

Improving Polyurethane Foam Composites through Bamboo Fibre Reinforcement: Effect of Fibre Loading

Mohd Radzi Ali ^{a,*} Mohd Zuhri Mohamed Yusoff,^{b,*} Muhammad Huzaifah Mohd Roslim,^c Khalina Abdan,^{a,d} Mohammad Jawaid,^e Ahmad Ilyas Rushdan,^{f,g} Thinesh Sharma Balakrishnan,^a and Rudi Hartono^h

Environmental concerns have been highlighted by the overuse of synthetic fibres and polymers in foam products because of their limited sustainability and low biodegradability. This study investigated the potential application of bamboo fibre (BF), a natural, renewable, and environmentally friendly material, as a reinforcement for polyurethane foam (PUF) to address this issue. This research aimed to evaluate the effects of different bamboo fibre loadings, ranging from 5 to 20 wt%, on the thermal, mechanical, and physical properties of BF/PUF composites. Composite samples were fabricated with different fibre loadings and analysed for thermal stability using thermogravimetric analysis (TGA), flexural and compression strength, and physical evaluations. The results showed that BF reinforcement improved the thermal stability of PUF, with BF5 and BF10 composites exhibiting the highest flexural strength (0.199 kPa at 10 wt%) and compression strength (0.223 kPa at 5 wt%), although higher fibre content reduced mechanical properties. In addition, the BF5 composites demonstrated the lowest percentage of moisture absorption (4.78%), thickness swelling (4.25%), and water absorption (49.7%), indicating better dimensional stability. With all factors, adding the bamboo fibre into PUF enhanced the eco-performance of polyurethane foams, making them promising candidates for environmentally friendly applications such as insulation, cushioning, and packaging.

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Contact information: a: Institute of Tropical Forestry and Forest Product (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; b: Advanced Engineering Materials and Composites, Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, UPM, Serdang 43400, Selangor, Malaysia; c: Department of Crop Science, Faculty of Agricultural and Forestry Sciences, Universiti Putra Malaysia Bintulu Campus, Bintulu 97008, Sarawak, Malaysia; d: Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; e: Department of Chemical and Petroleum Engineering, College of Engineering, United Arab Emirates University, P. O. Box 15551, Al Ain, Abu Dhabi, United Arab Emirates; f: School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor, Malaysia; g: Centre for Advance Composite Materials (CACM), Universiti Teknologi Malaysia, 81310, Johor, Malaysia; h: Forest Products Department, Faculty of Forestry, Universitas Sumatera Utara, Medan, 20155, Indonesia; * Corresponding authors: mohdradzi@upm.edu.my; zuhri@upm.edu.my

INTRODUCTION

Recently, the use and investigation of natural fibre resources is expanding worldwide. The increasing demand for natural fibre materials, such as kenaf, roselle, sugar palm, banana, and pineapple, is driven by availability, low cost, and environmental friendliness. Additionally, these fibres exhibit unique properties, such as low density,

biodegradability, good thermal insulation, and low energy consumption in processing (Odesanya *et al.* 2021; Zubair *et al.* 2022). The use of natural resources can reduce the dependence on conventional synthetic materials (glass, carbon fibre, *etc.*). Although synthetic fibres offer superior performance in composites, there are some problems related to human health (lung disease) and the environment (non-biodegradability). Furthermore, the use of plastics from petroleum sources is increasing globally every day. The use of plastic has caused concern among environmentalists and researchers due to increased carbon dioxide (CO₂) emissions (global warming), poor waste management, environmental pollution, and the depletion of fossil resources. Therefore, these issues encourage researchers to develop new sustainable strategies using environmentally friendly materials to reduce environmental pollution.

Natural fibres are among the most promising materials used as reinforcement in polymer matrices. Natural fibres, especially bamboo fibre (BF), have received attention because of their positive contributions to the economy. Bamboo trees produce various products for daily human use (textiles, furniture, *etc.*). Recently, fibre production from bamboo has also increased due to its ability to reduce the use of non-renewable synthetic fibres in the market. Bamboo fibres are often used because of their low cost, abundant availability, and ease of preparation and treatment. Bamboo in Malaysia is easy to find because it grows freely along rivers, forests, and wastelands. Both commercially cultivated and wild bamboo species are widely available. In Malaysia, 12 types of bamboo are grown commercially, including buluh beting, buluh galak, buluh minyak, buluh gading, buluh nipis, and others (Radzi *et al.* 2022). The nature of BF includes thick cell walls and aligned microfibrils, which contribute to forming natural glass-like fibres, as well as excellent strength and stiffness capabilities (Chee *et al.* 2017; Hassan *et al.* 2020). Thus, bamboo is one of the most suitable natural resources for polymer reinforcement due to its unique features.

Polyurethane (PU) is widely used in applications such as thermal and electrical insulation, adhesion, accessories, vehicle interiors, and construction materials (Kairyte *et al.* 2018). Generally, this polymer is combined with synthetic fibres (*e.g.*, glass fibre, carbon fibre, metal fiber, *etc.*), which indirectly increases the cost of materials and processing (de Carvalho *et al.* 2020). Therefore, BF is a suitable alternative reinforcement material to replace commercial fibres. The PU is produced by combining two main ingredients, polyol and isocyanate, which can produce various foam types such as rigid, soft, and elastomeric foams. The PU possesses a cellular structure for molecular expansion and is produced through two types of methods, chemical and physical blowing methods. As stated by El-Shekeil *et al.* (2011), using PU as a matrix reduces adhesion problems and improves fibre dispersion. Compared to thermoplastic polyurethane, polyurethane foam (PUF) has a larger pore volume and is a thermoset-type polymer. Previous investigations on PUF composites reinforced with various fibres, such as glass, carbon, and other natural fibres, have been reported (Yuvaraj *et al.* 2018; Lee *et al.* 2019; Zhang *et al.* 2020; Kim *et al.* 2021). Although PUF has been reinforced with different natural fibres, its combination with BF has not yet been widely explored. The advantages of PUF make this research more viable due to its low cost, durability, and excellent mechanical performance. The objectives of this research are to develop and characterise BF-reinforced PUF composites (BF/PUF) for application in the construction industry as heat-insulating materials.

The incorporation of compatibilizers is widely recognized as an effective strategy to enhance interfacial adhesion between hydrophilic natural fibers and hydrophobic polymer matrices, thereby improving the mechanical performance of natural fiber

reinforced composites. Liu *et al.* (2008), evaluated HDPE/bamboo flour (BF) composites modified with maleated polyethylene (PE-g-MA) and maleated ethylene/propylene elastomers (EPR-g-MA) compatibilizers at loadings of 0 to 8.3 wt%. The results showed that PE-g-MA provided the highest strength and modulus, while semi-crystalline EPR-g-MA (sEPR-g-MA) significantly improved impact strength. In contrast, amorphous EPR-g-MA (aEPR-g-MA) reduced composite strength. Impact toughness increased with aEPR-g-MA content up to 2.9 wt% before declining, and a balanced strength–toughness performance was achieved through the combined use of PE-g-MA and EPR-g-MA, supported by DMA and morphological observations indicating improved interfacial adhesion and matrix yielding. Zhang *et al.* (2024) investigated ASA/bamboo fiber (BF) composites compatibilized with chlorinated polyethylene (CPE) to enhance fiber dispersion and mechanical performance. The addition of 15 phr CPE significantly improved the reinforcing efficiency of tensile strength to 20%, compared with only 4.1% in the composite without CPE, representing nearly a four-fold improvement. This enhancement was attributed to the compatibilizing effect of CPE, which reduced BF aggregation and promoted stronger interfacial interactions with the fibers without requiring additional chemical surface treatments.

In this study, BF was used to improve the properties of PUF composites with differential fibre contents (5, 10, 15, and 20 wt%). Thermogravimetric analysis (TGA), flexural strength, compressive strength, and physical properties were evaluated. Additionally, a goal of this research was to introduce a structural-property framework to identify the optimal potential of bamboo fibers that can control the balance between mechanical and thermal insulation in polyurethane foam composites by using mechanical, physical, thermal, and morphology testing methods to evaluate the effectiveness of adhesion between fibers and matrix. The interfacial interaction between bamboo fibers and polyurethane foam is still not fully elucidated, especially the long-term mechanical, physical and thermal effects. The interfacial interaction between the BF and PUF has received only limited study, especially in terms of mechanical, physical, and thermal properties. The literature review also showed that although single-fiber effects are well reported, there are still shortcomings regarding the optimization of interfacial adhesion and material balance on PUF (Radzi *et al.* 2022; Xu *et al.* 2023; Dong *et al.* 2024; Li *et al.* 2024). Therefore, this study focused between BF and PUF for effect of BF percentage and interfacial compatibility and prevent cell collapse, which affects the mechanical, physical and thermal performance of PUF composites.

EXPERIMENTAL

Materials

The bamboo fibre was collected from Rembau, Negeri Sembilan, Malaysia. The PUF matrix was obtained from Evergreen Engineering & Resources, Selangor, Malaysia. The BF was sun-dried to eliminate any remaining moisture.

Sample Preparation

A crusher was used to crush the BF, and a sieve shaker was used to separate the material. The study employed a fixed fibre length of 300 to 425 μm . The BF/PUF composites were prepared by combining the two main components, polyol and isocyanate, in a specific ratio (1:1.1 wt%) with different amounts of fibre. All these materials were

combined using a stirrer machine. Then, BF/PUF was poured into the mould and allowed to cure for 2 h.

Table 1. Formulation of Different Fibre Percentages of BF/PUF

Polyurethane Foam (wt %)	Bamboo (wt%)	Designation
100	-	Neat
95	5	BF 5
90	10	BF 10
85	15	BF 15
80	20	BF 20

Thermogravimetric Analysis (TGA)

The Thermalgravimetric (TGA) was conducted to evaluate the thermal stability of the composite samples under heat exposure. TGA is one of the important tests for measuring the weight loss of samples upon heating using Q series thermal analysis model TA Instrument (TGA Q500 – USA 2011). Thermal stability testing was carried out according to ASTM D3850 (2006), with a temperature range of 30 to 600 °C and a heating rate of 10 °C/min.

Flexural Testing

The flexural test is one of the measurements used to determine the maximum strength of a composite. This test was carried out following ASTM D790 (2002) standards. The measurement was performed using a Universal Testing Machine (INSTRON P5567, Instron, USA) and a fixed speed of 2 mm/min.

Compression Testing

The compression test was measured according to the ASTM D1621 (2000) standard. The purpose is to measure the material's composite strength under load. This measurement was performed using the UTM. A total of 5 samples were tested for each composition at a fixed speed of 10 mm/min.

Water Absorption Test

Water absorption (WA) tests were conducted following ASTM D570 (1999) standard. This test was used to measure water uptake by the composites using distilled water as the medium for 24 h. For each composition, 5 specimens were prepared for the test. Equation 1 was used to calculate water absorption. The initial weight of the sample before immersion was recorded as W_0 . The samples were then soaked in distilled water for 24 h. Measurements were made at the end of each 24 h (W_1) consecutively for 7 d.

$$\text{Water Absorption (\%)} = \frac{W_1 - W_0}{W_1} \quad (1)$$

Thickness Swelling

Thickness swelling (TS) tests were conducted on the composites, with 5 samples prepared for each composition. This test was performed to evaluate the dimensional changes of the material due to water absorption. The initial thickness (T_0) was measured before the sample was immersed in distilled water. The final thickness was recorded (T_1)

after 24 h (Choupani Chaydarreh *et al.* 2017). Measurements were continued for 7 d. Equation 2 was used to calculate thickness swelling:

$$\text{Thickness swelling (\%)} = \frac{T_1 - T_0}{T_0} \times 100 \quad (2)$$

Moisture Content

All samples with different fibre-loading composites were investigated. Five samples were prepared for each composition. Equation 3 was used to determine the moisture content percentage. Initial weights were recorded before oven drying (M_0), and final weights (M_1) were recorded after the sample had been heated for 24 h.

$$\text{Moisture content, (\%)} = \frac{M_1 - M_0}{M_0} \times 100 \quad (3)$$

Morphology

Morphological studies were conducted on the surface of BF/PU composites using scanning electron microscopy (SEM) (COXEM: EM-30AX, COXEM Co., Ltd. Korea). The composite samples were gold-coated (Coxem Coater SPT-20; COXEM Co., Ltd. Korea) to enhance electrical conductivity, ensuring high-quality imaging prior to surface examination.

RESULTS AND DISCUSSION

TGA

Thermogravimetric analysis (TGA) was conducted to test the hypothesis that bamboo fibre incorporation would enhance thermal stability and char formation of PUF composites due to the lignocellulosic nature of the fibre, thereby improving their suitability for thermal insulation applications. The TGA is a test that provides accurate information on the thermal stability of composites, especially bamboo fibres. Degradation analysis of BF/PUF is essential because natural fibres are highly sensitive to elevated temperatures, especially during the pre-mixing process between matrix and fibre. The BF degradation occurred in 4 stages, including initial moisture evaporation. This was followed by the decomposition of cellulose and lignin in the second and third stages, while the final stage corresponds to further degradation of cellulose, lignin, and final residue (Huzaifah *et al.* 2017; Norizan *et al.* 2017; Azali *et al.* 2022). The TGA and differential thermogravimetric (DTG) curves of BF/PUF composites with varying fibre loadings are shown in Figs. 1 and 2, respectively, and summarised in Table 2. The table presents moisture loss, decomposition temperatures, and residual weight for all composites. From Figs. 1 and 2, all samples exhibited similar degradation trends. However, between 350 and 500 °C, BF/PUF composites showed improved stability compared to the neat sample. The initial moisture loss phase occurred at temperatures between 30 and 100 °C (Huzaifah *et al.* 2017), followed by lignocellulosic (hemicellulose) degradation at 220 to 315 °C (Jumaidin *et al.* 2017). The third phase, 315 to 400 °C, corresponded to cellulose degradation, while lignin continued gradually up to 600 °C, leaving ash residue (Huzaifah *et al.* 2019; Azali *et al.* 2022).

Table 2 shows that the ash content increases with fibre addition, with BF5 recording the highest ash residue at 25.0%. This showed that BF has the potential to be used as an improvement material (reinforcement) for polymer and can be applied to thermal insulation material. It was also observed that the first degradation temperature decreased once 5 wt%

BF was introduced; however, as the wt% increased, the first degradation temperature also increased. A similar trend was observed for the second degradation temperature.

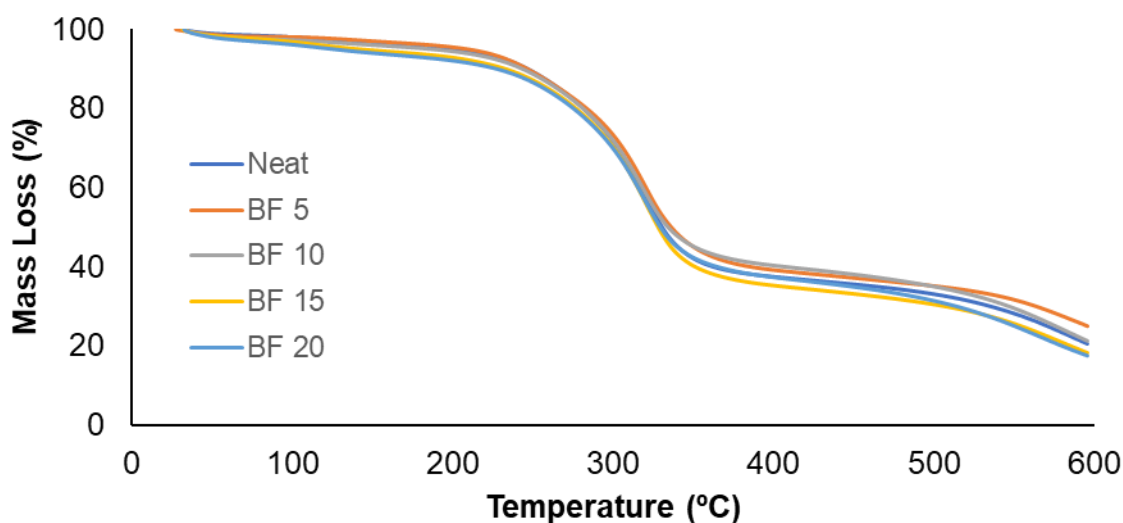


Fig. 1. TGA of neat and BF/PUF composites with varying fibre loadings

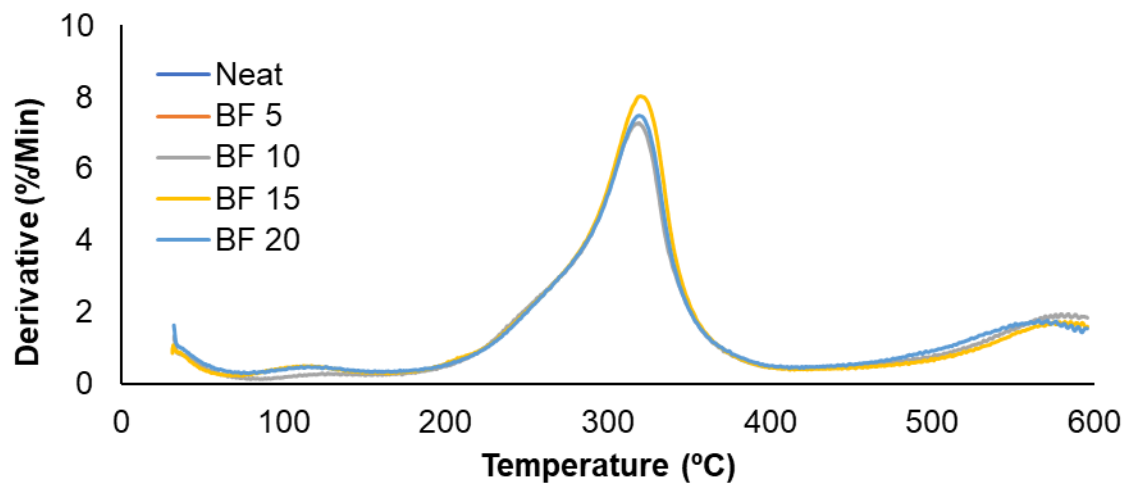


Fig. 2. DTG of BF/PUF and neat composites with varying fibre loadings

Table 2. Thermal Degradation Analysis of BF/PUF and Neat Composites with Varying Fibre Loadings

Sample	First Degradation		Second Degradation		Char at 600 °C (%)
	T_{on}	T_{max}	T_{on}	T_{max}	
Neat	235.0	282.5	276.8	320.9	20.6
BF 5	229.7	299.1	247.2	321.0	25.0
BF 10	232.8	237.9	301.9	317.0	22.0
BF 15	258.6	263.3	312.5	319.6	23.1
BF 20	255.6	273.5	311.8	320.1	21.4

The increase in char residue for BF-reinforced composites suggests that bamboo fibre promotes carbonaceous layer formation during degradation. The higher char content, particularly in BF5 (25.02%), indicates enhanced thermal barrier formation compared to neat PUF (20.55%). Moreover, the increased onset degradation temperatures at 15 to 20 wt% loading (up to 258.55 °C) suggest that fibre incorporation delays thermal decomposition. These results support the hypothesis that bamboo fibre can improve the thermal resistance of PUF composites, making them more suitable for insulation applications.

Flexural Testing

The fibre content in polymers is an important factor in determining the mechanical properties of a material (Navaneethakrishnan and Athijayamani 2016). Figure 3 displays the flexural strength and modulus of BF/PUF composites. The distribution, orientation, and uniformity of fibres within the matrix had a considerable influence on the mechanical properties of the composite. Additionally, the fibre-matrix interfacial adhesion was another crucial factor affecting the mechanical properties.

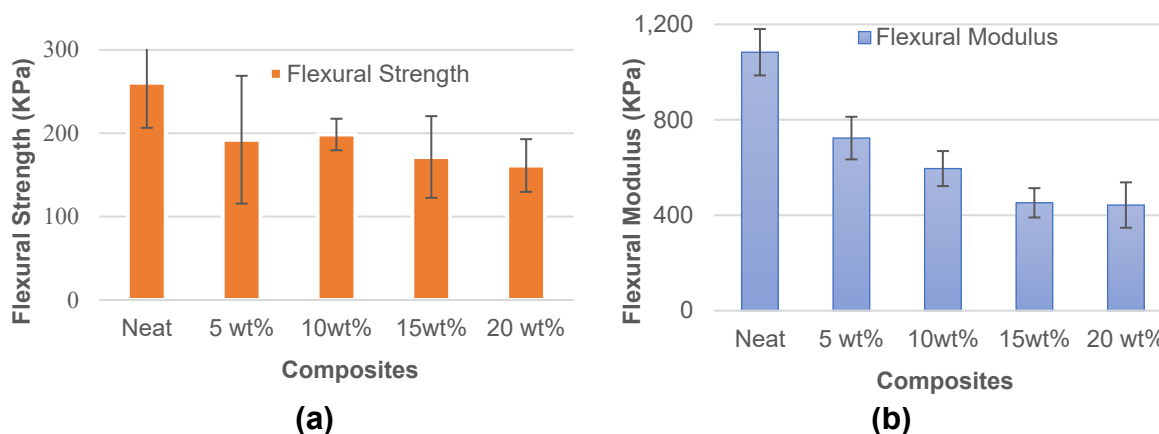


Fig. 3. (a) Flexural strength and (b) modulus of BF/PUF composites at different fibre loading

An increase of BF loading up to 10 wt% (BF10) produced the highest flexural strength and modulus. Lower fibre contents may lead to the irregular shape of the BF, which causes the weak surface adhesion between fibre, nonuniform dispersion, and matrix. The BF can support the stress applied by the PUF (Ismail *et al.* 2002; Huzaifah *et al.* 2019; Dong *et al.* 2021). Increasing the BF content from 5wt to 20 wt% resulted in a significant reduction in flexural strength, with losses reaching up to 38%. Although a reduction in flexural strength was observed, a slight increase was recorded as the BF content increased from 5 wt% to 10 wt%, before decreasing again at a fibre content of 20 wt%. A similar trend was also apparent with respect to the modulus, where the value of the modulus increased from 5 wt% to 10 wt% and decreased from 15 to 20 wt%. The modulus value for the neat PU was 1077.5 KPa, followed by 742.7 KPa (BF5), 951.9 KPa (BF 10), 769.83 KPa (BF 15), and 739.8 KPa (BF 20). For the comparison of all BF compositions, BF 10 showed good performance compared to other composites. Similar findings were reported by Huzaifah *et al.* (2019) and Ismail *et al.* (2002), who conducted a study on sugar palm fibre-reinforced vinyl ester and BF-filled natural fibre composites. In addition, Sair *et al.* (2018) and Czlonka *et al.* (2018) agreed that the weakness present is due to the uniform fibre distribution, fibre breakage at the weak point, and poor force transfer on the fibre and

matrix, which are the main contributors in determining strength in any natural fibre composites (Husainie *et al.* 2020).

Compression Testing

Figure 4 displays the compression strength of the composites. Increasing fibre loading resulted in a continuous decrease in compression strength (47.2%). The compressive strength was recorded as 282 KPa (neat), 222 KPa (BF 5), 162 KPa (BF10), 161 KPa (BF 15), and 149 KPa (BF 20). Figure 3 shows an insignificant difference compared to flexural strength. As the BF value increased, the compressive strength decreased for each composite composition. The BF5 composite showed the highest compression strength. The reduction was mainly due to fibre agglomeration, poor dispersion, non-uniform growth, and weak fibre-matrix interaction (Sinar *et al.* 2015; Członka *et al.* 2018; Leng and Pan 2019; Shalbafan *et al.* 2021)

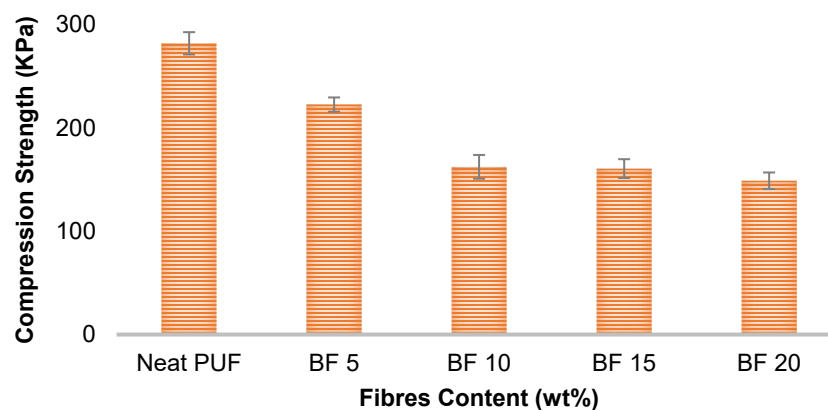


Fig. 4. BF/PUF composites compression strength at various fibre loadings

Water Absorption Test

Natural fibres are hydrophilic, meaning that they can absorb more moisture. Therefore, the water absorption test was to determine the ability of BF composite and the effect of swelling on the sample when immersed in water. The water absorption test was recorded for 24 h over 7 consecutive days. From Fig. 5, the water absorption of all BF/PUF composites was high compared to neat PU.

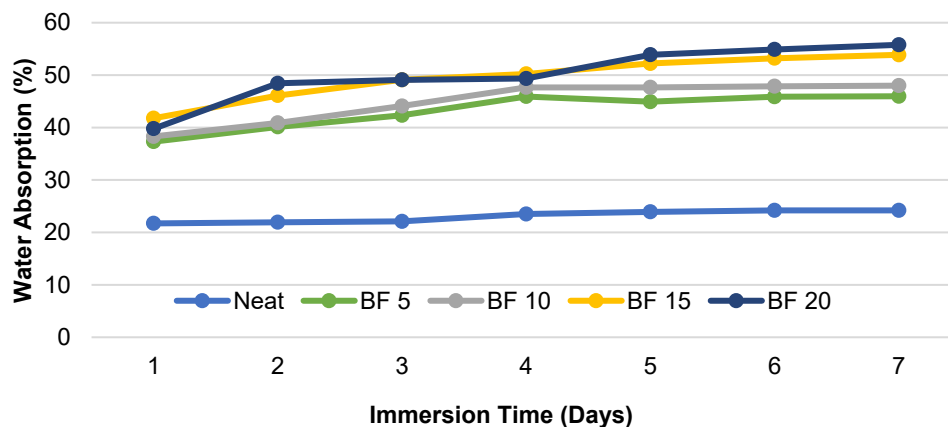


Fig. 5. Water absorption of BF/PUF composites with different fibre content

The highest water uptake of BF/PUF composites was 55.8% (BF 20), 53.9% (BF 15), 48% (BF 10), and 4.3% (BF 5), followed by neat PU (24.2%). From observation, the main cause of increased water uptake was due to the BF content of PUF compared to the neat matrix material. Water uptake increased with increasing BF fibre loading. High water absorption can affect the mechanical properties of BF composites because water molecules can change the shape of the structure (BF and PUF), lose compatibility between fibres and matrix, cause matrix shrinkage, and weaken the interface between the two materials (Sair *et al.* 2018). The PUF foam structure also contributes to the increase in water uptake of BF/PUF composites; it has various foam sizes that allow water to be trapped inside the PUF (Rodrigues Pereira de Paula *et al.* 2022). The PUF recorded the lowest percentage of water uptake compared to BF/PUF composites. The PUF is a polymer whose properties are more hydrophilic (less absorbent) compared to BF (hydrophilic) (Choupani Chaydarreh *et al.* 2017). The water that is absorbed by PUF is the result of the non-uniform size of the foam and becomes a barrier for water (El-Meligy *et al.* 2010; Rodrigues Pereira de Paula *et al.* 2022).

Thickness Swelling Test

The swelling test is an immersion process in water to analyse the dimensional stability of the BF/PUF composite. The test was conducted for 7 consecutive days to see the swelling effect of the composite thickness until the weight was constant. The results are shown in Fig. 6. The thickness swelling test was recorded for 24 h over 7 consecutive days. According to the findings, the BF/PUF composites with the highest thickness swelling value was BF 5 (4.3%), followed by BF 10 (4.4%), BF 15 (4.8%), BF 1 (4.9%), and neat (2.1%). There was no difference in results between the water absorption and the thickness swelling tests. Both graph trends were similar; the effect of increased BF fibre loading also has the effect of increasing the swelling thickness of BF/PUF composites. The main factor for swelling was the same as the water absorption test, namely the presence of hydrophilic properties (BF) causing thickness swelling to occur, low interaction between fibre and matrix, and the foam character of the PUF is also one of the causes of water being trapped in the pores (Chen *et al.* 2009; El-Meligy *et al.* 2010; Rodrigues Pereira de Paula *et al.* 2022). This finding was similar to the report by Qi *et al.* (2020), who concluded that the primary cause of instability in the composite's physical properties is the material's nature, the presence of voids, and the weak interaction between the two components, which is exacerbated by high thickness swelling and water absorption.

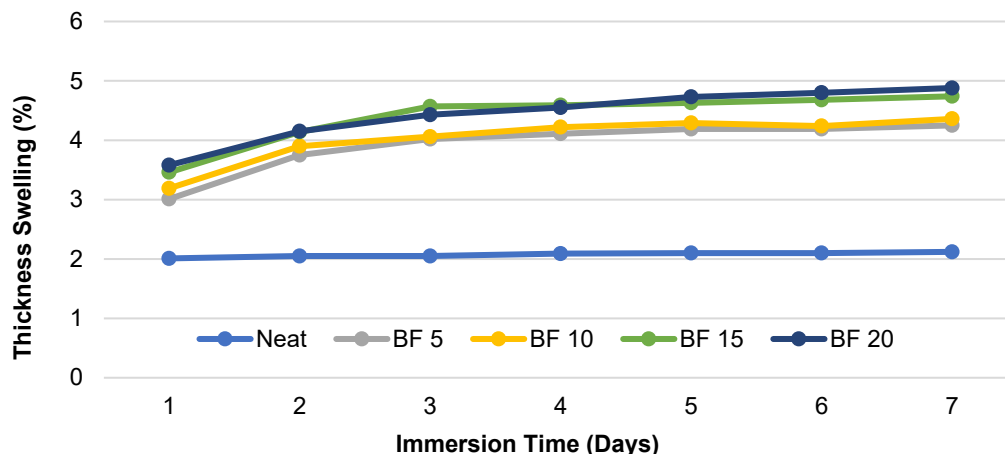


Fig. 6. Thickness swelling of BF/PUF composites with different fibre content

Moisture Content

Moisture content properties were tested on the developed composite. This test was conducted to measure the total moisture content of the BF/PUF composite within 24 h. Figure 7 shows the moisture content percentage data for BF/PUF composites. The data obtained after 24 h of exposure to heat shows that all composites had high moisture content compared to neat PU. Moisture content values were found to increase with increasing BF loading for PU composites. Figure 7 shows the percentage of moisture content of BF/PUF composites was 2.3% (neat), 4.8% (BF5), 5.4% (BF 10), 6.2% (BF 15), and 6.5% (BF 20). The addition of BF up to 20 wt% (BF20) resulted in a high-water moisture content compared to other composites. This showed that the moisture content of BF/PUF composites was more than that of neat PU. Overall, the trend of the displayed graph aligned with the results of the water absorption and swelling tests. When increasing the percentage of BF content in the matrix, the moisture content also increases. This phenomenon occurred due to BF being hydrophilic, which was exposed to environmental moisture. This was reflected in the mechanical properties, which exhibited decreasing values as the fibre content increased. In addition, the weak interfacial and adhesion interaction between fibre and the matrix is also one of the factors of high moisture content (Huang and Young 2019). Jyun-Kai Huang and Wen-Bin Young (2019), and Venkatesha, Saravanan and Anand (2020) have reported that when the moisture is high in the natural fibre composite, it will cause the physical and mechanical properties to be reduced.

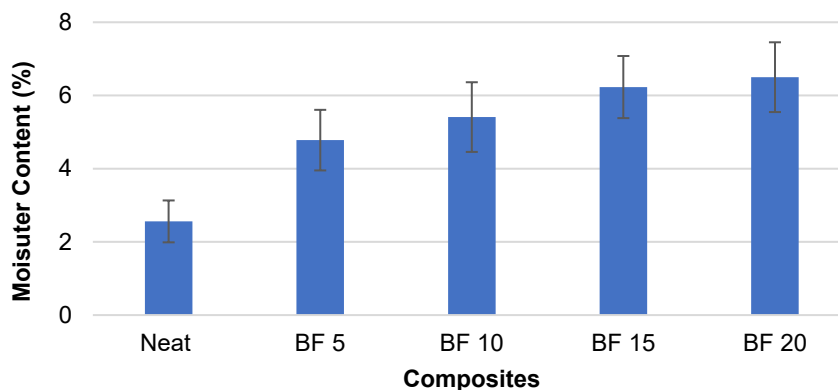


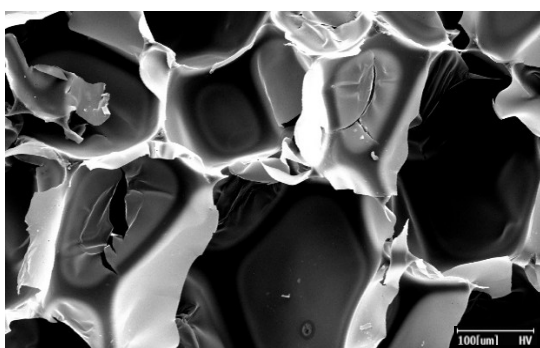
Fig. 7. Moisture content of BF/PUF composites with different fibre content

Morphology

Morphology analysis of composite materials revealed progressive structural changes, such as fibre distribution, matrix properties, and interfaces. The SEM offers high-resolution images, revealing fibre alignment, matrix structure, and bonding (Lai *et al.* 2014). The morphology of neat PUF and BF-reinforced PUF composites at different fibre content from 5 wt% to 20 wt%, is shown in Figs. 8a through 8e. These figures provide information on the microstructural changes that occur with fibre content percentage, which correlate with changes in the mechanical and physical properties.

As shown in Fig. 8a, the SEM image of the neat PUF shows smooth and homogeneous structure with well-formed and closed cell structures. There was no indication of BF content and displayed a uniform form and characteristics of a neat PUF structure. Because the cell walls are intact and less sensitive to moisture, the pore structure helps to achieve strong compression strength, which was 2870 kPa and 24.2% for water absorption.

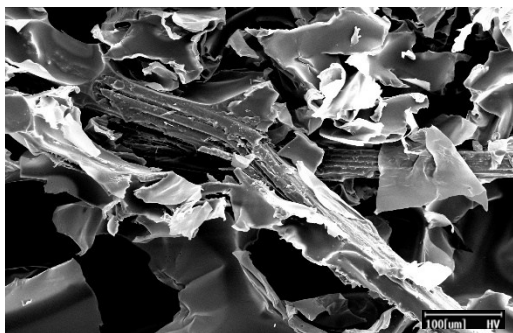
In Fig. 8b, the BF5 composites were well-incorporated into the PUF matrix. Cell deformation started to show up around the fibre-matrix surfaces, and the BF were partially embedded in substantial dispersion. There were several visible interfacial gaps and voids, which may have led to increased moisture content and swelling compared with the neat sample.



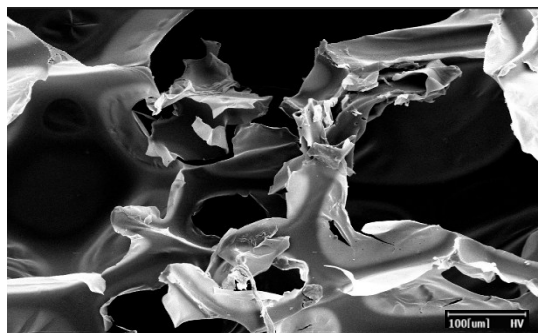
(a) Neat



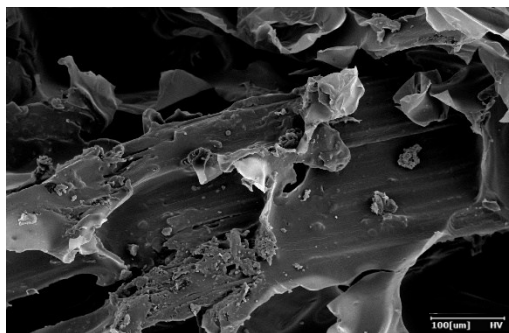
(b) BF5



(c) BF10



(d) BF15



(e) BF 20

Fig. 8. Morphological differences between the neat PUF and BF/PUF composites at various fibre loadings (a) Neat; (b) 5 wt%; (c) 10 wt%; (d) 15 wt%; (e) 20 wt%;

For Fig. 8c, there was fibre dispersion and some agglomeration. Large BF bundles emerging through the matrix suggested mechanical interlocking. This morphology supports the highest flexural strength (0.199 kPa) and modulus (951.9 kPa), indicating effective stress transfer. In contrast, the existence of a void and unstable shape of the foam structure indicated that high fibre loading hindered matrix continuity. In comparison to neat and BF5, this factor contributed to the decrease in compressive strength (162 kPa) and increased water absorption (48%).

The foam structure image for Fig. 8d (BF15) appeared more irregular and disturbed. It occurred due to a large amount of pore deformation and matrix fragmentation, which has a negative effect on mechanical properties. Larger gaps and areas of debonding between BF and PUF indicate a weaker fibre and matrix adhesion. These morphological defects led to a reduction in mechanical strength and increased water absorption (53.9%) and thickness swelling (4.8%). Figure 8e (BF20) shows fibre clustering, microcracks, and matrix fragmentation. The foam structure of BF20 showed irregular foam with many voids formed, indicating poor fibre dispersion and low interfacial adhesion between fibre and matrix. The morphology foam structure of the BF20 was consistent with the lowest compressive strength (148.8 kPa) and highest water absorption, thickness swelling, and moisture contents. The noticeable gaps between the fibre-matrix reduced the ability to bear load of the composites and increased water permeability.

In summary, SEM morphology showed a balance between fibre/matrix adhesion and enhanced reinforcement and foam structure in composites. This was seen at low fibre loading (BF5 and BF10), where improved dispersion of fibres and interaction adhesion fibre-matrix gave the foam composites improved flexural strength. However, at higher fibre content (15 to 20 wt%), agglomeration and voids dominated, weakening the composite's mechanical performance and making it more susceptible to moisture uptake and dimensional instability. The morphological analysis strongly supported the experimental findings, validating BF10 as the optimal formulation with a balance between reinforcement efficiency and microstructural integrity.

Future Work

Overall, this work has contributed to understanding of the effects of fibre stability and content of BF/PUF composites. Future work will focus on fibre BF treatment and compatibility agents to enhance interfacial adhesion with PUF. The future works methods

as follows: 1. Potential fibre treatment using alkaline (NaOH), silane, *etc.*, 2. Addition of compatibiliser such as maleic anhydride (MAPE) and polyurethane-grafted polymers (Grafted PU), and 3. Combining experiments such as dynamic mechanical analysis, long term aging performance, and flammability testing to further evaluate the multifunctional properties and durability of the composite.

CONCLUSIONS

1. The research evaluated the thermal stability, mechanical and physical properties of bamboo fiber (BF)-reinforced poly(urethane) (PU) composites at various fibre content percentages (5 wt% to 20 wt%). Based on the results, it was shown that the addition of BF content in PU up to 10 wt% increases the thermal stability, flexural strength, and compressive strength of the composites due to effective BF and PU interactions and stress transfer.
2. The scanning electron microscope (SEM) analysis observations revealed strong interaction and adhesion between the fibre-matrix. The BF5 and BF10 content showed more uniform fibre distribution and better interfacial bonding, which enhanced stress transfer and contributes to improved flexural strength of foam composites.
3. However, increasing the BF content caused higher water absorption, thickness swelling, and moisture content percentage. These changes were mainly attributed to the hydrophilic nature of BF, increased interfacial voids, and open-cell foam structure that facilitated moisture diffusion.
4. Overall, effects, such as the mixing process, fibre distribution, and adhesion, are factors that cause increases and decreases in thermal, mechanical, and physical properties. Therefore, considering the BF/PUF composites' outstanding performance and BF10 fibre loading, they may be most useful as building materials for applications such as roofing and insulation.

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