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A Novel Strategy for Fabrication and Performance Evaluation of Bamboo/E-Glass Fiber-Reinforced Polypropylene Hybrid Composites

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Abstract: In this study, a novel strategy was used to prepare a hybrid composite of polypropylene (PP), reinforced by bamboo and e-glass fiber (BGRP) were fabricated using a single screw extruder, then compression molds were made in presence and absence by maleated PP (MP). The effect of BF and maleated PP on the mechanical properties (tensile strength, tensile modulus, and impact strength) of bamboo fiber reinforced PP (BFRP) composites and BGRP hybrid composites were studied. The tensile strength, tensile modulus, and impact strength of the BGRP hybrid composite were improved performance with an optimum strength observed at 2 wt% MAP treated with BF to GF ratio of 15:15. The fiber matrix addition was examined through scanning electron microscopy (SEM) which showed a relatively small gap between the fiber and the base matrix in the case of the MAP treatment hybrid composite. The rate of water absorption in the composites decreased due to the presence of E-glass fiber and coupling agent.

Keywords: Polymer Composites, PP, Coupling Agent, Bamboo Fiber, E-glass Fiber, Mechanical Properties, Water Absorption.

1. Introduction

Composite materials based on natural fiber reinforcement of thermoplastics have become the subject of extensive research and development around the world and are now commercialized, especially in the automotive industries, i.e. boardwalks, decking, fencing, roofing, and window profiles for outdoor applications (HU Zaman, 2020; Zaman & Khan, 2019). Short natural fibers such as jute, coir, flax, sisal, pineapple leaf fiber, strong thermoplastic composites (Khan, Roy, Akter, Zaman, Islam & Khan, 2012; Mishra, Misra, Tripathy, Nayak & Mohanty, 2001; Rout, Misra, Tripathy, Nayak & Mohanty, 2001) are gaining increasing attention for their emerging application in the aerospace, construction as well as packaging industries in a few flawed fields. Advantages of natural fibers in composites are low cost, low density, easy availability, biodegradability, lightweight, high strength to weight ratio, less wear and tear in processing machinery, etc. Despite the advantages, the use of natural fiber-reinforced composites has been limited due to the tendency to absorb high moisture, weak wettability, thermal stability during processing, and poor adhesion of natural fibers with synthetic parts (Mohanty, Misra & Hinrichsen, 2000). Inherent differences between high hydrophilic natural fibers and hydrophobic polymer matrices like PP and PE may result in difficulties in the dispersion of natural fibers along with poor polymer-fiber interfacial adhesion (Lee, Yang, Kim, Jeong, Lim & Lee, 2004). The weakness of the natural fiber composites can be improved by pretreatment of the natural fibers using physical (corona discharge treatment and UV radiations) or chemical methods (coupling agents and graft

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copolymerization) to improve the interaction between the natural fiber and the matrix. Properties of fiber-reinforced composites can be greatly influenced by the adhesion characteristics of the fiber–matrix interface. Compatibilizers to improve the mechanical properties of reinforced plastics, which improve the adhesion between the filler and the matrix and the nature of the interface (Valadez-Gonzalez, Cervantes-Uc, Olayo & Herrera-Franco, 1999). The established method for improving the interfacial adhesion of polymers and natural fibers is usually the use of a coupling agent, resulting in a better chemical between the polymer matrix and the particle surfaces (Feng, Caulfield & Sanadi, 2001). Various fiber surface treatments such as alkali/mercerization, silane, a combination of alkali and silane have been reported by several authors (Herrera-Franco & Valadez-Gonzalez, 2004; Rong, Zhang, Liu, Zhang, Yang & Zeng, 2002). Similarly, other methods include polar maleic anhydride grafted polypropylene (MAPP) which hydrogen bonds between the hydroxyl group of natural fibers and the carbonyl groups of the maleic anhydride section of MAPP (Keener, Stuart & Brown, 2004). This results in reducing the rate of moisture absorption and increasing the mechanical strength in the composites. Only a few studies are available today on the natural and synthetic fiber reinforced polymer matrix hybrid composites.

Hybridization of natural fibers with synthetic fibers is one of the techniques adopted to overcome some of the drawbacks that have been identified (Ahmed, Vijayarangan & Rajput, 2006). Hybrid composites are materials made up of a combination of two or more different types of fibers in a common matrix. Hybridization of those fibers with stronger and more corrosion-resistant synthetic fibers, for example, glass fiber or carbon fiber can improve the stiffness, strength as well as moisture-resistant behavior of composites and thus achieve a balance between environmental impact and performance. The mechanical properties improve due to hybridization. The properties are constantly increasing due to the addition of glass fiber. The mechanical properties of fiber skin core construction are higher than the dispersed fiber construction. Thomas and coworkers (Pothan, Thomas & Neelakantan, 1997) have proved that bananas, as well as SFs, can be used as effective reinforcements in a polymer matrix. These fibers were hybridized with glass fibers to obtain better mechanical performance. Abdul Khalil et al. (Khalil, Hanida, Kang & Fuaad, 2007) reported that water absorption and thickness swelling of oil palm fiber/glass hybrids reinforced with polyester composites were enhanced by the attachment of glass fibers when the components of oil palm fiber are increased. Bamboo was selected for this work due to its better mechanical performance about other natural fibers. Based on its physiological characteristics, the ultra-structure and the fracture mechanism of plants establish bamboo itself as a superior natural fiber among other known natural fibers (like jute, coir, sisal, straw, banana, etc.). Jain et al. (Jain & Kumar, 1994) reported that bamboo contains 60% cellulose compared to lignin (~ 32%), with relatively small microfibrillar angles (2–10°). This information about bamboo supports its high tensile strength. In the present investigation, an attempt has been made to develop hybrid composites where the percentage of E-glass and bamboo fiber in the composition was different to evaluate the effect of hybridization on the properties of the composite. The enhancement in mechanical properties of PP reinforced with E-glass as well as a lignocellulosic BF has been examined. The effects of E-glass fiber hybridization on water absorption tendencies of the composites have also been studied.

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2. Experimental

2.1 Materials

Granules of PP were purchased from the Cosmoplene Polyolefin Company Ltd. (401, Ayer Merbau Road, Singapore), with a density of 0.90 g/cm^3 and a melt flow rate of 14 g/10 min (2.16 kg at 230°C) has been used as the base matrix for this study. The bamboo used in this work belongs to the species of Bambusa Paravariabilis, which grows abundantly in Asia. Bamboo fiber (2–4 mm length, diameter 70–110 μm, density 0.863 g/cm^3) and E-glass fiber (2–4 mm length, density 2.58 g/cm^3) were used as reinforcement. The properties of bamboo and E-glass fiber (GF) are enumerated in Table 1. Maleic anhydride grafted PP (MAP) (MA content: 0.6 wt%) pellets with a melt index of 115 g/10 min and graft efficiency of 0.485 wt% were purchased from Aldrich Chemicals (Milwaukee, Wisconsin, USA).

Table 1: Physical and Mechanical Properties of Bamboo and E-glass Fiber

Fiber Type	Density (g/cm^3)	Av. Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (MPa)	Moisture Absorption (%)
Bamboo	1.4	60-100	450-800	18500-30000	9
E-glass	2.5	5-20	2000-3500	70000	-

2.2 Fabrication of Hybrid Composites

BFs were scoured in a hot detergent solution (2%) at 70°C for 1 h to remove dirt and key components, then washed with distilled water, dried in a vacuum oven at 60°C for 2 h. The dried fibers were cut to the desired length of 2–4 mm using an electronic fiber-cutting machine. Before melt blending, both bamboo and E-glass fibers are pre-dried in a vacuum oven at 70°C for 1 h and 105°C for 25 h to remove surface moisture. BFs at different weight percentages (10, 20, 30, and 40%) and PP were compounded with and without MAP in an extruder (axon ab Plastic Machinery, S-26550, Machine Type BX 25, and Sweden). The process was performed at a heating program of 175-180-185-180-175°C with a screw speed of 15 rpm along the extrusion line. Repeated (3 times) extrusion was performed for a homogeneous mixture in BF and polymer melts. Then the melt mixture was cold-pressed to make the composite (3 mm thickness) using hot press (Carver Laboratory Press, model 2518, USA). A similar procedure was adopted for a homogenized melt mixing of BF/GF reinforced PP hybrid composites with and without MAP as coupling agent at a different weight ratios of Bamboo: E-glass (20:10, 15:15, and 10:20). MAP was used as a coupling agent to modify the interfacial region between the fiber and the matrix, the concentration of which was 2 wt%.

2.3 Testing and Characterization

2.3.1 Mechanical Testing

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Test specimens for analyzing mechanical properties were dried in a vacuum at 70°C and then kept in a sealed desiccator for 24 h before testing. These conditioned specimens were subjected to mechanical testing, and the average from the five measurements was reported. Corresponding standard deviation along with the measurement uncertainty value for the experimental data showing maximum deviation is also included.

2.3.1.1 Tensile Testing

The tensile strength and tensile modulus of virgin PP, untreated and MAP treated bamboo fiber reinforced PP composites (BFRP), and bamboo–E-glass fiber reinforced PP hybrid composites (BGRP) were measured using an Instron universal testing machine (Hounsfield series S testing machine, UK). Test specimens of dimensions 100 × 10 × 3 mm^3 were cut as per ASTM (American Society for Testing Materials) standard D 638 specifications. The tensile tests were conducted at a crosshead speed of 20 mm/min and a gauge length of 20 mm. The tensile stress was applied in the direction of the fiber axis (longitudinal axis). The temperature and humidity for this test were maintained at 25°C and 50%, respectively.

2.3.1.2 Impact Testing

Izod impact strength for the specimens was determined having dimensions 63.5 × 12.7 × 3 mm^3 as per ASTM-D 256, with ‘‘V” notch depth of 2.54 mm and notch angle of 45°, using impactometer 6545 (CEAST, Italy).

2.3.2 Microstructural Examination of Fracture Surfaces

The existence of fractured surfaces of the composites and the hybrid composite with and without MAP treatment was observed at 20 kV with a scanning electron microscope (SEM, model JEOL JSM-6301F). Before SEM, samples were covered with the silver under vacuum, using a silver sputter (50 nm) coater layer to avoid the accumulation of electrical charge.

2.3.3 Water Absorption

To measure the water-absorbing properties of the composites, three rectangular specimens of dimensions 25.4 mm × 76.2 mm were cut from a composite sheet. Three replicate samples were tested as per ASTM D-579-99 procedure and the results were presented as an average of the three. The samples were dried by heating in an oven at 70 ± 4°C for 24 h, subsequently cooled in a desiccator, and weighed to the nearest 0.001 g. All samples were immersed in distilled water for about 24 h at 25°C. The extra water on the composite surfaces was wiped with a cloth and then specimens were weighed. The water absorption, WA (%), was determined from the formula:

$$WA\ (\%) = 100[(W_2 - W_1)/W_1] \quad (1)$$

Where W_2 is the sample weight after immersion for 24 hours in water and W_1 is the sample weight before immersion.

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3. Results and Discussion

3.1 Mechanical Properties of the Composites

3.1.1 Tensile Properties

Tensile strength and tensile modulus of untreated BFRP and MAP (2 wt%) treated composites with BF content varied from 10–40 wt% are illustrated in Figure 1 (a). Virgin PP exhibits a tensile strength of 30.5 MPa and tensile modulus of 457 MPa. The tensile strength showed an increasing tendency up to 30 wt% of fiber loading with a subsequent decreased in tensile strength at 40 wt% of fiber loading. However, the tensile modulus increased steadily as the loading level of BF increased from 10 to 40 wt%. At 10-40 wt% loading level, the tensile modulus increased from 21.7 to 113.1% compared to virgin PP. The tensile strength of BFRP at 30 wt% of fiber loading showed an improvement of 38.3% when compared with the virgin PP matrix. This increase in tensile strength reveals that BFs with uniform cross-sections and high aspect ratios can support effective stress transformation from the matrix. At low BF loads, the improvement of mechanical performance is low because low fiber load is compared with 30 wt% of BF, the performance of fiber orientation composites plays a major role. Poor fiber alignment at low fiber loading results in a larger free space for fiber movement thereby reducing the effective stress transfer from fiber to the matrix. Furthermore, a minimum critical weight ratio fiber loading is required to reinforce the matrix, hence fiber loading at 10 wt% may not be sufficient to effectively reinforce the PP matrix and transfer stress. In this study, 30 wt% of BF loading is the critical wt% in which the fibers are sufficient to restrain the matrix leading to uniform stress distribution and offering effective reinforcement to the matrix. Deterioration in tensile strength at the higher fiber content of 40 wt% is a direct consequence of poor fiber/matrix adhesion, which leads to microcrack formation at the interface under loading and non-uniform stress transfer due to the fiber agglomeration in the matrix. The higher weight percent of fiber content also leads to an increase in fiber–fiber interaction, resulting in difficulties in the dispersion of the fibers within the polymer matrix.
One of the main factors that affect the mechanical properties of the BFRP composites is the adhesion between the fiber and the matrix. It is known that the use of the compatibilizer can improve the adhesion, and hence, improve the mechanical properties of the composites. Because BF surface is hydrophilic characterized by polar hydroxyl groups and because PP is hydrophobic polyolefin, the adhesion between the two materials is expected to be rather poor. Therefore, in this study, we used MAP as a compatibilizer to improve adhesion because maleic anhydride is strongly associated with the hydroxyl groups on the BF surface. With the incorporation of a compatibilizer (MAP), a further increase in tensile strength and modulus was observed for all the samples. BF content of 30 wt% has been retained for evaluation of the mechanical behavior of the composites in the presence of MAP. The tensile strength and modulus of 30 wt% reinforced BFRP compatibilized with 2 wt% of MAP increases to the tune of 16 and 15%, as compared with uncompatibilized BFRP with the same amount of BF reinforcement. This is mainly due to the covalent bond between the anhydride group of MAP and the hydroxyl groups of BF, along with chain entanglement between MAP and PP chains that create a good stress transfer at the interface.

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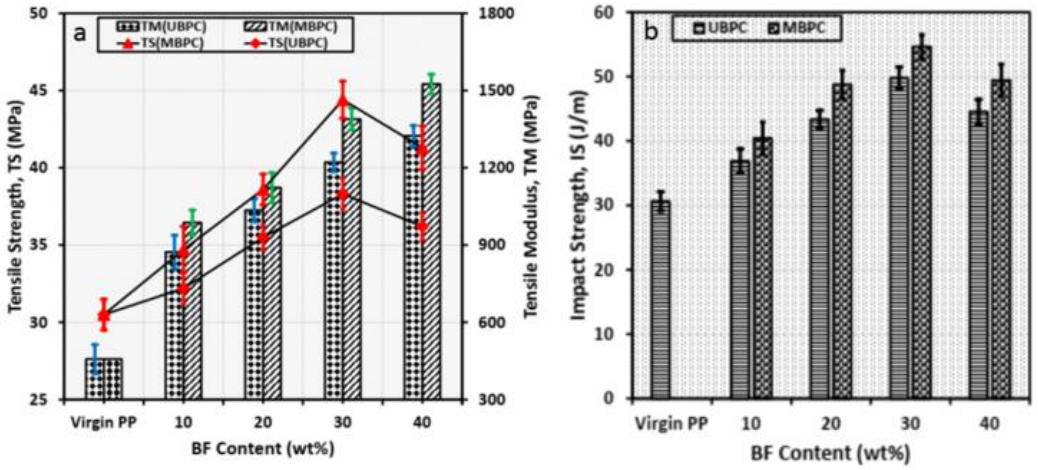

Figure 1: (a) Tensile strength and tensile modulus, and (b) impact strength of unmodified and modified BF reinforced PP composite

In the case of BGRP hybrid composites, the total fiber content was fixed at 30 wt% due to the optimum tensile strength in comparison to other variations. At a total of 30 wt % of fiber content, the amount of BF was replaced by 10, 15, and 20 wt% of E-glass fiber and BGRP hybrid composites have been prepared. It was observed that the tensile properties of BGRP hybrid composites increased substantially with the partial replacement BF with E-glass fiber. It was found that the E-glass fiber content increased from 10 to 15 wt%, the tensile strength of BGRP hybrid composites also increased from 5 to 13 wt% when compared with BFRP composites, when both bamboo and E-glass fiber were in the ratio of 50:50, i.e., 15 wt% of bamboo and 15 wt% of E-glass fiber had a total strength of 30 wt%. A similar enhancement in tensile modulus from 3 to 14% was observed. This behavior is mainly due to the replacement of weak and less stiff BFs with stronger and stiffer E-glass fibers. Kalaprasad et al. (Kalaprasad, Thomas, Pavithran, Neelakantan & Balakrishnan, 1996) have already reported that increasing the mechanical performance of banana/glass/HDPE hybrid composites has been mainly due to better dispersion of banana fiber, which includes GF. Above 15% of E-glass fiber content, the mechanical properties declined due to the agglomeration of E-glass fiber and fiber–fiber interaction, which in turn results in a negative hybrid effect. The addition of compatibilizer (2 wt%), results in an increase in the tensile strength and tensile modulus. BFRP composites prepared at 2 wt% of MAP and 30 wt% of BF displays efficient fiber-matrix interfacial adhesion. Incorporating 2 wt% of MAP in the BGRP hybrid composite prepared at 15: 15 wt% of BF:GF improves tensile strength and modulus at 10 and 9%, respectively. With the MAP incorporation, the anhydride group can present the MAP covalently to the interface BF surface and the glass fiber bond to the hydroxyl group of the SiO group thereby forming a strong interfacial region. In the form of acid, maleic anhydride can properly interact with the surface of the fiber through acid-base interactions. The improved interaction and adhesion between the fibers and matrix, either through covalent bonding or acid-base interaction (such as H-bonding), or a combination of both, leads to the better matrix to fiber stress transfer. The MAP provides a potential covalent bond at the interface with the chain entanglement between the MAP and PP chains of the hydride group and the hydroxyl group of BF and the SiO group of glass fiber. Bisanda and Ansell (Bisanda & Ansell, 1991) also reported that surface treatment of natural fiber improves the adhesive characteristics of banana fiber by removing

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the hemicelluloses, thereby producing a rough surface topography which results in improved fiber–matrix interface adhesion and an increase in the mechanical properties.

3.1.2 Impact Strength

Impact strength of a composite is a measure of the ability of the material to resist the fracture failure under stress applied at high speed and is directly related to the toughness and the ability of the materials to absorb applied energy (Rozman, Tay, Kumar, Abusamah, Ismail & Ishak, 2001). The fibers play an important role in the impact resistance of fiber-reinforced composites as they interact with the crack formation and act as a stress-transferring medium. The impact strength of BFRP and BGRP with and without MAP are exhibited in Figures 1(b) and 2(b). Virgin PP showed an impact strength of 30.6 J/m. The addition of 30 wt% of BF increased the impact strength by 63% due to better dispersion of fiber and effective stress transfer between the fiber and the matrix at this composition. At higher BF loading, the impact strength declined due to fiber-fiber contact increased and breakage of fiber occurs within the composites. This increased fiber-fiber contact reduced the effective stress transfer between the fiber and matrix. The amount of impact strength at 30 wt% of BF loading was 30.6 J/m, which increased to 51.45 J/m with the addition of 15 wt% E-glass fiber. A nearly 68% increase in impact strength of BGRP hybrid composites was observed at 15:15 wt% ratio of bamboo and E-glass fiber due to the synergistic effect of both fibers. The addition of MAP (2 wt%) between BFRP and BGRP has further improved the strength of impact strength due to the flexibility of the molecular chain of the interface, resulting in relatively high energy absorption.

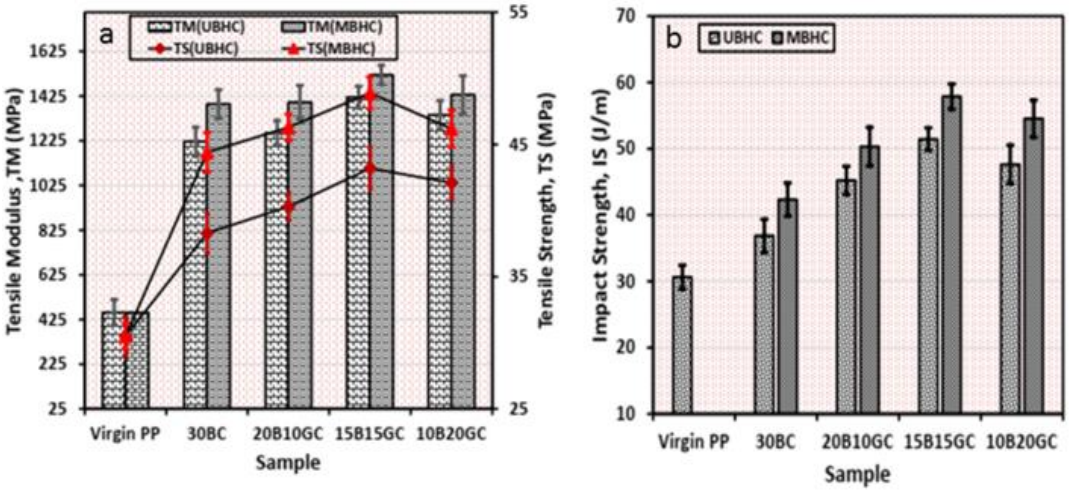

Figure 2: Effects of GF content on the (a) Tensile strength and tensile modulus, and (b) impact strength of virgin PP, unmodified BFRP, and modified BGRP composites

3.2 Scanning Electron Microscopy Studies

Figures 3(a) and (b) represents the SEM micrographs of the fracture surfaces of BFRP composites with 30 wt% of BF and BGRP hybrid composites with a 15:15 wt% ratio of BF and E-glass fiber. From Figures 3(a) and (b) micrographs, fiber breakage, fiber pullout, distinct gaps or/void were observed, which indicated poor adhesion or interaction. The fractured surface

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of the BGRP hybrid composites showed even more brittle texture with extensive fiber fractures and fewer fiber pullouts. However, evidence of improved BF and PP matrix adhesion can be seen in the MAP-linked BFRP (Fig. 3C) and BGRP (Fig. 3D) composites where fiber pullouts are less extensive. This confirms interfacial bonding anhydride groups of MAP with the –OH groups of BF and SiO group of the glass fiber. This characteristic of the composite with MAP causes brittle deformation of the composite when tensile stress was applied. The presence of MAP can increase the effective surface area available for contact between the matrixes and reduce the diameter of the BFs thereby increasing their aspect ratio resulting in increased compatibility with the BF and PP matrix. Improving wettability properties and increasing aspect ratios can offer better fiber-matrix adhesion and improve stress transfer, which ensures improvement of more mechanical properties. Furthermore, it was also observed that in the case of MAP treatment composites, the fibers were pulled together with the bulk matrix to ensure efficient interfacial adhesion. The morphologies of the fractured surfaces of the composites reflect the reasons why the mechanical properties have changed and instead of the reasons for fixing the mechanical properties of this polymeric composite.

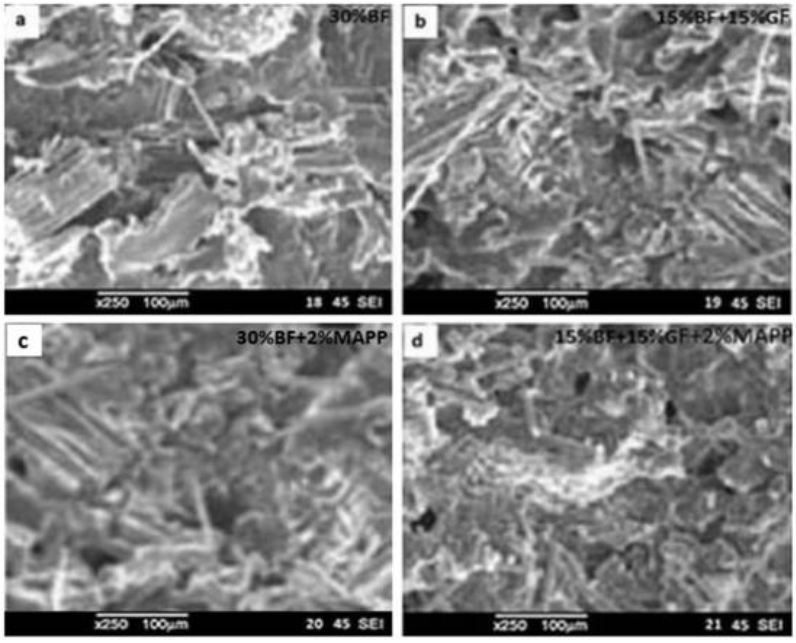

Figure 3: SEM images of (a) 30% BF + PP; (b) 15% BF + 15% GF + PP; (c) 30% BF + 2 wt% MAP + PP, (d) 15% BF + 15% GF + 2 wt% MAP + PP

3.3 Water Absorption

Water absorption and dimensional stability of lignocellulosic fiber composites is an important physical property that determines their end-use applications. Absorption of water by composites may result in a reduction of some mechanical and thermal properties and should be considered when selecting their applications. The moisture absorption caused a decrease in the mechanical properties of the hybrid composite. It is difficult to eliminate the absorption of moisture in the composite without using expensive surface barriers on the composite surface. Water absorption in BF-based composites can lead to a buildup of moisture in the

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lignocellulosic fiber cell wall and in the BF fiber-matrix interface region. The moisture build-up in the cell wall could result in fiber swelling and affect the dimensional stability. Figure 4 shows the effect of BF and MAP on the percentage of water absorption behavior of BFRP composites and BGRP hybrid composites at 25°C for 24 h was investigated. Virgin PP showed minor water absorption as expected. This indicates that the maximum percentage of water absorption with 30 wt% of BF (denoted as 30BC) because hydrophilic BF may have a hydrogen bond with the hydroxyl group in the water molecule. The addition of 2 wt% MAP to 30BC showed 1.9 times lower the water absorption than 30BC. This can be explained by the improved fiber-matrix interfacial interaction due to the coupling effect of MAP with –OH groups of BF resulting in a less hydrophilic composite. Replacement of BF with GF decreases the moisture absorption in the hybrid composites due to negligible water absorption capacity of water-impermeable GF, as compared with BF. GF acts as a barrier to the BF, thus preventing direct contact between the BF and water. However, in cases of BGRP (15 wt% of BF and 15 wt% of GF) with 2 wt% MAP, the water absorption was reduced considerably by 42% as compared with BGRP of the same composition without MAP. This can be explained by the results of improved fiber/matrix interfacial interaction results from the coupling effect of MAP with –OH group as well as SiO groups of glass fibers, resulting in the less hydrophilic composite. The improved fiber-matrix interfacial bonding also reduces water accumulation in the interfacial voids that prevent water from entering the BF.

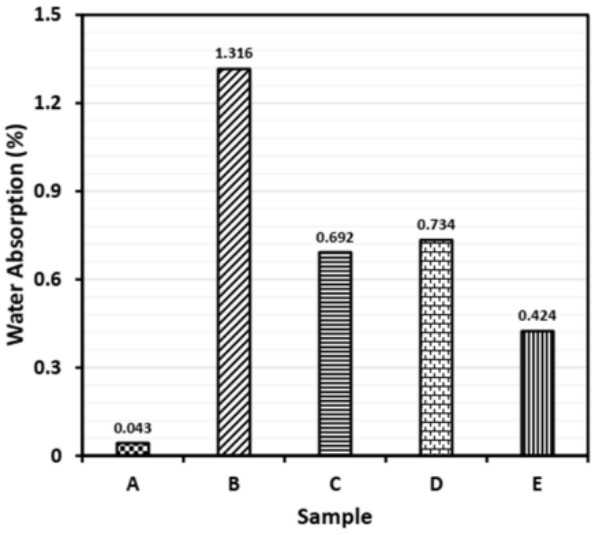

Figure 4: Water absorption (%) of (A) Virgin PP; (B) PP + 30% BF; (C) PP + 30% BF + 2 wt% MAP; (D) PP + 15% BF + 15% GF; (E) PP + 15% BF + 15% GF + 2 wt% MAP

4. Conclusions

This study inspected the effects of BF content of BFRP composites and GF loading of BGRP hybrid composites as well as the effect of the addition of MAPP coupling agent on the microstructure and mechanical properties. The following conclusions are given below:

1. Mechanical properties including tensile strength, tensile modulus, and impact strength improved as BF loading increased. With considering microstructure and mechanical

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properties, 30 wt% of BF loading was found to be optimal fiber loading for BFRP composites.

2. In the case of BFRP (30 wt% of BF) and BGRP (15 wt% of BF and 15 wt% of GF) with 2 wt% of MAP, the mechanical properties were increased considerably as compared with BFRP and BGRP composites of the same composition without MAP.
3. The improved interaction between bamboo/E-glass fiber and PP after MAP treatment, which was also verified from the SEM micrographs of the fractured surfaces in the composites, indicated that MAP could efficiently improve the fiber–matrix adhesion in the hybrid composites when used at an optimal concentration.
4. The water absorption of composites decreased by the process of hybridization.

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