

Preparation and Properties of Waste Polypropylene/Bamboo Fiber Composite

Miaoyun Wang,^{a,b} Chenyang Li,^{a,b} Binqing Sun,^{a,b} Lili Yu,^{a,b,*} Hui Li,^{c,*} Zhifeng Ma,^d Songting He^d and Hao Lyu,^{e,*}

With the continuous increase of waste PP plastics, how to recycle and reuse waste PP has become particularly important. In this study, waste PP and bamboo fiber (BF) were used as raw materials. The effects of bamboo fiber mesh size, bamboo fiber content, and hot-pressing process parameters (temperature, pressure, and time) on the physical and mechanical properties of waste PP/BF composites were systematically optimized through single-factor and orthogonal experiments. Composites prepared with 60 to 80 mesh bamboo fiber at 55% to 65% content exhibited the best physical and mechanical properties. The critical factors affecting the elastic modulus and bending strength were bamboo fiber content and hot-pressing temperature, while bamboo fiber content, hot-pressing temperature, and time had the greatest influence on the 72 h water absorption. The optimized process parameters were bamboo fiber content of 55%, hot-pressing temperature of 200 °C, hot-pressing pressure of 0.9 MPa, and hot-pressing time of 17.5 min. Under these conditions, the composite met the requirements of GB/T 29500 (2013) standard. Further research is needed to optimize performance for outdoor applications.

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Contact information: a: College of Light Industry Science and Engineering, Tianjin University of Science & Technology, Tianjin 300457, P. R. China; b: Tianjin Key Laboratory of Pulp and Paper, Tianjin University of Science and Technology, Tianjin 300457, P. R. China; c: Hubei Academy of Forestry, Wuhan 430075, Hubei P. R. China; d: Zhejiang Jinshi Packaging Co., Ltd., Wenzhou 325600, Zhejiang, P. R. China; e: Changjiang Polytechnic, Wuhan 430074, Hubei P. R. China; *Corresponding authors: yulilucky@tust.edu.cn; 827231442@qq.com; 11337801@qq.com

INTRODUCTION

Polypropylene (PP), with the chemical formula $(C_3H_6)_n$ and a density of approximately 0.90 to 0.91 g/cm³, is a white, waxy polymer material produced *via* the addition polymerization of propylene. PP has been widely used across various industries because of its transparency, low weight, non-toxicity, high softening point, chemical and heat resistance, wear resistance, high strength, and good electrical insulation properties. However, the extensive use of PP has led annually to the generation of large amounts of waste PP products (Zhang *et al.* 2023). Due to its high strength and chemical stability, PP has a half-life that may last for several centuries, making it difficult to degrade under natural conditions. Its slow degradation is due to its molecular structure; polypropylene is a long-chain hydrocarbon formed by the addition reaction of propylene monomers, and the strong carbon-carbon bond structure (Samir *et al.* 2022). The ecological hazards of waste

polypropylene are primarily manifested through physical harm at the macro level and microplastic pollution at the micro level (Li *et al.* 2023, Wei *et al.* 2023). At the macro level, discarded polypropylene products such as masks and packaging materials directly enter the environment and become “lethal traps” for wildlife. The French environmental organization “Operation Clean Sea” has warned that when people casually discard masks on the streets, they will end up in the ocean, as 80% of marine waste originates from land. These wastes are washed by rainwater into rivers and eventually reach the ocean, where they cause direct harm to marine life. At the micro level, the harm of microplastics to ecosystems is more insidious and far-reaching. Research has shown the presence of plastic particles in 73% of deep-sea fish. These microplastics are ingested by plankton, shellfish, and fish, and are then transmitted and accumulated through the food chain, ultimately affecting the entire ecosystem. Microplastics not only impact the growth, development, and cardiovascular systems of organisms but have also been found to hinder reproductive functions. Of particular concern is that the degradation process of polypropylene products in the environment releases additives and toxic substances. (Wei *et al.* 2023; Kadaczapska *et al.* 2023).

Waste plastics can be recycled through chemical, mechanical, or biological methods (Lubongo *et al.* 2024). Chemical recycling, primarily involving catalysis and thermal treatment, can convert plastic waste into value-added chemicals or fuels (Zhang *et al.* 2023; Pan *et al.* 2021). However, this method requires high temperatures and substantial energy input, resulting in high infrastructure and process investment costs for technology development (Dogu *et al.* 2021). Biological recycling is an environmentally friendly and resource-efficient treatment method that primarily utilizes microorganisms, enzymes, or other biologically active substances to degrade waste plastics into harmless or reusable materials, while it is expensive in price and complex in processing technology. In addition, the degradation rates of different types of plastics vary significantly during biological degradation (Taniguchi *et al.* 2019; Li 2023; Xu *et al.* 2024). Mechanical recycling involves reprocessing waste plastics to produce raw materials suitable for various plastic products (Mazhandu *et al.* 2020). This method is one of the most used for recycling plastic waste and is also the most suitable for PP plastic recycling (Hopewell *et al.* 2009).

Many scholars and enterprises have used plant fibers as fillers and waste PP plastics as matrices to prepare composite materials, aiming to achieve the dual goals of environmental protection and waste valorization (Salih *et al.* 2020; Zhang *et al.* 2021). Rice straw lignin has been studied as a filler in recycled polypropylene (RPP) and virgin polypropylene (PP) composites by melt blending, and the results revealed that the physical and mechanical properties of RPP and its virgin PP composites had no substantial differences (Karina *et al.* 2017). Leaf and stem fibers of *Sorghum halepense* L. (SH) were investigated as fillers for recycled polypropylene (RPP), and the results showed that mechanical properties of the RPP composites decreased. The addition of SH fibers to the polymer matrix changed the thermal properties of RPP polymer matrix without agglomeration, and the fracture sections of the composites were less rough than that of the RPP by itself (Eroğlu *et al.* 2020, Eroğlu *et al.* 2023).

Guo (2021) evaluated the synergistic effect of multiple interface modification technologies such as maleated polypropylene compatibilizer, alkali treatment, inorganic sol, and inorganic nanoparticles on the mechanical properties of bamboo / PP composite and found flexural the modulus and strength were improved significantly through reinforcement phase purification, fiber morphology control and molding process optimization. Li (2022) used hydrothermal bamboo fibers bamboo fibers as reinforcing

phases and blended with polypropylene to prepare composites. The study found that when the hydrothermal temperature was 160 °C and the additional amount of hydrothermal bamboo fibers was 40%, the prepared polypropylene-based composites exhibited optimal performance. However, due to processing (heat, shear force) and aging during use, the molecular chains of waste PP will break and degrade, resulting in the strength and toughness generally being lower than those of new materials. Moreover, inadequate interfacial bonding between waste PP and plant fibers can lead to a decrease in the mechanical properties of the composite material.

China is extremely rich in bamboo resources, with an annual output of over 7.7 million tons, accounting for more than one-third of the global total production (State Forestry and Grassland Administration of the People's Republic of China 2019). Among various plant fibers, bamboo offers advantages such as excellent mechanical properties, short growth cycles, renewability, and low cost (Li *et al.* 2022). Therefore, this study utilized bamboo and waste PP to prepare bamboo-plastic composites, with the aim of providing experimental basis and process references for the high-value utilization of waste PP plastics and bamboo fibers.

EXPERIMENTAL

Materials

Moso bamboo (*Phyllostachys edulis* (Carr.) H.de Lehaie), purchased from Sichuan Province, China, consists of approximately 35% cellulose, 15% hemicellulose, 20% lignin, and small amounts of proteins, starch, wax, fats, resins, and other compounds (Li *et al.* 2023). The bamboo was crushed using an SM100 Rostfre cutting mill (Retsch GmbH, Germany) and sieved through 40-, 60-, 80-, and 100-mesh screens for grading by a FW177 high-speed grinder (Tianjin Test Instrument Co., Ltd., China). Waste PP was obtained from recycled transparent PP injection-molded beverage cups, and the thickness was 0.2±0.1 mm. The cups were cleaned, dried, and cut into strips using a manual cutter, chopped into blocks, and finally pulverized using a high-speed grinder.



Fig. 1. Preparation process of waste PP/BF composites

Preparation of Waste PP/BF Composites

The BF and waste PP fragments were thoroughly mixed in a small mixer (YG-5L, Zhengzhou Kohler Machinery and Equipment Co., Ltd., China) following different process parameter ratios. The mixture was manually laid up in a 200 mm× 150 mm× 6 mm thickness gauge, pre-pressed, and then hot-pressed by a CARVER 3895 automatic hot press (Micronic Technologies Co., Ltd., USA) referring to GB/T 178657 (2022). After hot pressing, the composite panels were cooled to room temperature and cut into test specimens of specific dimensions using a bone saw machine for subsequent mechanical property testing.

Single-factor Experiments

Single-factor experiments, which could provide preliminary conclusions and parameter ranges for the orthogonal experimental design by “controlling irrelevant variables and focusing on a single factor,” were conducted to investigate the effects of bamboo fiber mesh size, bamboo fiber content, and hot-pressing parameters (temperature, pressure, and time) on the elastic modulus and bending strength of waste PP/BF composites. The experimental conditions are listed in Table 1. Three replicate specimens were prepared for each hot-pressing parameter condition, and the average values with standard deviations were calculated.

Table 1. Single-factor Experimental Conditions

Bamboo Fiber Mesh	Bamboo Fiber Content (%)	Hot-pressing Temperature (°C)	Hot-pressing Time (min)	Hot-pressing Pressure (MPa)
20 to 40, 40 to 60, 60 to 80, 80 to 100	50	190	20	1.2
60 to 80	50, 55, 60, 65, 70	190	20	1.2
60 to 80	50	170, 180, 190, 200, 210	20	1.2
60 to 80	50	190	5, 10, 15, 20, 25	1.2
60 to 80	50	190	20	0.3, 0.6, 0.9, 1.2

Orthogonal Experiment

On the premise of ensuring the comprehensiveness of experimental information, the orthogonal experiment can significantly reduce the number of experiments. At the same time, they can analyze the impact of multiple factors and their interactions on experimental indicators. Based on the results of single-factor experiments, the level ranges of the influencing factors for the orthogonal experiment were determined. In the orthogonal experimental design, four factors—bamboo fiber content (A), hot-pressing temperature (B), hot-pressing pressure (C), and hot-pressing time (D)—were selected as independent variables, along with one error column. Four different levels were chosen for each factor, resulting in an L16 (4⁵) orthogonal design with five factors and four levels. The factor level settings are shown in Table 2. Three replicate specimens were prepared for each hot-pressing parameter condition, and the average results were recorded. Waste PP/bamboo fiber composites were prepared according to the different process parameters designed in Table 2. Referring to GB/T 178657 (2022) and LY/T 3275 (2021), the elastic modulus, flexural strength, and 72 h water absorption rate of the 16 groups of panels prepared under

different process parameters were tested. Multiple tests were averaged to minimize errors. The optimal process parameters for different performance indicators were determined through range analysis, and the effects of the 16 groups of orthogonal level factors on various properties were clarified through variance analysis.

Table 2. Orthogonal Experimental Conditions

Test Group	Bamboo Flour Content (%)	Hot-pressing Temperature (°C)	Hot-pressing Pressure (MPa)	Hot-pressing Time (min)
L1	55	170	0.75	10.0
L2	55	180	0.90	12.5
L3	55	190	1.05	15.0
L4	55	200	1.20	17.5
L5	60	170	0.90	15.0
L6	60	180	0.75	17.5
L7	60	190	1.20	10.0
L8	60	200	1.05	12.5
L9	65	170	1.05	17.5
L10	65	180	1.20	15.0
L11	65	190	0.75	12.5
L12	65	200	0.90	10.0
L13	70	170	1.20	12.5
L14	70	180	1.05	10.0
L15	70	190	0.90	17.5
L16	70	200	0.75	15.0

Performance Evaluation

The bending strength and elastic modulus of waste PP/BF composites were tested and evaluated by the universal testing machine according to GB/T 178657 (2022). Specimens were conditioned at 20 ± 2 °C and $65 \pm 5\%$ relative humidity until constant mass with six replicates in each group and tested by the Universal Testing Machine. Bending strength was calculated using Eq. 1,

$$\sigma_b = \frac{3 \times F_{\max} \times l_1}{2 \times b \times t^2} \quad (1)$$

where σ_b is bending strength (MPa), $F_{\max}$ is the maximum load at failure (N), l_1 is the span between supports (mm), b is specimen width (mm), and t is specimen thickness (mm). Elastic modulus was calculated using Eq. 2,

$$E_b = \frac{l_2^3}{4 \times b \times t^3} \times \frac{F_2 - F_1}{a_2 - a_1} \quad (2)$$

where E_b is elastic modulus (MPa), l_2 is specimen length (mm), b is the width of the specimen (mm); t is the thickness of the specimen (mm); $F_2 - F_1$ is the load increment in the linear segment of the load-deflection curve (N) ($F_1 \approx 10\%$ of $F_{\max}$, $F_2 \approx 40\%$ of $F_{\max}$), and $a_2 - a_1$ is the corresponding deformation increment (mm).

The 72-h water absorption thickness expansion percentage of waste PP/BF composites was tested according to LY/T 3275 (2021). The specimens were immersed completely in a constant-temperature water bath at (20 ± 1) °C. After soaking for (72 ± 0.5) h, they were taken out, the surfaces of the specimens were wiped with test paper to remove residual moisture, and the specimens were weighed within 10 min, with an accuracy of 0.01 g. The water absorption rate of the specimens was expressed as the

arithmetic mean of the water absorption rates of 3 specimens, with an accuracy of 0.1%, and calculated using Eq. 3,

$$T = \frac{t_2 - t_1}{t_1} \times 100\% \quad (3)$$

where T is water absorption (%), t_2 is mass after immersion (g), and t_1 is mass before immersion (g).

RESULTS AND DISCUSSION

Single-factor Experiment Analysis

Effect of bamboo fiber mesh size on properties

The effects of bamboo fiber mesh size on the mechanical and water absorption properties of waste PP/BF composites are shown in Fig. 2(a) and Fig. 2(b). When the bamboo fiber mesh size increased from (20 to 40) mesh to (> 100) mesh, the elastic modulus and bending strength of the composites initially increased and then decreased. The 72 h water absorption percentages initially decreased and then increased, which demonstrated that the best overall performance was with (60 to 80) mesh bamboo fiber, with an elastic modulus of 816 MPa, bending strength of 9.82 MPa, and 72 h water absorption of 22.6%. The change of the mechanical properties was because larger bamboo fiber particles would result in poor interfacial bonding with the waste PP matrix, reducing mechanical properties, while smaller particles had a larger specific surface area, hindering waste PP from fully encapsulating the fiber. This led to agglomeration and reduced mechanical properties, consistent with the conclusions obtained by Bahari and Krause (2017) and Li *et al.* (2024). Bamboo fiber with 60 to 80 mesh had an appropriate fiber length, allowing uniform distribution within waste PP matrix and better interfacial compatibility and mechanical interlocking. The change of the 72-h water absorption was attributed to that larger mesh size of bamboo fiber meant a huge specific surface area, which can provide more sites to adsorb and lock water molecules. Therefore, the water absorption rate of composites using fine bamboo fiber (>100 mesh) increased. However, overly coarse bamboo powder particles (20 to 40 mesh) tend to form gaps, providing paths for water penetration. Thus, 60 to 80 mesh bamboo fiber was used in subsequent experiments.

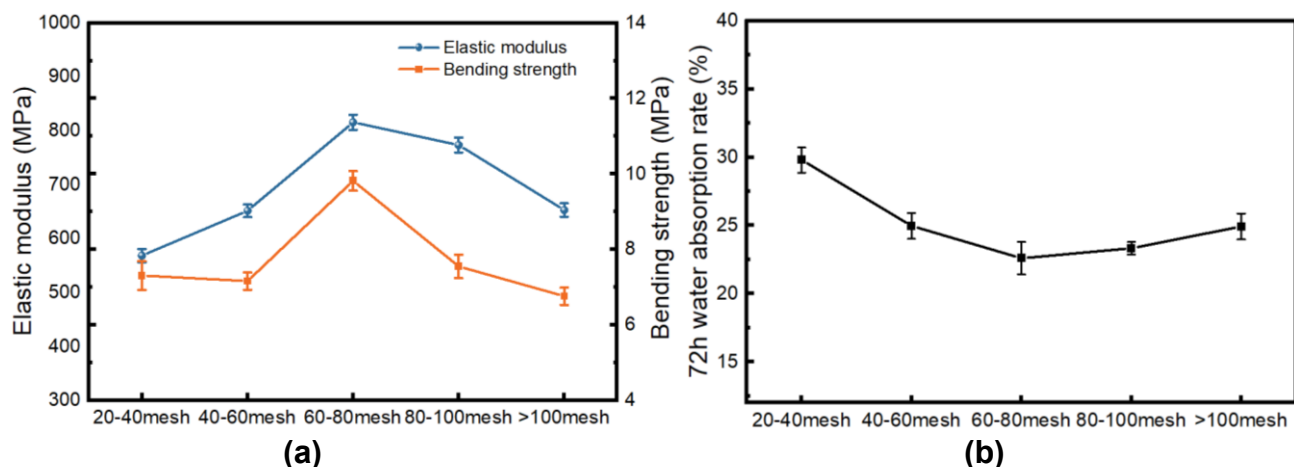


Fig. 2. Effect of bamboo fiber mesh size on properties of waste PP/BF composites

Effect of hot-pressing temperature on properties

The effects of hot-pressing temperature on the mechanical and water absorption properties of waste PP/BF composites are shown in Fig. 3(a) and Fig. 3(b). As shown, the mechanical properties of the composites rose initially, then declined with increasing temperature, while water absorption rate first increased, then decreased slightly, and then increased again as hot-processing temperature increased. The melting point of waste PP is between 160 and 170 °C. Below 170 °C, waste PP does not fully melt, leading to poor dispersion in bamboo fibers and inadequate bonding. As temperature increased, cellulose in bamboo fibers degraded, reducing surface polarity and hydrophilic hydroxyl groups, enhancing interfacial bonding and mechanical properties while reducing water absorption. However, excessive temperature caused thermal degradation of other bamboo fiber components, reducing composite stability and mechanical properties while increasing water absorption (Nkeuwa *et al.* 2022). Thus, 170, 180, 190, and 200 °C were selected as hot-pressing temperature levels for orthogonal experiments.

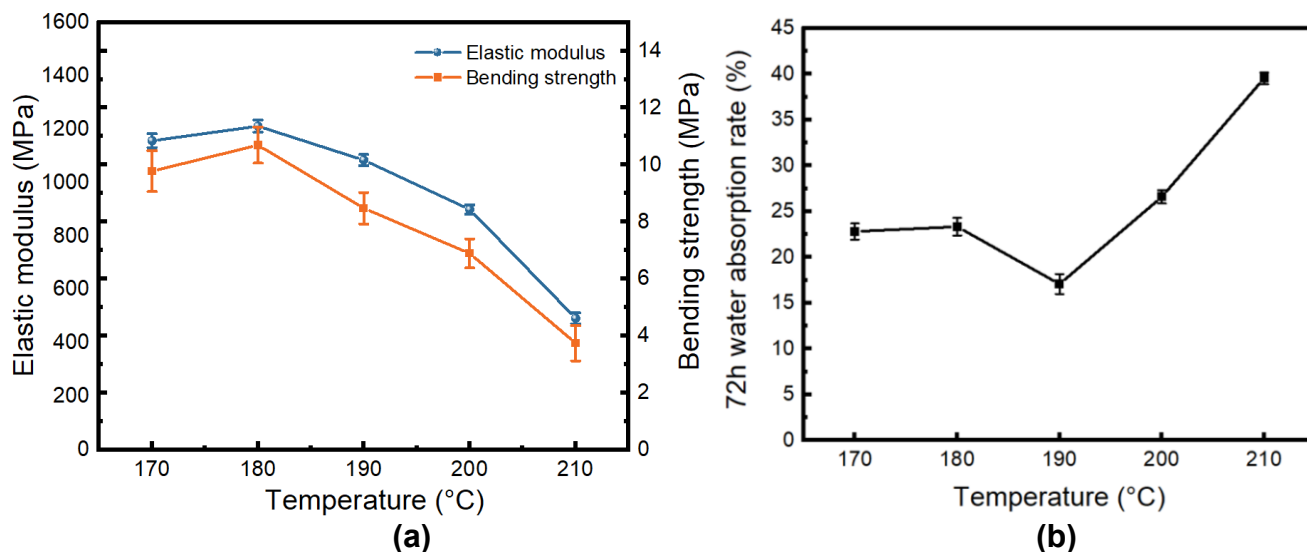


Fig. 3. Effect of hot-pressing temperature on properties of waste PP/BF composites

Effect of hot-pressing pressure on properties

The effects of hot-pressing pressure on the mechanical and water absorption properties of waste PP/BF composites are shown in Fig. 4(a) and Fig. 4(b). Hot-pressing pressure is a key factor affecting the encapsulation of bamboo fibers by the plastic matrix. As shown in Fig. 4, elastic modulus and bending strength initially increased and then decreased with increasing pressure, while 72 h water absorption first decreased and then increased, in which the best mechanical properties and the lowest water absorption rate of the composite occurred at a pressure of 0.9 MPa. This result demonstrated that higher pressure could enhance encapsulation and bonding between bamboo fibers and waste PP, as the result the internal voids could be reduced significantly, which is the positive factor for the improvement of mechanical properties and hydrophobicity of the composites. Yu *et al.* (2025) also pointed out that in the flat-press hot-pressing process, an increase in pressure also reduced the time required for the composite to be pressed to the specified thickness. This, in turn, improved the efficiency of internal convective heat transfer and thermal conduction, thereby promoting the enhancement of the mechanical properties of the composite material. However, excessive pressure (above 0.9 MPa) over-compressed

the composite, would damage its structure and lowering its performance. Thus, 0.3 MPa, 0.6 MPa, 0.9 MPa, and 1.2 MPa were selected as the pressure levels for orthogonal experiments.

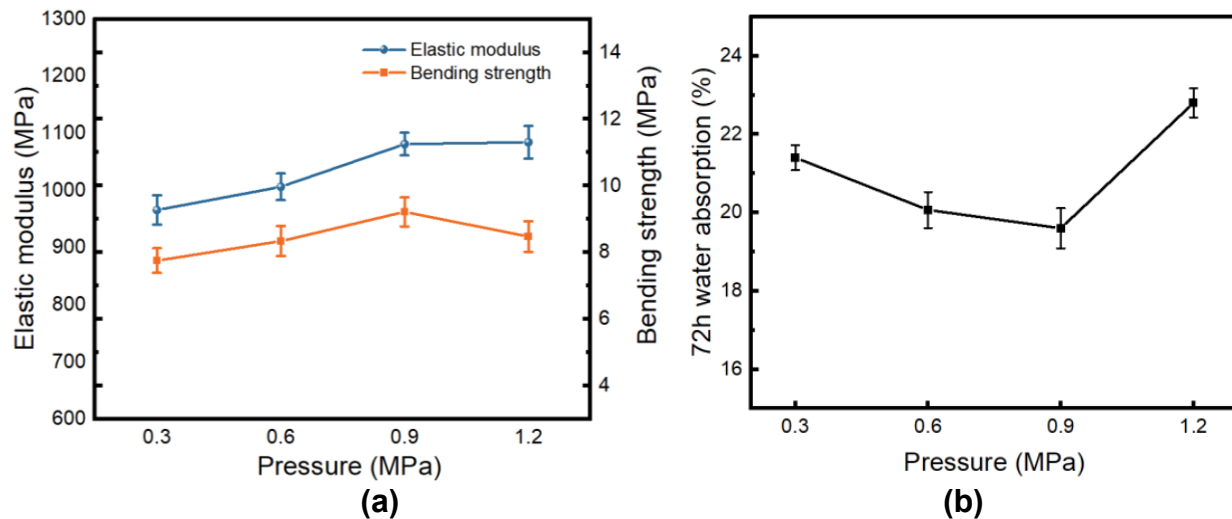


Fig. 4. Effect of hot-pressing pressure on properties of waste PP/BF composites

Effect of hot-pressing time on properties

The effects of hot-pressing time on the mechanical and water absorption properties of waste PP/BF composites are shown in Fig. 5(a) and Fig. 5(b). As shown in Fig. 5, elastic modulus and bending strength first increased and then decreased, while 72 h water absorption first decreased and then increased as hot-pressing time increased. This result showed that prolonged time could improve contact and bonding between bamboo fibers and waste PP, relieve internal stresses, and enhance the strength and stability of the composite (Yu *et al.* 2025). In contrast, excessive time led to over-compression and thermal decomposition of bamboo fibers, reducing mechanical properties and hydrophobicity. Thus, 10 min, 12.5 min, 15 min, and 17.5 min were selected as the time levels for orthogonal experiments.

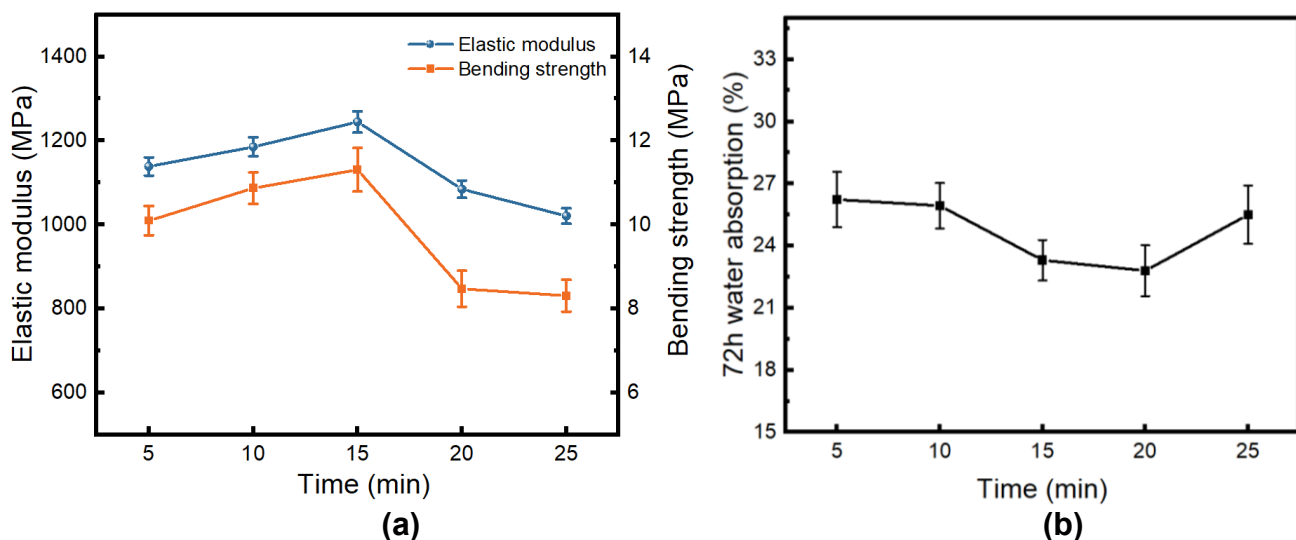


Fig. 5. Effect of hot-pressing time on properties of waste PP/BF composites

Effect of bamboo fiber content on properties

The effects of bamboo fiber content on the mechanical and water absorption properties of waste PP/BF composites are shown in Fig. 6(a) and Fig. 6(b). As shown in Fig. 6, elastic modulus and bending strength first increased, then decreased, and finally increased again with increasing bamboo fiber content, while 72 h water absorption rate initially decreased and then increased as bamboo fiber content increased. This may be caused by the excessive bamboo fiber content, which would limit the complete encapsulation of waste PP and increase the hydrophilic hydroxyl groups, which could provide the water absorption sites for the composite (Tang *et al.* 2019). However, insufficient bamboo fiber content could reduce the mechanical properties of the composite significantly. According to LY/T 3275 (2021), bamboo fiber content should be no less than 50%. Considering both mechanical properties and water absorption, 55%, 60%, 65%, and 70% were selected as content levels for orthogonal experiments.

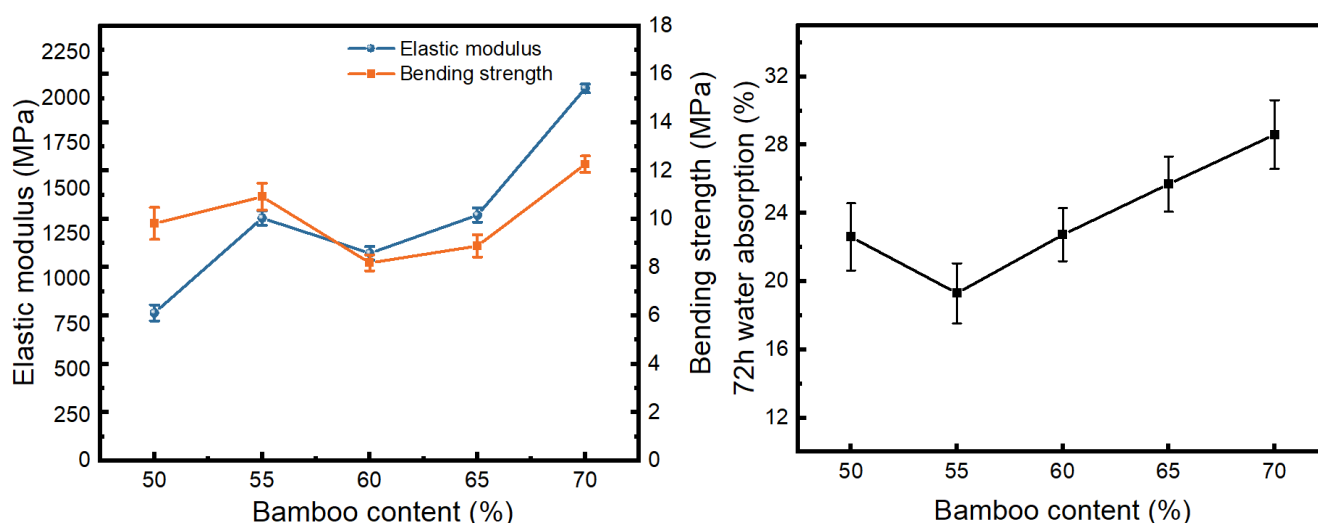


Fig. 6. Effect of bamboo fiber content on properties of waste PP/BF composites

Orthogonal Experiments

As shown in the range analysis of the orthogonal experiment results in Table 3, for waste PP/BF composites with elastic modulus as the detection indicator, the optimized process parameters were: bamboo powder content 55%, hot-pressing temperature 200 °C, hot-pressing pressure 0.75 MPa, and hot-pressing time 17.5 min, *i.e.*, A1B4C1D4. Range analysis indicated that the influence of the four experimental factors on the elastic modulus of the composites decreased in the order: bamboo powder content > hot-pressing temperature > hot-pressing pressure > hot-pressing time. When flexural strength was used as the detection indicator, the optimized process parameters were: bamboo powder content 55%, hot-pressing temperature 200 °C, hot-pressing pressure 1.05 MPa, and hot-pressing time 17.5 min, *i.e.*, A1B4C3D4. Range analysis showed that the influence of the four experimental factors on the flexural strength of the composites, in descending order, was: bamboo powder content > hot-pressing temperature > hot-pressing pressure > hot-pressing time. When the 72-h water absorption was used as the detection indicator, the optimized process parameters were: bamboo powder content 55%, hot-pressing temperature 200 °C, hot-pressing pressure 0.9 MPa, and hot-pressing time 17.5 min, *i.e.*, A1B4C2D4. Range analysis revealed that the influence of the four experimental factors on the 72 h water absorption of the composites, in descending order, were: bamboo powder content > hot-

pressing temperature > hot-pressing time > hot-pressing pressure. This indicated that the elastic modulus and flexural strength of the composite materials were primarily influenced by hot-pressing factors, especially hot-pressing temperature. In contrast, the 24 h water absorption thickness swelling mainly depended on the adhesive application amount. Generally, a higher application amount of phenolic resin resulted in better dimensional stability of the composite materials. This was primarily because phenolic resin is insoluble in water. Under high temperature and pressure, phenolic resin penetrated and dispersed into the interior of the composite material, blocking some channels for water ingress and egress. Additionally, under high temperature and pressure, phenolic resin reacted with free hydroxyl groups in the fibers, thereby reducing the number of sites available for water adsorption in the fibers (He *et al.* 2014; Li *et al.* 2021; Ren *et al.* 2024).

Table 3. Range Analysis of Orthogonal Experiment Results

Performance Indicator	Level	Hot-pressing Temperature (A) (°C)	Hot-pressing Time (B) (min)	Hot-pressing Pressure (C) (MPa)	Bamboo Flour Content (D) (%)
Elastic Modulus (MPa)	k1	1305.66	944.22	1207.42	1101.73
	k2	1115.43	1106.07	1178.69	1150.72
	k3	1260.76	1258.28	1112.94	1163.67
	k4	908.81	1282.09	1091.60	1174.53
	R	396.84	337.87	115.82	72.80
Bending Strength (MPa)	k1	10.07	5.42	7.45	7.25
	k2	7.74	7.01	7.52	7.69
	k3	7.34	8.14	7.82	7.13
	k4	4.63	9.21	6.99	7.71
	R	5.44	3.79	0.83	0.59
72 h Water Absorption (%)	k1	23.93	34.90	31.55	29.20
	k2	27.85	32.6225	29.23	33.45
	k3	31.53	29.325	31.55	32.68
	k4	40.28	26.725	31.25	28.25
	R	16.35	8.175	2.33	5.20

Verification of Optimized Process

Based on range analysis results (Xue and Qian 2007), three sets of parameters ($A_1B_4C_1D_4$, $A_1B_4C_3D_4$, and $A_1B_4C_2D_4$) were selected for verification (Table 4). The optimal parameters were $A_1B_4C_2D_4$: bamboo fiber content 55%, hot-pressing temperature 200 °C, pressure 0.9 MPa, and time 17.5 min, in which the elastic modulus and bending strength could reach the maximum value, and the 72 h water absorption was the lowest.

Table 4. Verification of Optimized Process

Experiment	Elastic Modulus (MPa)	Bending Strength (MPa)	72 h Water Absorption (%)
$A_1B_4C_1D_4$	1189.42	12.21	17.20
$A_1B_4C_3D_4$	1209.63	11.78	18.81
$A_1B_4C_2D_4$	1261.23	13.87	16.54

Although the preparation process was optimized, the bending strength and water absorption did not fully meet outdoor application standards. Future work should aim to improve interfacial bonding and hydrophobicity to further enhance mechanical properties

and water resistance. For example, some research has showed that the compatibilizer (maleated polypropylene) provided increased resistance to stress and maximum deflection attributed to the wetting of the cellulosic charge by the thermoplastic polymer with the compatibilizer, which corroborated the possible occurrence of an esterification reaction and hydrogen bonding interactions in the matrix-particle interface (Maziero *et al.* 2019; Vedat 2020). Furthermore, as mentioned earlier, the use of a simple dry mixer to blend waste PP with bamboo fibers results in low mixing efficiency, which leads to a decline in the performance of the composites. Therefore, the next step may consider realizing the conventional melt blending of PP and bamboo powder *via* a Haake torque rheometer (Beigloo *et al.* 2017).

CONCLUSIONS

1. Composites prepared with (60 to 80) mesh bamboo flour at 55% to 65% content exhibited the best overall performance. This mesh size encouraged good interfacial bonding with the PP matrix while avoiding the agglomeration issues of finer particles. However, when bamboo flour content exceeded 65%, inadequate encapsulation by PP led to markedly increased water absorption (> 22.6%) and reduced mechanical properties.
2. The physical and mechanical properties of waste PP/BF composites were most sensitive to hot-pressing temperature. At 200 °C, PP melted sufficiently, ensuring tight bonding with bamboo fibers and maximum elastic modulus. Temperatures above 200 °C accelerated thermal degradation of bamboo fibers, deteriorating material properties. A pressure of 0.9 MPa and times between 15 min and 17.5 min were optimal. Higher pressure (> 1.2 MPa) or longer time (> 20 min) damaged the material structure.

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