Pertanika J. Sci. & Technol. 34 (4): 2385 - 2401 (2026)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Characterisation of Bamboo Fibre-Reinforced Polyurethane Foam Composites with Varying Fibre Sizes

A.M. Radzi[1], M.Y.M. Zuhri[1,2]*, S. Ayu Rafiqah[3], R.A. Ilyas[4,5], Muhammad Asyraf Muhammad Rizal[5,6], Ahmad Safwan Ismail[7], A.B.M. Supian[8], and Agusril Syamsir[9]

[1]*Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[2]*Advanced Engineering Materials and Composites Research Centre, Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[3]*Engineering and Technology Division, Malaysian Rubber Board (MRB), 47000 Sungai Buloh, Selangor, Malaysia*

[4]*Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

[5]*Centre for Advanced Composite Materials (CACM), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

[6]*Department of Applied Mechanics and Design, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

[7]*Chemical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia*

[8]*Centre for Defence Research and Technology (CODRAT), National Defence University of Malaysia, Sungai Besi Camp, 57000 Kuala Lumpur, Malaysia*

[9]*Institute of Energy Infrastructure, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia*

ARTICLE INFO

Article history:
Received: 25 May 2026
Accepted: 09 July 2026
Published: 20 August 2026

DOI: https://doi.org/10.47836/pjst.34.4.21

E-mail addresses:
mohdradzi@upm.edu.my (A.M. Radzi)
zuhri@upm.edu.my (MYM Zuhri)
ayu.rafiqah@lgm.gov.my (S. Ayu Rafiqah)
ahmadilyas@utm.my (R. A. Ilyas)
muhammadasyraf.mr@utm.my (Muhammad Asyraf Muhammad Rizal)
ahmadsafwanismail@ums.edu.my (Ahmad Safwan Ismail)
mohdsupian7779@gmail.com (A.B.M. Supian)
agusril@uniten.edu.my (Agusril Syamsir)
* Corresponding author

ABSTRACT

This study investigates the influence of varying bamboo fibre (BF) sizes on the thermal, mechanical, and physical characteristics of composites made from bamboo fibre and polyurethane foam (PF). BF/PF composites were fabricated using fibre sizes less than 150µm, and within 150–300 µm, 300-425 µm, and 425-600 µm ranges. Thermogravimetric analysis (TGA) identified three primary decomposition phases, corresponding to moisture removal, hemicellulose breakdown, and cellulose degradation. The results demonstrated that incorporating different BF sizes enhanced the

e-ISSN: 2231-8526

composites' thermal stability. The thermal stability of BF/PF composites was improved; the results show that BFP3 (299.07°C) has a higher onset of degradation compared to neat and other composites. In terms of mechanical properties, larger fibre sizes improved both flexural and compressive strength, with the 300-425 µm (BFP3) size yielding the highest flexural (0.192 MPa) and compressive (0.232 MPa) strengths. However, water uptake, moisture content, and thickness swelling increased with fibre size. Notably, composites using fibres smaller than 150 µm (BFP1) recorded the lowest values in water absorption (42.54%), thickness swelling (3.66%), and moisture content (3.48%).

Keywords: Bamboo fibre, fibre size, foam composites, mechanical properties, polyurethane foam

INTRODUCTION

The compatibility and ease of availability of raw materials, combined with a polymer matrix (thermosetting or thermoplastic), allow for balanced properties. Natural fibre-based polymer composites have attracted more interest as a possible replacement for traditional materials (Ilyas et al., 2021; Sanjay et al., 2018; Sanmuham et al., 2021). Natural fibre composites have the potential to further the development of environmentally friendly materials; researchers are interested in the subject of study. Due to their enhanced productivity, variety of application designs and easy access to raw materials, these fibres can enhance the manufacturing sector (Bahari & Krause, 2016; Saheb & Jog, 1999; Supian et al., 2018). To meet the growing demands for environmental sustainability, researchers are now working on reducing the use of synthetic fibres (carbon and glass fibres) in manufacturing applications. By replacing more sustainable materials for natural resources as the main component in the reinforcement of polymer composites, this material may greatly decrease the consumption of fossil resources (Syafiq et al., 2020; Syafiq et al., 2021; Zia et al., 2015). Apart from that, the use of natural resources can reduce crop waste and open burning by farmers, offering a manageable waste solution with lower environmental impact (Ishak et al., 2013; Nadlene et al., 2016; Suhot et al., 2021). Through this innovative approach, the growing concerns of issues such as global warming and waste management can be reduced. The implementation of various initiatives, such as eco-friendly projects, trash sorting by type for appropriate disposal, and the marketing of eco-friendly materials in diverse applications, has resulted from this increased awareness. (Beran et al., 2021; Davoodi et al., 2012; Huzaifah et al., 2017; Jawaid et al., 2022; Radzi et al., 2018). Bamboo, a fast-growing member of the grass family (Gramineae), shares common characteristics with species such as corn, sugarcane and rice. Numerous genera, including Bambusa, Dinochloa, Gigantochloa, Dendrocalamus, Holttumochloa, Schizostachyum, Kinabaluchloa, Melocanna, Chusquea, Maclurochloa, Phyllostachys, Sphaerobambos, Soejatmie, and Thyrsostambos, among others, are planted and grow naturally (Radzi et al., 2022).

Natural resources that have the potential to be used as alternative materials in polymer composites come from the bamboo tree. Bamboo cultivation is an easy-to-manage, cost- and time-efficient practice that provides a wide range of valuable resources, especially in high-quality fibres. In the bamboo family, nearly 200 bamboo species are found across Southeast Asia, either naturally occurring or cultivated, with notable presence in Malaysia, Indonesia, Myanmar, and Papua New Guinea (Anwar et al., 2011; Siam et al., 2019). In the tropical environment of Malaysia, bamboo plants can grow widely along rivers, in the forest and in undeveloped areas or wasteland. Various species of bamboo can be found in the wild and in commercial plantations for any purpose (Siam et al., 2019). Of the 63 species of bamboo, only 13 are commonly used in traditional or commercial applications to make various products (Anwar et al., 2011). In general, the anatomy of a bamboo tree has several parts such as roots, rhizomes, branches, leaves and shoots. This bamboo consists of approximately 10% vessels, 40% fibre, 50% parenchyma and a sieve tube (Chen et al., 2021; Kadivar et al., 2020). In fact, the bamboo tree is not a flowering type like most other trees. However, there are a few types of bamboo tree produce flowers, such as Phyllostachys edulis (Moso) and Phyllostachys elegans, which can produce flowers due to changes in environmental conditions (Roslan et al., 2018). In recent years, the utilisation of bamboo has increased due to its remarkable properties, such as strength, sustainability and versatility, making it a valuable resource in manufacturing industries (textiles, construction materials, automotive parts, etc.). These trends also create opportunities for small industries to generate income through the fabrication and commercialisation of handicraft products. Besides, bamboo has its own characteristics, making it one of the choices integrated with the polymer matrix as reinforcement. Due to its potential, bamboo fibre (BF) has been studied widely as reinforcement in polymer composites. In addition, BF is a low-cost, eco-friendly material, and the ease of extraction and treatment also contributes to its attractiveness for a variety of products (Hong et al., 2019; Md Shah et al., 2016). BF has a thick cell wall and microfibrils capable of forming natural glass fibre, as well as stiffness and strength (Al-oqla & Sapuan, 2014; Chee et al., 2017; Hassan et al., 2020; Ibrahim et al., 2015). Besides, bamboo comprises approximately 60% cellulose and lignin and typically features microfibril angles that fall within the range of 2 to 10 degrees (Radzi et al., 2022).

In general, polyurethane materials are mostly used for interior car applications, building materials, furniture, and electrical insulation (Azmi et al., 2012; Kairytė et al., 2018). This polymer is highly adaptable and presently finds application in a broad array of uses. This polymer stands out due to its exceptional wear resistance and favourable tribological and mechanical qualities when incorporated into a polymer composite. Polyurethane offers the versatility to be cast under either high or low pressure, injection moulded, extruded, pressed, or foamed, and it can take on a multitude of shapes, presenting both rigid and flexible options. Typically, this polyurethane is mixed with synthetic fibres, and indirectly, it raises the expenses associated with both materials and manufacturing (de Carvalho et. al, 2020). Hence, natural fibres offer a substitute material for reinforcement to diminish reliance on industrial fibres. This category of polymer is manufactured using a blend of two primary components, specifically polyol and isocyanate (Chaydarreh et al., 2017).

Polyurethane (PU) is one of the thermoplastic polymers, which has a cellular structure that promotes molecular expansion and is prepared via two methods: physical and chemical foaming. Researchers have investigated and explored mixing different fibres with polyurethane foam (PF), such as glass and carbon fibres (Kim et al., 2021; Lee et al., 2019; Zhang et al., 2020). Prior investigations have examined various natural fibres, including coconut, coir and kenaf, for their mechanical performance with PF composites (Azmi et al., 2012;Yuvaraj et al., 2018). However, research on BF/PF composites is still limited and less focused on use in building insulation panels. This study aims to evaluate the mechanical, thermal, and physical performance of the composites, focusing on the effects of fibre sizes on flexural and compressive strength, thermal stability, moisture uptake, water absorption, and dimensional swelling.

METHODOLOGY

Preparation of Materials

PF was obtained from Taat Bestari Sdn. Bhd., Selangor, Malaysia. BF used in this study were sourced from Negeri Sembilan, Malaysia.

Preparation of Fibre Composites

The BF were air-dried under sunlight to lower their moisture content, then ground using a crushing machine and separated into four particle size ranges, such as <150 µm, 150-300 µm, 300-425 µm, and 425-600 µm using a sieve shaker machine (Bryśkiewicz et al., 2016; Gu & Sain, 2012). Figure 1 shows the stages of fibre preparation, from raw bamboo to crushed and sieved fibres. To fabricate the BF/PF composites, polyol and isocyanate

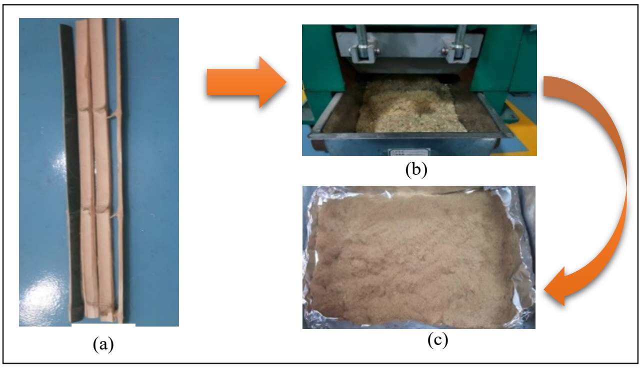

Figure 1. (a) Raw bamboo, (b) crushed BF, and (c) sieved BF

were blended at a weight proportion of 1:1.1 using a mechanical stirring machine (Sinar et al., 2015a). The prepared mixture was cast into moulds, left to solidify for an hour, and subsequently post-cured in an oven at 80 °C for two hours. The composites consisted of 5 wt.% BF and 95 wt. % PF as the matrix with different fibre sizes, as shown in Table 1.

Table 1
Composite formulation of various bamboo fibre sizes

Polyurethane Foam (wt. %)	Bamboo weight (wt. %)	Bamboo Size (µm)	Designation
100	-	-	Neat
95	5	<150	BFP1
		150-300	BFP2
		300-425	BFP3
		425-600	BFP4

Thermogravimetric Analysis (TGA)

The thermal degradation of the composites was examined with a TGA Q50 analyser (TA Instruments). Samples were heated from 30 °C to 600 °C at a rate of 10 °C/min under a nitrogen atmosphere to reduce oxidative effects. The obtained data were then analysed to determine the composites' thermal stability and decomposition behaviour.

Flexural Test

Flexural strength and modulus were evaluated following ASTM D790 (2002). The tests were carried out on a Universal Testing Machine (UTM) fitted with a 5 kN load cell and operated at a crosshead speed of 5 mm/min. For each composition, five samples with dimensions of 160 mm × 40 mm × 20 mm were examined.

Compression Test

The compression test was evaluated in accordance with ASTM D1621 (2000), using the same UTM and testing speed as the flexural test. Five specimens per fibre size category were tested under a constant rate of 5 mm/min with a 5 kN load cell.

Water absorption Test

The water absorption test was conducted following ASTM D570 (1998). Each sample was weighed before immersion (W_0) and then soaked in water for 24 hours. Subsequently, the samples were reweighed at 24-hour intervals over 7 days (W_1). Water uptake was calculated using the following Equation 1:

$$Water\ absoprtion, (\%) = \frac{W_1 - W_0}{W_0} \times 100 \qquad [1]$$

Thickness Swelling Test

The thickness swelling test is used to determine the effect of water absorption on the composite sizes. This test requires 5 samples of each fibre size. The dimensions of the BF/PF composites were measured before and after immersion (T_0 and T_1). The following Equation 2 is calculated for thickness swelling:

$$Thickness\ swelling, (\%) = \frac{T_1 - T_0}{T_0} \times 100 \qquad [2]$$

Moisture Content Test

Five samples are required for each fibre size. The samples were weighed to determine their initial mass (M0), then reweighed after 24 hours of oven drying to record the final mass (M_1). The percentage of moisture was determined using Equation 3:

$$Moisture\ content, (\%) = \frac{M_1 - M_0}{M_0} \times 100 \qquad [3]$$

RESULT AND DISCUSSIONS

Thermogravimetric Analysis

The thermal stability of BF/PF composites was evaluated using thermogravimetric analysis (TGA). In general, natural fibres are easily degraded at high temperatures during the processing of composites. Therefore, understanding the degradation of natural fibres is crucial to ensure that the thermal stability and usability of the composites are maintained in the manufacturing process. Natural fibre composites degrade in a few stages. The first stage is moisture loss occurring at 30-100°C, followed by hemicellulose decomposition (temperature range: 200-300°C) and lignin decomposition (temperature range: 300-400°C), and the last stage is residual ash formation.(Azali et al., 2022; Huzaifah et al., 2017; Norizan et al., 2017).

Figure 2 presents the TGA curves of the BF/PF composites, whereas Figure 3 shows their corresponding DTG curves, from which the influence of fibre size on thermal stability can be analysed. The effect of fibre size on the thermal stability of the composites can be studied from this graph. The results showed that there is no significant difference in the thermal properties of the composites when fibre sizes vary. This is due to the similar composition

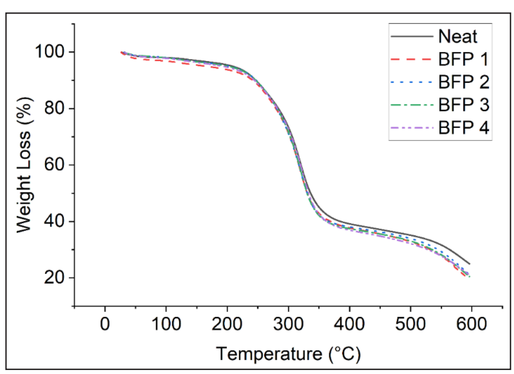

Figure 2. TGA curve of BF/PF composite.

of the fibre, where the individual thermal properties of the materials significantly influence the thermal properties.

All materials, as in the initial stage, were subjected to moisture evaporation at temperatures ranging from 30 to 100 °c (Rasheed et al., 2020; Syafiq et al., 2020). This demonstrates that BF retained more moisture when it started, and the peak degradation temperatures were lower. Decomposition of lignocellulose (hemicellulose) often occurs in the second phase. Observations show that lignocellulose decomposition occurred between 200°C and 300°C, where a small shoulder peak in the DTG curve was observed.

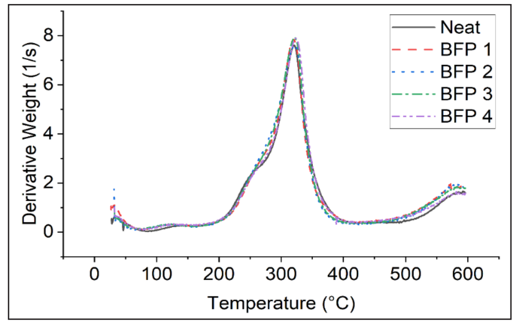

Figure 3. DTG curve of BF/PF composites

The researcher claims that the small shoulder peak before the major decomposition peak was attributed to the decomposition of hemicellulose (Chee et al., 2017; Ishak et al., 2012; Lei et al., 2023). During this stage, cellulose and lignin degradation took place and persisted into the second phase, which was associated with hemicellulose breakdown (Huzaifah et al., 2019; Jumaidin et al., 2017). The thermal degradation behaviour of neat samples and BFP composites with different fibre sizes is summarised in Table 2. In TGA analysis, T_{on} (initial decomposition temperature) marks the onset of material change when heat is applied and mass loss occurs, while Tmax (final decomposition temperature) represents the maximum point of mass change. Among all tested samples, including neat and composite materials, BFP3 exhibited the highest char residue (25.02%), while BFP1 demonstrated the least char residue (19.45%). The percentage of char residue detected in the composites is substantial compared to the neat material, indicating that each of the composite formulations exhibits great heat stability. Thus, the presence of greater lignin levels in BF plays a significant role in strengthening the composites' thermal stability.

Table 2
Thermal decomposition behaviour of BF/PF composites with various fibre sizes

Sample	**First degradation**		**Second degradation**		**Char at 600°c (%)**
	Ton	**Tmax**	**Ton**	**Tmax**	
Neat	235.02	282.49	276.8	320.91	20.55
BFP 1	223.84	278.42	297.83	317.25	19.45
BFP 2	236.96	270.54	303.42	320.61	21.21
BFP 3	229.66	299.07	247.18	321.02	25.02
BFP 4	250.37	296.45	303.48	322.22	21.09

Note. Ton: initial decomposition temperature; Tmax: final decomposition temperature

Flexural Test

The mechanical characteristics of a material are used to determine its composite strength. Figure 4 depicts the flexural strength and modulus of neat and BF/PF composites. Overall, both the modulus and flexural strength of BF/PF composites decrease when BF is added to PF. Flexural strength values are 0.261 MPa (neat), 0.119 MPa (BFP1), 0.151 MPa (BFP2), 0.192 MPa (BFP3), and 0.188 MPa (BFP4). 1.077 (neat) was the highest modulus value for neat PF and BP/PF, followed by 0.735 (BFP4), 0.723 (BFP3), 0.344 (BFP2), and 0.377 (BFP1). The results indicate that Neat Polyurethane foam exhibited higher flexural strength than all BFP composites. Although the incorporation of BF reduced the flexural strength, differences in performance were observed among BFP composites. This reduction is owing to the relatively poor adhesive surface between BF and PF, as well as the nonuniform distribution of fibres, as demonstrated by Huzaifah et al. (2019). Furthermore, the reduction can be attributed to the increase in the BF size and the presence of weak intrinsic strength of the BF compared to the matrix, which can reduce the performance of the mechanical performance. The behaviour of BF/PF composites has been found to increase up to the maximum load. BFP3 excelled over other composites in terms of interfacial adhesion and fibre dispersion, while BF filled voids in the PF. According to Sair et al. (2018), the weakness of composite characteristics can be attributed to low fibre dispersion, fibre breakage at the weakest location, and low distribution of force over fibres and matrix. Czlonka et al. (2018) verified the same finding, indicating that the weak corporate factor between fibres and matrix is similarly the main contributor to weak composites. As a result, the mechanical properties of the composite are crucial and should be optimised so that the composite material remains strong when an external force is applied.

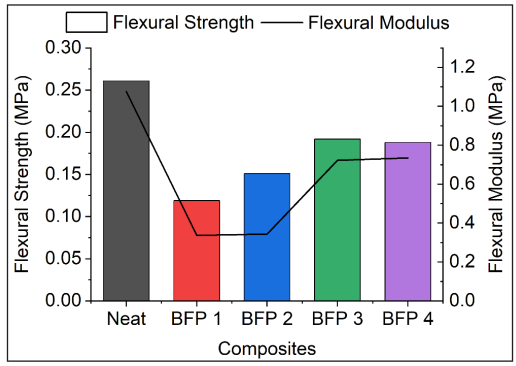

Figure 4. Effect of fibre size on flexural properties of BF/PF composites

Compression Test

Compression test results, presented in Figure 5, indicate that fibre size influenced the compressive properties of the composites. The compressive strength values were 0.203 MPa (BFP1), 0.214 MPa (BFP2), 0.232 MPa (BFP3), 0.221 MPa (BFP4), and 0.282 MPa for the neat sample. The increase in BF size causes a decrease in compaction strength, which is a similar phenomenon to the flexural strength behaviour. The increase in BF size causes a larger dispersion and non-uniform distribution of stress transfer during the compaction test.

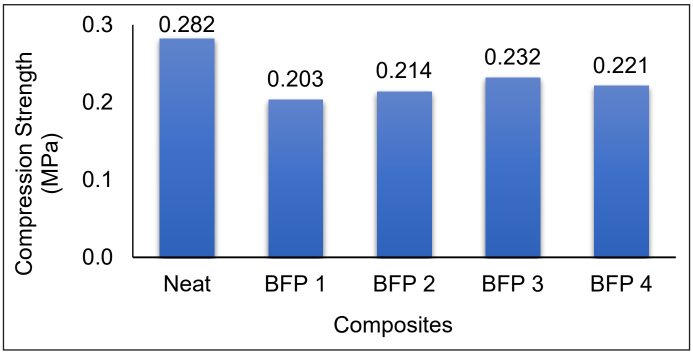

Figure 5. Compression strength of BF/PF composites with various fibre sizes

In addition, the adhesion between BF and PF is weak and leads to uneven force transfer, thereby causing a decrease in mechanical properties. As compared to the compressive strength of BF/PF composites, neat composites showed substantial properties. The results indicate that Neat Polyurethane foam exhibited higher compaction strength than all BFP composites. Although the incorporation of BF reduced the compaction strength, differences in performance were observed among BFP composites. The compression strength of the trend appears to be comparable to the flexural strength graph. Like the flexural behaviour, composites with larger fibre sizes tended to exhibit higher compressive strength. The low strength may be due to poor adhesion between the BF and PF, leading to non-uniform stress transfer, thereby causing a reduction factor on mechanical properties.

BFP3 excelled over other composites in terms of interfacial adhesion and fibre dispersion, while BF filled voids in the PF. This improvement may be due to better load transfer between the fibres and matrix at larger particle sizes. The low failure factor at the lowest values is also related to factors such as poor interaction, fibre agglomeration, and uneven mixing, which may have reduced the mechanical efficiency in some samples (Członka et al., 2018; Sinar et al., 2015b).

Water Absorption

Water absorption was recorded over 24 hours for seven consecutive days. Due to their hydrophilic nature, BF tend to absorb moisture compared to PF. Therefore, evaluating the water absorption properties of BP/PF composites is essential for understanding their performance under immersion conditions (Radzi et al., 2019). Figure 6 shows the water absorption assessment of BF/PF composites with different fibre sizes. After 7 days of immersion, BFP4 has been recorded as having the highest water absorption of 52.92%, followed by BFP3 (45.97%), BFP2 (43.99%), BFP1 (42.54%), and the neat composite (24.2%). From observation, the results of water absorption are greatly influenced by different fibre sizes in this test. Figure 6 shows that an increase in fibre size corresponds

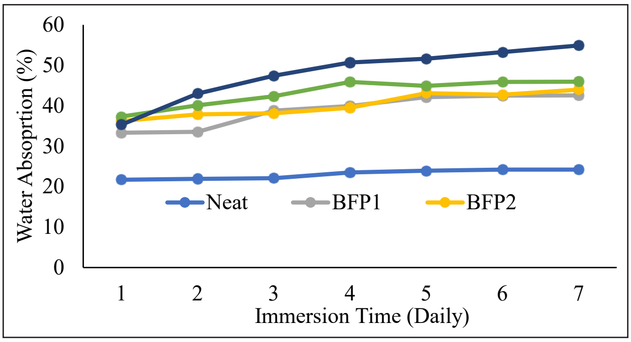

Figure 6. Water absorption properties of BF/PF composites with various fibre sizes

to higher water absorption. This behaviour is also influenced by the PF, which produces high and non-uniform voids. The characteristic facilitates an increased water absorption value, as moisture is easily retained within the foam and by the hydrophilic nature of BF (Chaydarreh et al., 2017; Radzi et al. 2019). Neat PF shows less water uptake due to its hydrophobic nature. As stated by Shalbafan et al. (2021) Polyurethane with a hydrophobic nature can limit water uptake since water primarily penetrates the foam's pores and interacts minimally with its closed-cell structure.

Thickness Swelling

Thickness swelling tests were carried out to determine the dimensional stability of BF/PF composites after seven days of immersion in water. Thickness swelling is closely related to the change in the dimensional stability of the composites. It occurs because the increased water absorption contributes to the expansion and dimensional stability of the composites. The low thickness swelling indicates that its dimensional stability is very good, and it's less susceptible to deformation due to moisture. For 7 days, measurements were recorded every 24 hours. From the fourth day, the BF/PF composites showed improved stability, with less variation in thickness compared to the initial measurements on the first day. The thickness swelling results for BF/PF composites with different fibre sizes are demonstrated in Figure 7. After 7 days, the highest thickness swelling was observed in BFP4 (4.7%), followed by BFP3 (4.29%), BFP2 (3.78%), BFP1 (3.66%), and neat PF (2.12%). Figure 7 shows similar trends with water absorption, which increases fibre size and increases the thickness swelling value. The behaviour of thickness swelling contributed to the same phenomenon as the factors of water absorption properties. Due to its hydrophilic nature, BF shows higher water absorption compared to the hydrophobic PF, which shows weaker interaction between the fibre and matrix. According to Caroline et al. (Rodrigues Pereira de Paula et al., 2022), who noted that weak interfacial bonding between the matrix and fibres increases void content, thereby facilitating high water uptake into the composite.

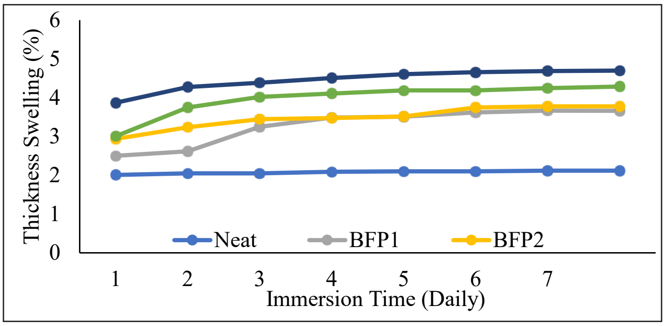

Figure 7. Thickness swelling properties of BF/PF composites with various fibre sizes

Moisture Content

The moisture content test was conducted to measure the amount of water absorbed by the material. These measurements were recorded after the BF/PF composites were immersed for 24 hours. From Figure 8, BFP 4 showed the highest moisture content of 4.79%, followed by BFP3 (4.79%), BFP2 (3.74%), and BFP1 (3.48%). The neat PF (2.26%) was recorded with less moisture content compared to the BF/PF composites.

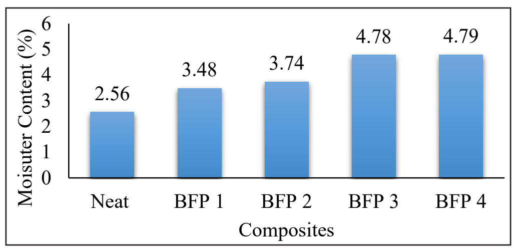

Figure 8. Moisture content properties of BF/PF composites with various fibre sizes

The results show a similar trend consistent with the water absorption and thickness swelling test, where larger fibre sizes contribute to increased moisture content. The graph trend can be attributed to the weak bonding between fibres and matrix, and the inherent differences in nature (hydrophilic and hydrophobic) of the physical properties of BFP and PF. The increase in moisture content percentage is further attributed to the hydrophilic nature of BFP, which easily absorbs moisture. The excess water either penetrates the PF matrix (hydrophobic) or is trapped and forms an additional layer within the PF foams. This behaviour is similar to findings by Chen et al. (2011) who explored the relationship between moisture content and interfacial strength in bamboo-reinforced vinyl ester composites. The researchers highlighted that the hydrophilic nature drives higher moisture absorption, and that residual water can interact with the hydrophobic polymer matrix, forming a surface layer on the composite materials Chen et. al, 2011; Noori et al., 2021).

CONCLUSION

The influence of the different fibre sizes on the mechanical, thermal, and physical properties of BF/PF composites has been thoroughly measured. Increasing the fibre size of BF in the PF matrix positively influenced the mechanical properties (flexural and compression tests). Among the different fibre sizes, BF3 showed the highest mechanical strength, with flexural strength reaching 0.192 MPa and compression strength at 0.221 MPa. The factors causing the mechanical performance are due to excellent fibre dispersion, mixing uniformity and crosslinking between BF and PF. In comparison to neat PF and BFP/PF from thermal properties (TGA), BF/PF composites showed good enhanced thermal stability. However, physical properties show that increasing the fibre size caused higher water absorption, which in turn contributed to the highest thickness swelling and moisture content in all composite samples. Therefore, with its good performance, BF/PF composites with BFP3 show excellent performance for manufacturing applications such as thermal insulation and acoustic products. Furthermore, the BF/PF composites produced in this study have good potential as an alternative and environmentally friendly material. The continued development of natural fibre-based composites, such as those reinforced with BF, can give further support for combination materials in practical applications, including building parts (e.g., roofing and acoustic) and thermal insulation systems.

ACKNOWLEDGEMENT

The authors are grateful for the financial support given by the Geran Inisiatif Putra Muda (GP-IPM) (Vot-9774700). Additionally, we thank the Laboratory of Biocomposite Technology at Universiti Putra Malaysia for their invaluable collaboration.

LIST OF ABBREVIATIONS

BF	:	Bamboo fibre
PF	:	Polyurethane foam
MPa	:	Megapascal
TGA	:	Thermal Gravimetric Analysis
DTG	:	Derivative Thermogravimetry
ASTM	:	American Society for Testing and Materials
UTM	:	Universal Tensile Machine
w_0	:	Weighed before immersion
w_1	:	Weighed after immersion
T_o	:	measure the thickness before
T_1	:	measure the thickness after
m_0	:	measure the mass before immersion
m_1	:	measures the mass after
T_{on}	:	initial decomposition temperature
T_{max}	:	initial decomposition temperature

REFERENCES

Al-Oqla, F. M., & Sapuan, S. M. (2014). Natural fibre reinforced polymer composites in industrial applications: Feasibility of date palm fibres for sustainable automotive industry. *Journal of Cleaner Production, 66*, 347-354. https://doi.org/10.1016/j.jclepro.2013.10.050

Anwar, U. M. K., Hiziroglu, S., Hamdan, H., & Abd. Latif, M. (2011). Effect of outdoor exposure on some properties of resin-treated plybamboo. *Industrial Crops and Products, 33*(1), 140-145. https://doi.org/10.1016/j.indcrop.2010.09.014

ASTM International. (1998). *Standard test method for water absorption of plastics* (ASTM Standard D570-98).

ASTM International. (2000). *Standard test method for compressive properties of rigid cellular plastics* (ASTM Standard D1621).

ASTM International. (2002). *Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials* (ASTM Standard D790-02).

Azali, N. S. Z., Mustafa, N., Jumaidin, R., Abdul Kudus, S. I., Razali, N., Taha, M. M., Yusuf, Y., & Ali, M. R. (2022). Thermal properties of wood dust fibre and recycled polypropylene (r-WoPPc) for development of thermoplastic composites filaments of fused deposition modelling. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 96*(2), 42-50. https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/article/view/387

Azmi, M. A., Yusoff, M. F. C., Abdullah, H. Z., & Idris, M. I. (2012). Rigid polyurethane foam reinforced coconut coir fibre properties. *International Journal of Integrated Engineering, 4*(1), 11–15. https://penerbit.uthm.edu.my/ojs/index.php/ijie

Bahari, S. A., & Krause, A. (2016). Utilising Malaysian bamboo for use in thermoplastic composites. *Journal of Cleaner Production, 110*, 16-24. https://doi.org/10.1016/j.jclepro.2015.03.052

Beran, R., Zárybnická, L., Machová, D., Večeřa, M., & Kalenda, P. (2021). Wood adhesives from waste-free recycling depolymerisation of flexible polyurethane foams. *Journal of Cleaner Production, 305*, Article 127142. https://doi.org/10.1016/j.jclepro.2021.127142

Bryśkiewicz, A., Zieleniewska, M., Przyjemska, K., Chojnacki, P., & Ryszkowska, J. (2016). Modification of flexible polyurethane foams by the addition of natural origin fillers. *Polymer Degradation and Stability, 132*, 32-40. https://doi.org/10.1016/j.polymdegradstab.2016.01.002

Chaydarreh, K. C., Shalbafan, A., & Welling, J. (2017). Effect of ingredient ratios of rigid polyurethane foam on foam core panels properties. *Journal of Applied Polymer Science, 134*(17), Article 44722. https://doi.org/10.1002/app.44722

Chee, S. S., Jawaid, M., & Sultan, M. T. H. (2017). Thermal stability and dynamic mechanical properties of kenaf/bamboo fibre reinforced epoxy composites. *BioResources, 12*(4), 7118–7132. https://bioresources.cnr.ncsu.edu/resources/thermal-stability-and-dynamic-mechanical-properties-of-kenafbamboo-fibre-reinforced-epoxy-composites/

Chen, H., Miao, M., & Ding, X. (2011). Chemical treatments of bamboo to modify its moisture absorption and adhesion to vinyl ester resin in humid environment. *Journal of Composite Materials, 45*(14), 1533-1542. https://doi.org/10.1177/0021998310385023

Chen, M., Weng, Y., Semple, K., Zhang, S., Hu, Y., Jiang, X., Ma, J., Fei, B., & Dai, C. (2021). Sustainability and innovation of bamboo winding composite pipe products. *Renewable and Sustainable Energy Reviews, 144*, Article 110976. https://doi.org/10.1016/j.rser.2021.110976

Członka, S., Sienkiewicz, N., Strąkowska, A., & Strzelec, K. (2018). Keratin feathers as a filler for rigid polyurethane foams on the basis of soybean oil polyol. *Polymer Testing, 72*, 32-45. https://doi.org/10.1016/j.polymertesting.2018.10.032

Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., & Jonoobi, M. (2012). Effect of polybutylene terephthalate (PBT) on impact property improvement of hybrid kenaf/glass epoxy composite. *Materials Letters, 67*(1), 5-7. https://doi.org/10.1016/j.matlet.2011.08.101

de Carvalho, P. S., Nora, M. D., & da Rosa, L. C. (2020). Development of an acoustic absorbing material based on sunflower residue following the cleaner production techniques. *Journal of Cleaner Production, 270*, Article 122478. https://doi.org/10.1016/j.jclepro.2020.122478

Gu, R., & Sain, M. M. (2013). Effects of wood fibre and microclay on the performance of soy based polyurethane foams. *Journal of Polymers and the Environment, 21*(1), 30-38.

Hassan, M. Z., Roslan, S. A., Sapuan, S. M., Rasid, Z. A., Mohd Nor, A. F., Md Daud, M. Y., Dolah, R., & Mohamed Yusoff, M. Z. (2020). Mercerisation optimisation of bamboo (*Bambusa vulgaris*) fibre-reinforced epoxy composite structures using a Box–Behnken design. *Polymers, 12*(6), Article 1367. https://doi.org/10.3390/polym12061367

Hong, C., Li, H., Lorenzo, R., Wu, G., Corbi, I., Corbi, O., Xiong, Z., Yang, D., & Zhang, H. (2019). Review on connections for original bamboo structures. *Journal of Renewable Materials, 7*(8), 713-730. https://www.techscience.com/jrm/v7n8/30574

Huzaifah, M. R. M., Sapuan, S. M., Leman, Z., & Ishak, M. R. (2017). Comparative study on chemical composition, physical, tensile, and thermal properties of sugar palm fibre (*Arenga pinnata*) obtained from different geographical locations. *BioResources, 12*(4), 9366-9382. https://bioresources.cnr.ncsu.edu/resources/comparative-study-on-chemical-composition-physical-tensile-and-thermal-properties-of-sugar-palm-fiber-arenga-pinnata-obtained-from-different-geographical-locations/

Huzaifah, M. R. M., Sapuan, S. M., Leman, Z., & Ishak, M. R. (2019). Effect of fibre loading on the physical, mechanical and thermal properties of sugar palm fibre reinforced vinyl ester composites. *Fibers and Polymers, 20*(5), 1077-1084. https://doi.org/10.1007/s12221-019-1040-0

Huzaifah, M. R. M., Sapuan, S. M., Leman, Z., Ishak, M. R., & Maleque, M. A. (2017). A review of sugar palm (*Arenga pinnata*): Application, fibre characterisation and composites. *Multidiscipline Modeling in Materials and Structures, 13*(4), 678-698. https://doi.org/10.1108/MMMS-12-2016-0064

Ibrahim, I. D., Jamiru, T., Sadiku, R. E., Kupolati, W. K., Agwuncha, S. C., & Ekundayo, G. (2015). The use of polypropylene in bamboo fibre composites and their mechanical properties: A review. *Journal of Reinforced Plastics and Composites, 34*(16), 1347-1356. https://doi.org/10.1177/0731684415591302

Ilyas, R. A., Sapuan, S. M., Kirubaanand, W., Zahfiq, Z. M., Atikah, M. S. N., Ibrahim, R., Radzi, A. M., Nadlene, R., Asyraf, M. R. M., Hazrol, M. D., Sherwani, S. F. K., Harussani, M. M., Tarique, J., Nazrin, A., & Syafiq, R. (2021). Roselle: Production, product development, and composites. In *Roselle* (pp. 1-23). Elsevier. https://doi.org/10.1016/B978-0-323-85213-5.00009-3

Ishak, M. R., Sapuan, S. M., Leman, Z., Rahman, M. Z. A., & Anwar, U. M. K. (2012). Characterisation of sugar palm (*Arenga pinnata*) fibres. *Journal of Thermal Analysis and Calorimetry, 109*(2), 981-989. https://doi.org/10.1007/s10973-011-1785-1

Ishak, M. R., Sapuan, S. M., Leman, Z., Rahman, M. Z. A., Anwar, U. M. K., & Siregar, J. P. (2013). Sugar palm (*Arenga pinnata*): Its fibres, polymers and composites. *Carbohydrate Polymers, 91*(2), 699-710. https://doi.org/10.1016/j.carbpol.2012.07.073

Jawaid, M., Chee, S. S., Asim, M., Saba, N., & Kali, S. (2022). Sustainable kenaf/bamboo fibres/clay hybrid nanocomposites: Properties, environmental aspects and applications. *Journal of Cleaner Production, 330*, Article 129938. https://doi.org/10.1016/j.jclepro.2021.129938

Jumaidin, R., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2017). Effect of seaweed on mechanical, thermal, and biodegradation properties of thermoplastic sugar palm starch/agar composites. *International Journal of Biological Macromolecules, 99*, 265-273. https://doi.org/10.1016/j.ijbiomac.2017.02.092

Kadivar, M., Gauss, C., Ghavami, K., & Savastano, H. (2020). Densification of bamboo: State of the art. *Materials, 13*(19), Article 4346. https://doi.org/10.3390/ma13194346

Kairytė, A., Kirpluks, M., Ivdre, A., Cabulis, U., Vaitkus, S., & Pundiene, I. (2018). Cleaner production of polyurethane foam: Replacement of conventional raw materials, assessment of fire resistance and environmental impact. *Journal of Cleaner Production, 183*, 760-771. https://doi.org/10.1016/j.jclepro.2018.02.164

Kim, M. S., Kim, J. D., Kim, J. H., & Lee, J. M. (2021). Mechanical performance degradation of glass fibre-reinforced polyurethane foam subjected to repetitive low-energy impact. *International Journal of Mechanical Sciences, 194*, Article 106188. https://doi.org/10.1016/j.ijmecsci.2020.106188

Lee, D.-J., Kim, M.-K., Walsh, J., Jang, H.-K., Kim, H.-I., Oh, E.-Y., Nam, J., Kim, M., & Suhr, J. (2019). Experimental characterisation of temperature-dependent dynamic properties of glass fibre reinforced polyurethane foams. *Polymer Testing, 74*, 30-38. https://doi.org/10.1016/j.polymertesting.2018.12.013

Lei, J., Ye, X., Wang, H., & Zhao, D. (2023). Insights into pyrolysis kinetics, thermodynamics, and the reaction mechanism of wheat straw for its resource utilisation. *Sustainability, 15*(16), Article 12536. https://doi.org/10.3390/su151612536

Md Shah, A. U., Sultan, M. T. H., Jawaid, M., Cardona, F., & Abu Talib, A. R. (2016). A review on the tensile properties of bamboo fibre reinforced polymer composites. *BioResources, 11*(4), 10654-10676.

Nadlene, R., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Yusriah, L. (2016). A review on roselle fibre and its composites. *Journal of Natural Fibers, 13*(1), 10-41. https://doi.org/10.1080/15440478.2014.984052

Noori, A., Lu, Y., Saffari, P., Liu, J., & Ke, J. (2021). The effect of mercerisation on thermal and mechanical properties of bamboo fibres as a biocomposite material: A review. *Construction and Building Materials, 279*, Article 122519. https://doi.org/10.1016/j.conbuildmat.2021.122519

Norizan, M. N., Abdan, K., Salit, M. S., & Mohamed, R. (2017). Physical, mechanical and thermal properties of sugar palm yarn fibre loading on reinforced unsaturated polyester composite. *Journal of Physical Science, 28*(3), 115-136. http://jps.usm.my/properties-sugar-palm-yarn-fibre/

Radzi, A. M., Sapuan, S. M., Jawaid, M., & Mansor, M. R. (2018). Mechanical and thermal performances of roselle fibre-reinforced thermoplastic polyurethane composites. *Polymer-Plastics Technology and Engineering, 57*(7), 601-608. https://doi.org/10.1080/03602559.2017.1332206

Radzi, A. M., Sapuan, S. M., Jawaid, M., & Mansor, M. R. (2019). Water absorption, thickness swelling and thermal properties of roselle/sugar palm fibre reinforced thermoplastic polyurethane hybrid composites. *Journal of Materials Research and Technology, 8*(5), 3988-3994. https://doi.org/10.1016/j.jmrt.2019.07.007

Radzi, A. M., Zaki, S. A., Hassan, M. Z., Ilyas, R. A., Md Daud, M. Y., Abd Aziz, S., & Jamaludin, K. R. (2022). Bamboo-fibre-reinforced thermoset and thermoplastic polymer composites: A review of properties, fabrication, and potential applications. *Polymers, 14*(7), Article 1387. https://doi.org/10.3390/polym14071387

Rasheed, M., Jawaid, M., Parveez, B., Zuriyati, A., & Khan, A. (2020). Morphological, chemical and thermal analysis of cellulose nanocrystals extracted from bamboo fibre. *International Journal of Biological Macromolecules, 160*, 183-191. https://doi.org/10.1016/j.ijbiomac.2020.05.170

Rodrigues Pereira de Paula, C., Trianoski, R., & Azevedo, E. (2022). Development and characterisation of sawdust and sisal fibre reinforced vegetable based polyurethane foam hybrid composites. *Journal of Natural Fibers, 19*(9), 3265-3274. https://doi.org/10.1080/15440478.2020.1841067

Roslan, S. A. H., Rasid, Z. A., & Hassan, M. Z. (2018). Bamboo reinforced polymer composite: A comprehensive review. *IOP Conference Series: Materials Science and Engineering, 344*(1), Article 012008. https://doi.org/10.1088/1757-899X/344/1/012008

Saheb, D. N., & Jog, J. P. (1999). Natural fibre polymer composites: A review. *Advances in Polymer Technology, 18*(4), 351-363. https://doi.org/10.1002/(SICI)1098-2329(199924)18:4%3C351::AID-ADV6%3E3.0.CO;2-X

Sair, S., Oushabi, A., Kammouni, A., Tanane, O., Abboud, Y., & El Bouari, A. (2018). Mechanical and thermal conductivity properties of hemp fibre reinforced polyurethane composites. *Case Studies in Construction Materials, 8*, 203-212. https://doi.org/10.1016/j.cscm.2018.02.001

Sanjay, M. R., Madhu, P., Jawaid, M., Senthamaraikannan, P., Senthil, S., & Pradeep, S. (2018). Characterisation and properties of natural fibre polymer composites: A comprehensive review. *Journal of Cleaner Production, 172*, 566-581. https://doi.org/10.1016/j.jclepro.2017.10.101

Sanmuham, V., Sultan, M. T. H., Radzi, A. M., Shamsuri, A. A., Md Shah, A. U., Safri, S. N. A., & Basri, A. A. (2021). Effect of silver nanopowder on mechanical, thermal and antimicrobial properties of kenaf/HDPE composites. *Polymers, 13*(22), Article 3928. https://doi.org/10.3390/polym13223928

Shalbafan, A., Chaydarreh, K. C., & Welling, J. (2021). Effect of blowing agent concentration on rigid polyurethane foam and the properties of foam-core particleboard. *Wood Material Science and Engineering, 16*(2), 85-93. https://doi.org/10.1080/17480272.2019.1626480

Siam, N. A., Uyup, M. K. A., Husain, H., Mohmod, A. L., & Awalludin, M. F. (2019). Anatomical, physical, and mechanical properties of thirteen Malaysian bamboo species. *BioResources, 14*(2), 3925-3943. https://bioresources.cnr.ncsu.edu/resources/anatomical-physical-and-mechanical-properties-of-thirteen-malaysian-bamboo-species/

Sinar, A. A., Firuz, Z., Nur Azni, M. A., Ahmad Zaidi, N. H., Hazizan, M. A., & Sahrim, H. A. (2015a). Compression test and energy absorption of polyurethane/multi-walled carbon nanotubes foam composites. *Materials Science Forum, 819*, 246-250. https://doi.org/10.4028/www.scientific.net/MSF.819.246

Sinar, A. A., Firuz, Z., Nur Azni, M. A., Hazizan, M. A., & Sahrim, H. A. (2015b). Flexural performance of polyurethane/multi-walled carbon nanotubes foam composites. *Applied Mechanics and Materials, 754–755*, 8-12. https://doi.org/10.4028/www.scientific.net/AMM.754-755.8

Suhot, M. A., Hassan, M. Z., Abdul Aziz, S., & Md Daud, M. Y. (2021). Recent progress of rice husk reinforced polymer composites: A review. *Polymers, 13*(15), Article 2391. https://doi.org/10.3390/polym13152391

Supian, A. B. M., Sapuan, S. M., Zuhri, M. Y. M., Zainudin, E. S., & Ya, H. H. (2018). Hybrid reinforced thermoset polymer composite in energy absorption tube application: A review. *Defence Technology, 14*(4), 291-305. https://doi.org/10.1016/j.dt.2018.04.004

Syafiq, M. O., Razali, Sapuan, S. M., & Zuhri, M. R. M. (2020). Effect of cinnamon essential oil on morphological, flammability and thermal properties of nanocellulose fibre-reinforced starch biopolymer composites. *Nanotechnology Reviews, 9*(1), 1147-1159. https://doi.org/10.1515/ntrev-2020-0087

Syafiq, R., Sapuan, S. M., & Zuhri, M. R. M. (2021). Antimicrobial activity, physical, mechanical and barrier properties of sugar palm based nanocellulose/starch biocomposite films incorporated with cinnamon essential oil. *Journal of Materials Research and Technology, 11*, 144-157. https://doi.org/10.1016/j.jmrt.2020.12.091

Syafiq, R., Sapuan, S. M., Zuhri, M. Y. M., & Khalina, A. (2020). Antimicrobial activities of starch-based biopolymers and biocomposites incorporated with plant essential oils: A review. *Polymers, 12*(10), Article 2403. https://doi.org/10.3390/polym12102403

Yuvaraj, L., Jeyanthi, S., & Lenin Babu, M. C. (2018). Sound absorption analysis of castor oil based polyurethane foam with natural fibre. *Materials Today: Proceedings, 5*(11), 23534-23540. https://doi.org/10.1016/j.matpr.2018.10.141

Zhang, Y., Yan, X., Huang, W., & Lin, J. (2020). Experimental investigations on mechanical behaviour of the carbon fibre tube reinforced polyurethane foam. *Thin-Walled Structures, 155*, Article 106899. https://doi.org/10.1016/j.tws.2020.106899

Zia, F., Zia, K. M., Zuber, M., Kamal, S., & Aslam, N. (2015). Starch based polyurethanes: A critical review updating recent literature. *Carbohydrate Polymers, 134*, 784-798. https://doi.org/10.1016/j.carbpol.2015.08.034