Kathmandu University Journal of Science, Engineering and Technology, Vol. 17, No. 1, June 2023

Kathmandu University
Journal of Science, Engineering and Technology

Study of the mechanical properties of bamboo and glass fiber reinforced hybrid polymer matrix composites

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Abstract

Bamboo and glass fibers reinforced hybrid epoxy matrix composites were produced by stir casting method and the effects of production parameters (temperature, drying time, particle concentration, and bamboo-to-glass fiber ratio) on the mechanical properties were investigated. Overall optimum fabrication parameters are a bamboo fiber drying temperature of 25°C, a drying time of 20 mins, a particle size of 0.75 mm, and a bamboo-to-glass fiber ratio of 1:3. An in-depth analysis of the results shows that the improvement of different composite properties can be specifically targeted using different parameter combinations. Specifically, the shortest fibers below 0.75 mm, dried at room temperature for 60 minutes, and a bamboo-glass fiber ratio of 1:3 yielded the highest tensile strength of 7.47 MPa, which represents about 120 % increase as compared to unreinforced epoxy. Similarly, the longest fibers between 1 to 2.8 mm, dried at 110°C for 60 minutes, and a bamboo-glass fiber ratio of 1:1, exhibited the highest impact energy of 37.2 J, corresponding to about 79 % improvement. Moreover, the medium length fibers between 0.75 and 1 mm, dried at 80°C for 60 minutes, and a bamboo-glass fiber ratio of 3:1, exhibited the highest hardness of 16.73 HV, translating to 37% increase. Sample S8, which is the hybrid reinforced composite containing <0.75 mm bamboo fiber-particle size exhibited the lowest wear rate of 1.09 g/Nm implying the highest wear resistance. All these show the effectiveness of the mixture of bamboo and glass fibers in improving the mechanical properties of the composites. However, excessive bamboo concentration led to a significant reduction in wear properties.

Keywords: Bamboo-glass fibers; Epoxy resin; Hybrid composites; Mechanical properties

1. Introduction

The increase in technological advancement has facilitated much development of composites for various applications. In composites, materials are combined via some methods to use their virtues better while minimizing the effects of their deficiencies. This optimization process can release a designer from the constraints associated with selecting and manufacturing conventional materials. An engineer can use tougher and lighter materials with properties tailored to suit specific design requirements and simplify the fabrication of complex shapes. The complete rethinking of an established design in composites can often lead to cheaper and better solutions [1].

Public attention is now being placed on environmental-friendly composite materials made from natural fillers and polymeric materials. Eco-composites are made of natural materials that are nontoxic and biodegradable. The development of eco-composite materials has accelerated rapidly, primarily due to improvements in process technology and economic competitiveness [2]. Many research groups have directed their studies toward defining numerous combinations of biodegradable matrix/natural fillers to promote new biodegradable composites with improved mechanical properties and achieve products at a lower cost. Wood flour is among the most promising natural fibers for polymer composite reinforcement [3-5].

Generally, polymers exhibit low resistance to deformation and low impact fracture energy, which limits their application in many areas. In particular, their strength and stiffness (modulus of elasticity) are low compared to metals and ceramics. In order to overcome these shortcomings, fiber reinforced polymer matrix composites (FRPMCs) have been developed [6-11]. Natural fibers (organic fillers) such as jute, flax, ramie, bamboo fiber, coconut fiber, coir, hemp, coir, sisal, banana fiber, and pineapple are often stronger compared to inorganic fillers. Therefore, they can be effectively utilised for composite reinforcement in various applications. In addition, natural fibers have the advantages of low-density, low cost, broad availability, renewability, biodegradability, and ease of preparation. In addition, natural fibers do not need to be artificially produced thereby saving energy consumption and making them more environmental-friendly. Moreover, resulting composites have exhibited lower abrasiveness compared to composites reinforced with traditional fibers [6-11].

Several studies have been conducted to modify the properties of epoxy resin by reinforcing them with natural fibers and other synthetic fillers or with dissimilar natural fibers to develop hybrid epoxy bio-composites [12]. Natural fibers can be readily extracted from flax, jute, and bamboo using water retting, mechanical decorticator, and chemical retting. Combining dissimilar fibers can produce hybrid composites with increased load-bearing capacity than mono reinforced composites. The dissimilar fibers can be arranged optimally in specific direction while the surrounding matrix maintains them in the desired location and orientation [10, 13]. In this context, many researchers have focused attention on the effect of bamboo fibers in polymer matrix composites in recent years [14-16]. The current study aims at contributing in this effort of investigating bio-ecofriendly fillers for the development of novel engineering materials. The focus is to develop hybrid epoxy resin poly-

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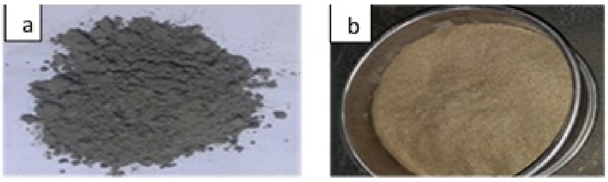

Figure 1: (a) Sieved particulates of (a) glass fibers (b) bamboo fibers.

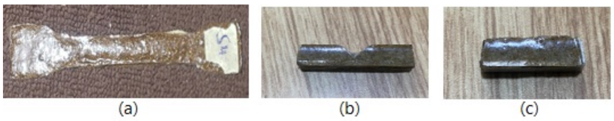

Figure 2: Cured samples for: (a) tensile test; (b) impact test; and (c) microstructural examination.

mer matrix composites with bamboo and glass fibers hybrid reinforcement.

2. Methodology

2.1. Production of samples

The samples were produced using bamboo and glass fibers, epoxy resin, and amine-based hardener. Using the method of water retting, the bamboos were split at the nodes and divided into sections along the fiber length. The outer layer of each strip was then peeled-off and the strips were soaked in water for four weeks, which allowed softening of the bamboo strips and removing lignin and hemicellulose. Subsequently, the bamboo strips were divided along the fiber length to obtain a fiber bundles diameter between 2 mm and 3 mm. The bundles were ground using a grinding machine and sieved to the desired particles size (<0.75 mm, 0.75-1 mm, and 1-2.8 mm) using British standardised sieves (BSS). Finally, the fibers were dried at 25°C, 80°C, and 110°C. Similarly, dried glass fibers were ground and sieved to 2.8 mm particle size. The fibers are shown in Fig. 1(a) and (b). The epoxy resin and hardener were weighed using adventure electronics' weighing balance. A weight ratio of epoxy resin–to-amine-based hardener of 3:1 was used to constitute the sample matrix. A wooden mould, which was lined with paper tape for easy removal of the samples, was made for the production of the samples. The formulations of the two control samples (C1 and C2) and nine test samples (S1-S9) in weight percent is shown in Table 1. 20 wt.% reinforcements were mixed with different fractions of bamboo fiber-to-glass fiber ratios of 1:3, 1:1 and 3:1. For composite samples production, bamboo fibers, glass fibers, epoxy resin, and hardener were mixed and stirred well for proper blending. The mixture was poured into the mould and allowed to solidify. The samples were removed from the mould for tensile, impact, and microstructural tests. Some of the samples are shown in Fig. 2a to 2c.

2.2. Microscopy and mechanical testing

Microstructural characterisation was carried out on the samples using a scanning electron microscope (SEM) at 500X magnification. Mechanical testing was performed on thirty-three samples with two controls (C1and C2) and 9 test samples (S1, S2, S3, S4, S5, S6, S7, S8 and S9) with three trials per sample. The flat tensile test samples were fabricated to ASTM D3039 standard dimensions with a reduced gauge length of 12.5 mm. Tensile testing was performed until fracture of the samples using an XLC digital universal tensile testing machine. Impact testing was conducted on 55 mm × 10 mm × 10 mm dimension samples with a 2 mm deep V-notch at the center using an Izod impact-testing machine according to ASTM D256 standard. The striking pendulum was released from a height of 1.5 m, hitting the sample with a velocity of 5 ms^{-1}. The energy absorbed to break each sample was read from the dynamometer. For microhardness testing, the samples were polished using a surface grinder-polisher. Microhardness testing was then done according to ASTM E384 standard using a Vickers hardness tester with a test load of 1.91N. The specific abrasive wear rate was measured using a pin-on-disc set up, the counter surface was a grounding paper made of aluminum oxide abrasive. A custom-made pin on disc testing machine was used according to ASTM G99 standard with a load of 11.25 N and a rotating speed of 125 rpm for 2 min. Prior to the wear test, the initial weight of the samples were taken and subsequently repeated after, with the aid of electronic weighing balance to 0.01 mg accuracy. To avoid over-estimation, the worn-out samples were thoroughly cleaned with wool soaked in acetone and wear particles removed. The difference between the initial weight and final weight was designated as mass loss, Δm. Wear rate was determined according to eq. 1 [17].

Table 1: Input materials formulation.

Sample	Bamboo fiber particle size (mm)	Bamboo fiber (wt.%)	Glass fiber (wt.%)	Epoxy (wt.%)	Hardener (wt.%)
C1	-	0	0	75	25
C2	-	0	20	60	20
S1	<0.75	5	15	60	20
S2	0.75-1.00	10	10	60	20
S3	1.00-2.80	15	5	60	20
S4	0.75-1.00	15	5	60	20
S5	1.00-2.80	5	15	60	20
S6	<0.75	10	10	60	20
S7	1.00-2.80	10	10	60	20
S8	<0.75	15	5	60	20
S9	0.75-1.00	5	15	60	20

$$W = \frac{\Delta m}{L \times \rho} \quad (1)$$

Where, W is wear rate (g/Nm), Δm is mass loss (mg), ρ is applied load (N) and L is sliding distance (m).

3. Results and discussion

3.1. Microstructure of composites

The SEM micrograph of unreinforced epoxy control sample C1 is shown in Fig. 3a while control sample C2 (Fig. 3b) reveals evenly distributed glass fiber particles in pure epoxy matrix. The investigation of selected test samples S1, S4, and S5 indicate that shorter fibers tend to be more evenly distributed, and thus resulted in stronger fiber-matrix interaction. In contrast, fiber agglomeration, fiber attrition, and holes were observed in the composites with longer fibers, resulting in poor interface region and reduced strength, as seen later in the tensile test result in Fig. 4, which agrees with earlier reports [18].

3.2. Mechanical and wear characteristics of composites

Fig. 4, 5, 6 and 7 show the results of the tensile, impact, hardness, and wear tests, respectively. Fig. 4 shows that hybrid samples reinforced with bamboo and glass fibers exhibited improved tensile strength compared to both control samples: pure epoxy resin sample C1 and glass fiber reinforced epoxy sample C2. The addition of 20 wt. % glass fiber to pure epoxy resin led to a decrease in strength, indicating that this level of glass fiber addition weakens

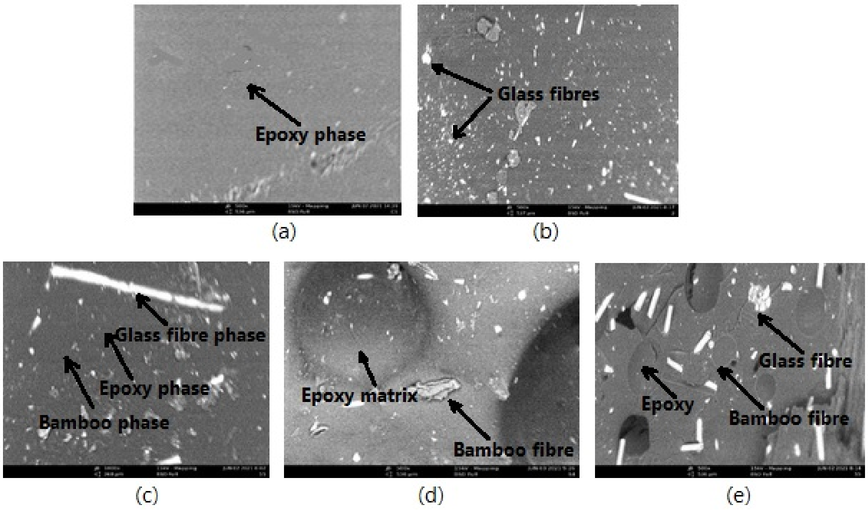

Figure 3: SEM images of the as cast samples (a) C1: pure epoxy resin; (b) < 2.8 mm glass fiber reinforced; (c) S1: < 0.75 mm bamboo and < 2.8 mm glass fiber reinforced; (d) S4: 0.75-1.00 mm bamboo and <2.8 mm glass fiber reinforced; (e) S5: 1.00-2.80 mm bamboo and glass fiber reinforced.

the composites, probably due to particle agglomeration. However C2 exhibits improved impact fracture energy by 11 J as can be seen in Fig. 5, probably due resistance to fiber pull-out during fracture. In contrast, hybrid reinforcement consistently increases both the impact fracture energy and the strength, in agreement with earlier reports [9, 10, 14, 18], except for samples S4, S7 and S8 with either higher drying temperature or longer drying duration of the bamboo fibers. As shown in Fig. 6, the hardness of all composite samples is higher compared to unreinforced epoxy. Moreover, all hybrid reinforced composites exhibited higher hardness than the samples reinforced with glass fiber alone. Equally, the wear rate plot in Fig. 7 shows an increase in wear resistance for all hybrid reinforced composites compared to both control samples with bamboo fiber. Particularly, the composites (S1, S2, and S3) fabricated with bamboo fibers dried at room temperature (25 °C) showed significant improvement in wear resistance. Sample S8, which is the hybrid reinforced composite containing <0.75 mm bamboo fiber-particle size exhibited the lowest wear rate of 1.09 g/Nm implying the highest wear resistance. Overall, the results are in line with earlier reports [10-12, 14].

The results suggest that specific composite properties can be improved by selecting the corresponding combination of fiber reinforcement parameters. For instance, hybrid sample S1, with short bamboo fibers below 0.75 mm and a bamboo-to-glass fiber ratio of 1:3, exhibited the highest tensile strength of 7.47 MPa compared to the unreinforced epoxy sample C1 with a tensile strength of 3.4 MPa, which represents about 120 % increase. Similarly, the hybrid sample S7, with long bamboo fibers between 1 mm and 2.80 mm and a bamboo-to-glass fiber ratio of 1:1, exhibited the highest impact energy of 37.2 J compared to the unreinforced epoxy with an impact energy of 20.81 J, which represents about 79 % increase. Moreover, the hybrid sample S4, with medium bamboo fibers between 0.75 mm and 1 mm and a bamboo-to-glass fiber ratio of 3:1, exhibited the highest hardness of 16.73 HV compared to the unreinforced epoxy with an hardness of 12.2 HV, which represents 37 % increase.

3.3. Effect of fabrication parameters on composites properties

The hybrid composite samples with bamboos dried at room temperature showed the highest tensile strength and wear resistance. The composite strength and wear resistance decreased with increased bamboo drying temperature, probably due to the thermal

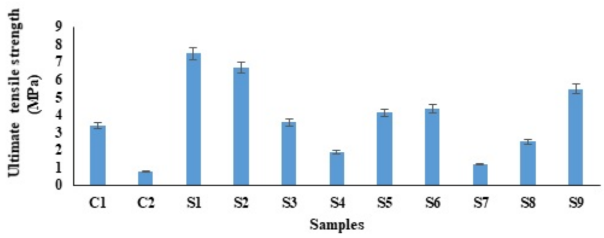

Figure 4: Ultimate tensile strength of the samples.

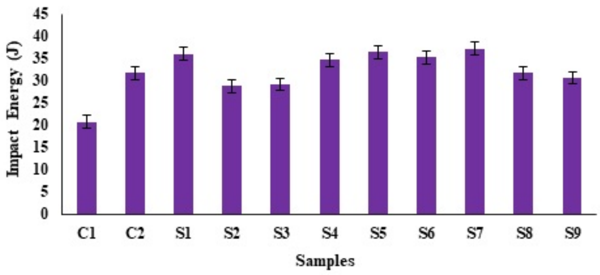

Figure 5: Izod impact fracture energy of the samples.

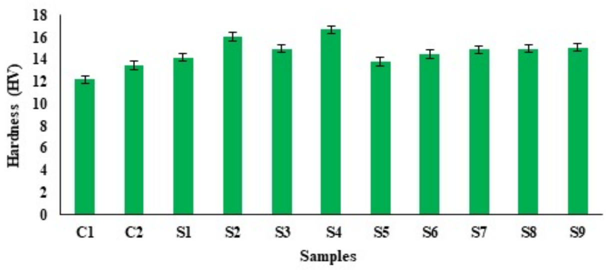

Figure 6: Vickers microhardness of the samples.

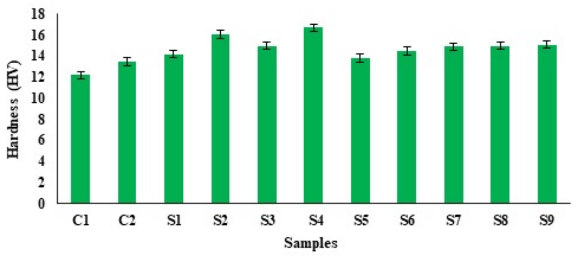

Figure 7: Specific abrasive wear rate of the samples.

degradation of the fibers during preparation prior to production, which was also earlier reported by [18], and can be expected to also deteriorate interface adhesion. However, higher drying temperature of bamboo fibers does not seem to affect their capacity to increase impact fracture energy, which also agrees with the results of [18]. Materials removal by wear was found to occur by thermo-mechanical loading between the interacting wear surfaces of the test samples and counterface, causing interface temperature build-up, which agrees with the report by [19]. Furthermore, microstructure investigations indicated that the finer bamboo particles with length below 0.75 mm showed improved surface bonding and uniform particle dispersion. On the other hand, bamboo fiber particles of sizes between 1.00 and 2.8 mm showed higher porosity and deteriorated interface bonding [20]. The bamboo fiber-to-glass fiber reinforcement ratio also significantly affects the mechanical properties of the composites. Specifically, the tensile strength decreases when the concentration of bamboo fiber exceeds that of glass fiber, as seen in Fig. 4 probably because of agglomeration and deteriorated interface bonding with the polymer matrix. In contrast, the hardness increases when the bamboo concentration exceeds that of the glass fibers, indicating their capacity to further increase the composite strength if agglomeration can be prevented, and interface adhesion can be improved. Overall, all investigated fabrication parameters (temperature, drying time, particle size, and bamboo-glass fiber ratio**)** prove to substantially affect the mechanical properties of the composites.

3.4. Relationship between hardness and wear rate

While all hybrid composites exhibit lower wear rate as compared to unreinforced epoxy and the composite reinforced with only glass fiber, no clear correlation is found between the composite hardness and the wear rate. For instance, sample S2 with an equal proportion of bamboo fiber and glass fiber exhibits the second highest hardness of 16.1 HV compared to the unreinforced epoxy resin sample C1 with a hardness of 12.2 HV. This represents a significant increase in hardness by 32 %, which translates into the second lowest wear rate, corresponding to a substantial reduction by 77.9 % as illustrated in Fig. 8 and in agreement with earlier work by [12]. However, sample S4 exhibits the highest hardness but the second highest wear rate among all hybrid composites, indicating the second last increase in wear resistance. This is thought to be due to inappropriate production parameters such as the higher bamboo fiber drying temperature, longer drying time, and the increased bamboo to glass fiber ratio of 3:1. In general, it can be expected that higher hardness will lead to higher wear resistance. However, this may not be the case if the reinforcement caused a considerable decrease in toughness [21]. Therefore, the increased wear rate of samples S4, S6, and S9 compared to their other hybrid composite counterparts can be primarily related to the higher bamboo fiber drying temperatures of 80 °C and 110 °C, which degrades the fibers and interfacial adhesion strength, causing reduced wear resistance, in agreement with earlier reports [19, 22].

4. Conclusion

Experimental investigation of mechanical properties of bamboo and glass fibers reinforced hybrid epoxy matrix composites have been studied using four production parameters. The hybrid sample S1, with the shortest fibers below 0.75 mm dried at room temperature for 60 minutes, and a bamboo-glass fiber ratio of 1:3, exhibited the highest tensile strength of 7.47 MPa compared to the unreinforced epoxy sample C1 with a tensile strength of 3.4 MPa, which represents about 120 % increase. Similarly, the hybrid sample S7, with the longest fibers 1 to 2.8 mm in length dried at 110 °C for 60 minutes, and a bamboo-glass fiber ratio of 1:1, exhibited the highest impact energy of 37.2 J compared to the unreinforced epoxy with an impact energy of 20.81 J, which represents about 79 % increase. Moreover, the hybrid sample S4, with the medium length fibers between 0.75 and 1 mm dried at 80 °C for 60 minutes, and a bamboo-glass fiber ratio of 3:1, exhibited the highest hardness of 16.73 HV compared to the unreinforced epoxy with a hardness of 12.2 HV, which represents 37 % increase. Sample S8, which is the hybrid reinforced composite containing <0.75 mm bamboo fiber-particle size exhibited the lowest wear rate of 1.09 g/Nm implying the highest wear resistance. In summary, the results demonstrated the effectiveness of the mixture of bamboo and glass fibers in improving the mechanical properties of the composites, with different production parameter combinations yielding different optima for the different investigated properties. Overall, the most defining parameter was found to the bamboo fiber drying temperature, with higher temperatures leading to reduced properties due to potential deterioration of the fibers and their interface bonding to the epoxy matrix. Similarly, shorter drying times, reduced fiber length and lower bamboo-to-glass fiber ratio tend to improve the composite properties.

Acknowledgments

The authors are thankful to Prof. Michel Nganbe of the Department of Mechanical Engineering, University of Ottawa, Ottawa, Canada and Prof. Raphael Edokpia of the Department of Production Engineering, University of Benin, Benin, Nigeria for their preliminary reviews of the manuscript.

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