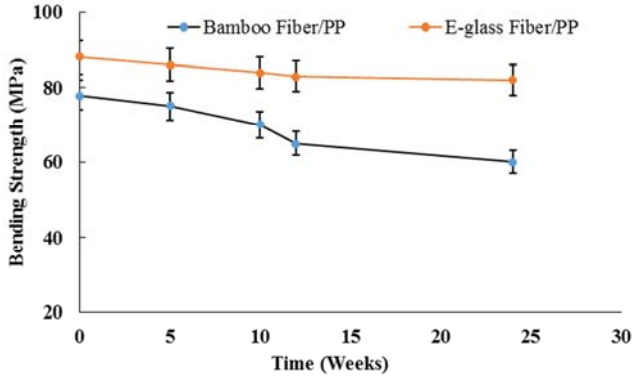

Figure 7. *Degradation of BS of the composites during soil degradation tests.*

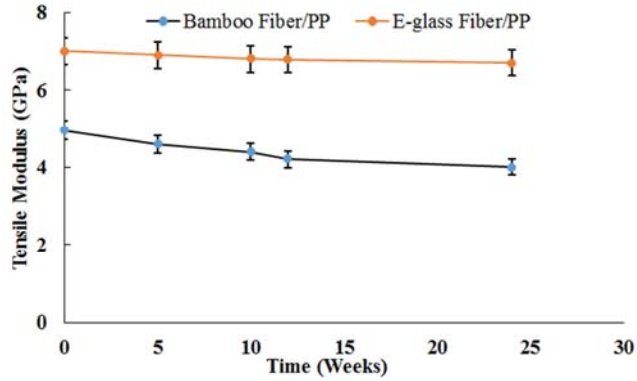

Figure 8. *Degradation of TM of the composites during soil degradation tests.*

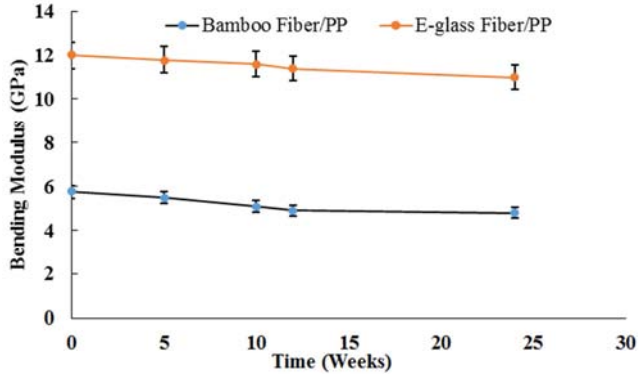

Figure 9. *Degradation of BM of the composites during soil degradation tests.*

3.5. SEM Images of the Composites

To find out the fiber matrix adhesion inside the composites, SEM studies were carried out. SEM images of the fractured sides of the bamboo fiber/PP composites (a) and the fracture surface of the E-glass fiber/PP (b) are presented in Figure 10. The SEM image of the fracture surface of bamboo fiber/PP explained that the fiber pull-out is quite low and fractures between bamboo fiber and PP matrix were clearly evident which indicated excellent fiber-matrix adhesion. Whereas, the SEM image of the fracture surface explains that the fiber pull-out is quite low and fractures between E-glass fibers and PP matrix are clearly evident which indicates excellent fiber-matrix adhesion. It also reported very few holes in the matrix suggesting very good bonding between E-glass fiber and the polymer matrix. From the SEM images of the fracture surfaces of both bamboo/PP and E-glass/PP, a clear pictorial view is evident and this reveals the interfacial properties of the composites as well as explains why bamboo-based composites have low mechanical and interfacial properties as compared to the E-glass-based composites. From the comparative studies of the mechanical properties between bamboo fiber/PP and E-glass fiber/PP composites, it was found that the mechanical properties of bamboo composites are quite low compared to that of the E-glass-based composites. So, further investigation will have to be carried out to reduce the hydrophilic nature of bamboo and to try and improve the interfacial bonds between bamboo and PP but retaining the inherent biodegradable properties of bamboo fibers. This research opens new doors for further study to bring the mechanical properties of bamboo composites closer to that of the E-glass-based composites.

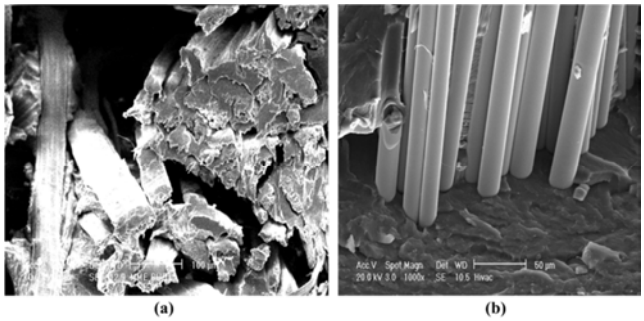

Figure 10. *SEM images of the fracture surface of Bamboo fiber/PP composite (a) and fracture surface of E-glass fiber/PP composite (b).*

4. Conclusion

Water uptake of bamboo fibers were studied and it was found that bamboo fiber gained higher percentage of water within a very short time. Bamboo fiber-reinforced PP-based composites (50% fiber by weight) were fabricated by compression molding, and the mechanical properties evaluated. TS, BS, TM, BM and Eb% of the composites were found to be 62 MPa, 78 MPa, 4.96 GPa, 5.76 GPa, and 5% respectively. Then, E-glass fiber-reinforced PP-based composites (50% fiber by weight) were fabricated and the mechanical properties were investigated. For bamboo-based composites, TS, BS, TM, BM and Eb% were found to be 86 MPa, 88 MPa, 7 GPa, 12 GPa and 16% respectively. From this investigation, it was found that E-glass fiber/PP composite showed almost 38.71% and 12.82% improvements in TS and BS over the bamboo composites. It was also revealed that TM and BM improved by 41.13% and 108.33%, respectively, than that of the bamboo/PP composites. Degradation tests of the composite in soil medium showed that, E-glass fiber/PP composites retained much of their mechanical properties compared to the bamboo fiber/PP composite. SEM images of the fracture sides of the composite supported the fact that bamboo fiber-based PP

composite had poorer fiber matrix adhesion than the E-glass fiber-based PP composite.

Author Contributions

Author 1: Kamrun N. Keya
(i) Conceived and designed and analysis data
(ii) Collected data
(iii) Performed the analysis
(iv) Wrote the paper
(v) Revised this manuscript
Author 2: Nasrin A. Kona
(i) Contributed data and analysis tools
(ii) Co-wrote the paper
(iii) Helped to revise the manuscript
Author 3: Ruhul A. Khan
(i) Supervised the whole research work
(ii) Corresponding Author
(iii) Review the manuscript

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Conflict of Interest

The authors have declared that there is no conflict of interest exists in this works.

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