Effects of Hot-pressing Parameters on the Properties of Waste Tetra Pak/Bamboo Composites

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Waste Tetra Pak containers, from the same brand of milk, were crushed into fibers. They were formed into composites with 40-mesh bamboo fibers with phenolic resin and hot pressed with different parameters. The effects of hot-pressing temperature, hot-pressing time, hot-pressing pressure, phenolic resin amount, and the ratio of Tetra Pak and bamboo on the elastic modulus, static bending strength, internal adhesive bonding strength, and 24 h thickness swelling rate of the composites were investigated by orthogonal testing. The results showed that during the hot-pressing process, hot-pressing temperature was the most important factor for the elastic modulus and static bending strength of the composites and the hot-pressing pressure was the most important factor for the 24 h thickness swelling of the composites. Optimal hot-pressing parameters of TP/bamboo composites were a hot-pressing temperature of 180 °C, hot-pressing time of 16 min, hot-pressing pressure of 1.0 MPa, phenolic resin amount of 12%, and ratio of Tetra Pak/bamboo of 9:1, in which the least phenolic resin and the most Tetra Pak materials were added. Moreover, the elastic modulus was 7670 MPa, the bending strength was 40 MPa, the internal adhesive bonding strength was 0.86 MPa, and 24 h thickness swelling rate was 10.6%, meeting the requirements for MDF in different states.

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INTRODUCTION

Tetra Pak has become one of the predominant materials in the packaging industry because of the higher barrier and sterilization abilities (Muhammadi *et al.* 2021). However, with the widespread use of Tetra Pak, it is inevitable to face the production of a large amount of Tetra Pak waste materials every year. It was reported that the annual usage of Tetra Pak packaging in China had exceeded 100 billion units, while the recycling rate was less than 20% (Chen *et al.* 2022). Many researchers have made great efforts to utilize the waste Tetra Pak, and the main reuse technologies include the overall utilization and the separation utilization (Muhammadi *et al.* 2021; Stramarkou *et al.* 2021; Ekere1 *et al.* 2022).

For the overall utilization reuse technology, waste Tetra Pak packaging materials are directly used as raw materials to produce various composites, such as wood-based panels, fillers, roof panels, and polymer concretes, without undergoing component separation (Bekhta *et al.* 2016a). Ebadi *et al.* (2016, 2018) studied the effects of Tetra Pak waste and maleic anhydride-grafted polyethylene on the physical and mechanical properties of wood-plastic composites. The results revealed that the composite containing 30% of Tetra Pak and 3% maleic anhydride grafted polyethylene (MAPE) had the highest strength and tensile modulus, and the samples containing 3% of MAPE had the highest impact resistance. After the addition of Tetra Pak and MAPE, the flexural strength and elastic modulus of the samples were improved, the 24-h water absorption and thickness swelling rates were decreased. Kolyada *et al.* (2021) found that the introduction of polyvinyl acetate suspension into the waste Tetra Pak packaging materials could effectively increase the density and strength properties of the wood-plastic composites. Auriga *et al.* (2021) had placed Tetra Pak waste material in the core layer of the chipboard and found that the content of Tetra Pak waste had no significant effect on the static bending strength, elastic modulus, swelling, and water absorption of the chipboard, but could significantly reduce the tensile strength of the board. Rhamin *et al.* (2013) investigated the effects of resin contents, pressing time, and overlaying methods on the physical and mechanical properties of carbonized wood-based panels made by recycled Tetra Pak and melamine-urea formaldehyde resin. The results showed that the pressing time and resin contents did not have obvious effects on the mechanical properties of the carbonized composites, but the overlaying methods could significantly increase the mechanical properties and reduce the physical properties of all the samples.

The separation utilization technologies of waste Tetra Pak that refer to the mechanical separation of cardboard from polyethylene (PE) and aluminum (AL) using appropriate separation techniques (*e.g.*, hydropulping technology), only allow for the recovery of substantial amounts of cellulose, which can be reused in the manufacture of paper and packaging materials. The PE-AL composite materials can be converted into other useful products for reuse, such as panels, roofing sheets, waterproof boards, and furniture, or it can undergo incineration for energy recovery (Sahin and Karaboyac 2021). Xing *et al.* (2018) successfully extracted cardboard and polyethylene films from the waste Tetra Pak packaging and then employed a three-step process of dewaxing, sodium chlorite oxidation, and alkaline leaching to purify the paper fibers and achieve the isolation of cellulose fibers (CFs). Balti *et al.* (2024) used the long fibers extracted from Tetra Pak waste as reinforcement in gypsum-paper mortars. Compared to conventional gypsum, the results exhibited a remarkable 34% increase in flexural strength, accompanied by a substantial decrease in both density (20%) and thermal conductivity (17%). This notable achievement was attributed to the incorporation of Tetra Pak fibers into the novel material composition.

Many studies have been performed to optimize the preparation parameters of new bio-fiber based composites. Sumesh *et al.* (2023) selected hybrid ramie/flax natural fiber reinforcement along with epoxy resin as the matrix material, and compression molding as the fabrication method to prepare the composites. They found that higher pressure, higher operating temperature, and time could lead to a decline in the mechanical properties of the polymer composites, and combination with 40 wt.% natural fiber in the composites had good fiber distribution leading to better properties observed by SEM analysis. Another study (Sumesh *et al.* 2024a) evaluated the natural fibers along with glass fibers as the reinforcement to improve the mechanical and wear applications of the epoxy polymer composites. The interfacial adhesion of fiber with matrix created a pressure-absorbing zone that was positively influenced with applying higher loads. The frictional rate was highly increasing with increase in hybrid fiber wt% and also with higher loads applied due to the improved adhesion of fiber with matrix phase. Some researchers (Jagdeva *et al.* 2023; Sumesh *et al.* 2024b; Feng *et al.* 2024) had shown that the natural fibers treated with sodium hydroxide (NaOH) could provide considerable advantages to the growing mechanical quantities of the fiber composites, due to the strengthening of the fiber-matrix bonding by roughening the fiber surface, which promoted better interaction with the polymers.

The overall utilization reuse technology of waste Tetra Pak is simple to execute, and the prepared composites are useful in many fields, such as furniture, construction, packaging, and so on. So it was selected to prepare the waste TP/bamboo composites in this study. Hot-pressing temperature, hot-pressing time, hot-pressing pressure, phenolic resin amount, and the ratio of TP and bamboo on the elastic modulus, static bending strength, internal adhesive bonding strength, and 24 h thickness swelling rate of the composites were investigated by orthogonal testing. The aim of this study was to find the optimal hot-pressing parameters of the composites and provide useful information for industrial production.

EXPERIMENTAL

Materials

Moso bamboo (*Phyllostachys edulis* (Carr.) H. de Lehaie) was taken from Jiangxi Province of China and ground with a cutting grinder with a particle size of 40 mesh. Waste Tetra Pak was cleaned and dried. Then it was crushed using a high-speed crusher (FW177, Tianjin Taiste Instrument Co., Ltd.) with a particle size of 40 mesh. Phenolic resin was purchased from Dynea Adhesives Co., Ltd. (Zhaoqing, China), with a solid content of 43%.

Optimization of Hot-pressing Parameters for Waste TP/Bamboo Composites

The 40-mesh Tetra Pak and bamboo fibers were mixed using a small high-speed hybrid machine, and the ratio of Tetra Pak to bamboo was set as shown in Table 1. After that, the mixture was evenly spread in the hot press, and the hot-pressing parameters—including hot-pressing temperature (A), hot-pressing time (B), hot-pressing pressure (C), phenolic resin amount (D), and the ratio of Tetra Pak to bamboo (E)—are shown in Table 1. The orthogonal test L16 (45) was designed to determine the optimal hot-pressing treatment conditions for waste TP/bamboo composites based on the range analysis results. Range is an index that describes the range of the data distribution, demonstrating the difference between the maximum and minimum values (Li *et al.* 2024) and can be calculated by the following formulas. The larger the range value, the greater influence of the lever for the factor on the composite properties. Equations 1 and 2 are as follows,

$$k_j = \frac{1}{n} K_j \ \text{(where } n \text{ is the number of occurrences at the same level)} \tag{1}$$

$$R = \max\left(k_1, k_2, \ldots k_j\right) - \min\left(k_1, k_2, \ldots k_j\right) \tag{2}$$

where Kj (j = 1, 2, 3, 4) is the sum of the values of the j^{th} level of each factor; k_j is the mean value of the j^{th} level of each factor; and R is the range of the j^{th} level of each factor.

Table 1. Orthogonal Test Design of Hot-pressing Parameters

Test Group	Factors				
	A	B	C	D	E
	Hot-pressing Temperature (°C)	Hot-pressing Time (min)	Hot-pressing Pressure (MPa)	Phenolic Resin Amount (%)	Tetra Pak/Bamboo Ratio
L1	150	10	1.0	10	9:1
L2	150	12	1.2	12	8:2
L3	150	14	1.4	14	7:3
L4	150	16	1.6	16	6:4
L5	160	10	1.2	14	6:4
L6	160	12	1.0	16	7:3
L7	160	14	1.6	10	82
L8	160	16	1.4	12	9:1
L9	170	10	1.4	16	8:2
L10	170	12	1.6	14	9:1
L11	170	14	1.0	12	6:4
L12	170	16	1.2	10	7:3
L13	180	10	1.6	12	7:3
L14	180	12	1.4	10	6:4
L15	180	14	1.2	16	9:1
L16	180	16	1.0	14	8:2

Mechanical Property Test

The samples with 150 mm×50 mm×6 mm prepared under different hot-pressing parameters were conditioned at the temperature of (20±2)°C and relative humidity of (65±5)% until the difference between the two weights obtained at 24 h interval did not exceed 0.1% of the specimen mass (the specimen mass is regarded as constant). The static bending strength (σ_b), elastic modulus (E_b), and internal adhesive bonding strength ($\sigma_\perp$) of the samples were selected as the main evaluation indexes according to GB/T 17657 (2022) and were tested by an Instron 3369 universal mechanical experimental machine (Instron, Boston, MA, USA), and 5 repeated samples were tested for each preparation condition. The strength properties were calculated using the following formulas,

$$\sigma_b = \frac{3\times F_{max}\times l_1}{2\times b\times t^2} \tag{3}$$

where σ_b is the static bending strength of the samples (MPa); F_{max} is the maximum load at failure of the samples (N); l_1 is the distance between two supports (mm); b is the width of the samples (mm); and t is the thickness of the samples (mm).

$$E_b = \frac{l_2^3}{4\times b\times t^3} \times \frac{F_2-F_1}{a_2-a_1} \tag{4}$$

In Eq. 4, E_b is the elastic modulus of the samples (MPa); l_2 is the length of the samples (mm); b is the width of the samples (mm); and t is the thickness of the samples (mm). Equation 5 was used to calculate the adhesive bonding strength,

$$\sigma_{\perp} = \frac{F_{max}}{l \times b} \tag{5}$$

where $\sigma_{\perp}$ is the internal adhesive bonding strength of the samples (MPa); F_{max} is the maximum load at failure of the samples (N); l is the length of the samples (mm); and b is the width of the samples (mm).

24 h Thickness Swelling Test

The samples, with 50 mm × 50 mm × 6 mm dimensions prepared under different hot-pressing parameters, were conditioned at (20±2)°C and relative humidity of (65±5)% to reach the room temperature, and then they were immersed into the water at 20 ℃ for 24 h. The calculation formula of the 24 h thickness swelling rate according to GB/T 17657 (2022) was as follows:

$$T = \frac{t_2 - t_1}{t_1} \times 100 \tag{5}$$

where T is the thickness swelling of the samples (%); t_2 is the thickness of the samples after immersion (mm); and t_1 is the thickness of the samples before immersion (mm).

RESULTS AND DISCUSSION

Holistic Analysis of the Orthogonal Test

The elastic modulus, static bending strength, internal adhesive bonding strength, and 24 h thickness swelling rate of the waste TP/bamboo composites with different hot-pressing parameters are shown in Fig. 1. These are according to the orthogonal test design. The main dimensional and mechanical properties of the medium-density fiberboard (MDF) in different states according to GB/T 11718 (2021) are shown in Table 2.

Similar with the results obtained in Sumesh *et al.* (2023), different hot-pressing parameters had great effects on the dimensional and mechanical properties of the composites. For the elastic modulus, except for the samples in the groups of L1 and L2, the other groups of the samples reached the requirements for different applications according to GB/T 11718 (2021).

For the static bending strength, the samples in the groups of L8, L11, L12, L13, L14, L15, L16 reached the requirements in different indoor applications, and L8, L11, L12, L15, L16 could be even used as outdoor furniture materials. For the internal adhesive bonding strength, L3 and L8 only could be used as indoor building materials, while L4, L6, L9, L15, L16 could reach the requirements in higher humidity conditions and outdoor exposure as furniture material.

For the 24 h thickness swelling, all 16 groups of the samples reached the requirements for application in the dry state, and except for L11, all the other groups reached the requirements for outdoor application. In general, the samples in the groups of L15, L16 reached the requirements of main dimensional and mechanical properties of MDF in different applications.

Table 2. Dimensional and Mechanical Properties of MDF in Different States According to GB/T 11718 (2021)

Applications	Elastic Modulus (MPa)	Bending Strength (MPa)	Internal Adhesive Bonding Strength (MPa)	24 h Thickness Swelling (%)
Ordinary MDF used in dry state ((20±2)°C, relative humidity ≤(65±5)%)	≥ 26.0	≥ 2600	≥ 0.60	≤ 35.0
Ordinary MDF in middle humidity state ((20±2) °C, (65±5)%<relative humidity ≤(85±5)%)	≥ 26.0	≥ 2600	≥ 0.60	≤ 18.0
Ordinary MDF in high humidity state ((20±2) °C, relative humidity >(85±5)%)	≥ 26.0	≥ 2600	≥ 0.60	≤ 14.0
Furniture MDF in dry state ((20±2) °C, relative humidity ≤(65±5)%)	≥ 28.0	≥ 2600	≥ 0.60	≤ 35.0
Furniture MDF in middle humidity state ((20±2) °C, (65±5)%<relative humidity ≤(85±5)%)	≥ 28.0	≥ 2600	≥ 0.70	≤ 18.0
Furniture MDF in high humidity state ((20±2) °C, relative humidity >(85±5)%)	≥ 28.0	≥ 2600	≥ 0.70	≤ 14.0
Furniture MDF for outdoor exposure	≥ 30.0	≥ 2600	≥ 0.70	≤ 12.0
Building MDF in dry state ((20±2) °C, relative humidity ≤(65±5)%)	≥ 27.0	≥ 2300	≥ 0.50	≤ 25.0
Building MDF in middle humidity state ((20±2) °C, (65±5)%<relative humidity ≤(85±5)%)	≥ 28.0	≥ 2400	≥ 0.50	≤ 14.0

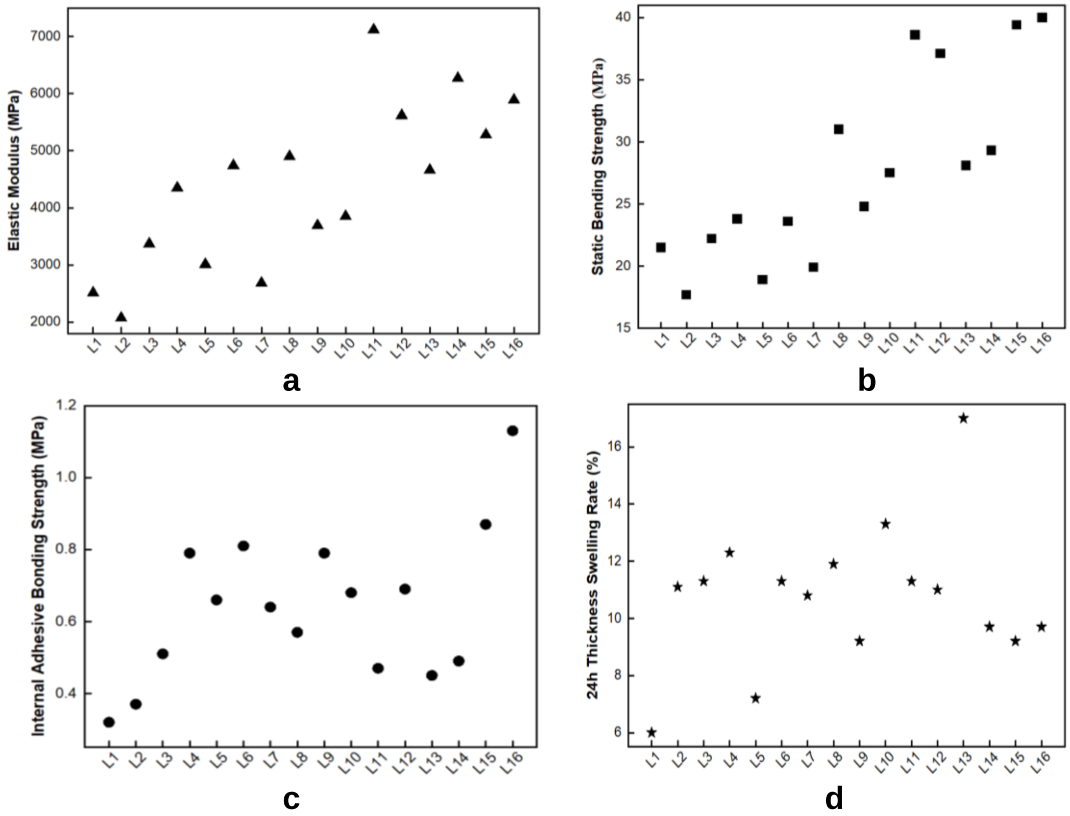

Fig. 1. Properties change in the orthogonal test: (a) elastic modulus; (b) static bending strength; (c) internal adhesive bonding strength; (d) 24 h thickness swelling

Range Analysis of the Orthogonal Test

Elastic modulus analysis

The range analysis of the elastic modulus is shown in Table 3. The most important factor for the elastic modulus of the composites was hot-pressing temperature, and the least important factor was phenolic resin amount.

Table 3. Range Analysis of Elastic Modulus

	A	B	C	D	E
K_1	12300	13870	20260	17080	16540
K_2	15330	16930	15980	18750	14330
K_3	20280	18450	18230	16120	18390
K_4	22100	20760	15540	18060	20750
k_1	3075	3467.5	5065	4270	4135
k_2	3832.5	4232.5	3995	4687.5	3582.5
k_3	5070	4612.5	4557.5	4030	4597.5
k_4	5525	5190	3885	4515	5187.5
R	2450	1722.5	1180	657.5	1605
Influence Order	A > B > E > C > D				
Optimal Level	A4	B4	C1	D2	E4

The significance sequence of each factor on the elastic modulus of the composites was A (hot- pressing temperature) > B (hot-pressing time) > E (TP/bamboo) > C (hot pressing pressure) > D (phenolic resin amount). The optimal hot-pressing conditions were hot-pressing temperature 180 ℃, hot-pressing time 16 min, hot-pressing pressure 1.0 MPa, the phenolic resin amount 12%, and the ratio of Tetra Pak/bamboo 6:4.

The effects of influencing factors on the elastic modulus of TP/bamboo composite are shown in Fig. 2. It seemed that the hot-pressing temperature played the most important role in the elastic modulus of TP/bamboo composite, which would increase as the hot-pressing temperature increased. The reason was attributed to the more heat energy produced at higher hot-pressing temperatures, which was essential for the curing polycondensation reaction of phenolic resin in the composites (Wu *et al.* 2016; Han *et al.* 2023). Moreover, bamboo plasticity could be enhanced at higher hot-pressing temperatures, and it was conductive to pressing the composites more tightly, which could bring positive impacts on the mechanical properties (Xu *et al.* 2016; Qiu *et al.* 2024). The elastic modulus of TP/bamboo composite could be also increased as the hot-pressing time increased in this study, because to ensure the sufficient reactions between phenolic resin and fibers, enough reaction time was necessary. The optimal hot-pressing pressure was observed at 1.0 MPa, and the higher hot-pressing pressures produced different negative effects on the static bending strength of TP/bamboo composite. It seemed that the elastic modulus of the composite initially increased, then decreased, and finally increased again as the hot-pressing pressure increased, which demonstrated that the complex reactions between phenolic resin and fibers had occurred. The elastic modulus would be reduced initially from the composites made by the ratio of TP/bamboo 9:1 to the composites made by the ratio of TP/bamboo 8:2, then increased to the maximum observed in the composites made by the ratio of TP/bamboo 6:4, because the elastic modulus of bamboo fibers was higher than the waste Tetra Pak fibers (Yao and Jiang 2011; Bekhta *et al.* 2016b).

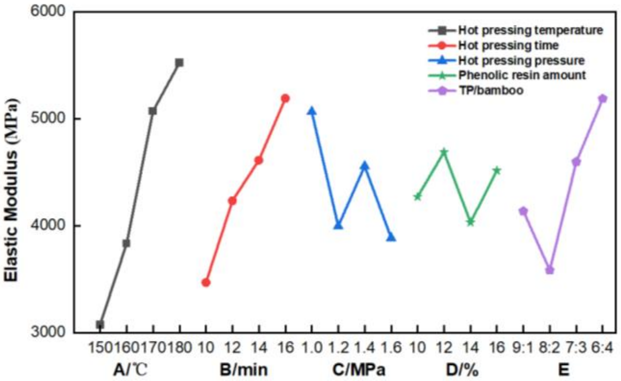

Fig. 2. Effects of influencing factors on the elastic modules of TP/bamboo composite

Static bending strength analysis

The range analysis of the static bending strength is shown in Table 4. The most important factor for the static bending strength of the composites was hot-pressing temperature, and the least important factor was phenolic resin amount. The significance sequence of each factor on the composite properties was A (hot-pressing temperature) > B (hot-pressing time) > C (hot pressing pressure) > E (TP/bamboo) > D (phenolic resin amount). The optimal hot-pressing parameters were hot-pressing temperature 180 ℃, hot pressing time 16 min, hot pressing pressure 1.0 MPa, the phenolic resin amount 12%, and the ratio of Tetra Pak/bamboo 9:1.

Table 4. Range Analysis of Static Bending Strength

	A	B	C	D	E
K_1	85.2	93.3	123.7	107.8	119.4
K_2	93.4	98.1	113.1	115.4	102.4
K_3	128	120.1	107.3	108.6	111
K_4	136.8	131.9	99.3	111.6	110.6
k_1	21.3	23.325	30.925	26.95	29.85
k_2	23.35	24.525	28.275	28.85	25.6
k_3	32	30.025	26.825	27.15	27.75
k_4	34.2	32.975	24.825	27.9	27.65
R	12.9	9.65	6.1	1.9	4.25
Influence Order	A > B > C > E > D				
Optimal Level	A4	B4	C1	D2	E1

The effects of influencing factors on the static bending strength of TP/bamboo composite are shown in Fig. 3. The effects of the hot-pressing temperature and hot-pressing time on the static bending strength of TP/bamboo composites were the same as those obtained from the results of the elastic modulus, which would increase as the hot-pressing temperature and hot-pressing time increased. However, as the hot-pressing pressure increased, the static bending strength of TP/bamboo composite would decrease significantly, which may be attributed to the fact that the higher hot-pressing pressures had shortened the press closing time (Zhou and Hua 2016), and the heat energy could not be distributed evenly in the thickness direction of the composites. The trends of the effect of phenolic resin amount and the ratio of TP/bamboo on the composites were similar with those obtained from the results of the elastic modulus, and these two factors seemed to have slight effects on the static bending strength of TP/bamboo composites.

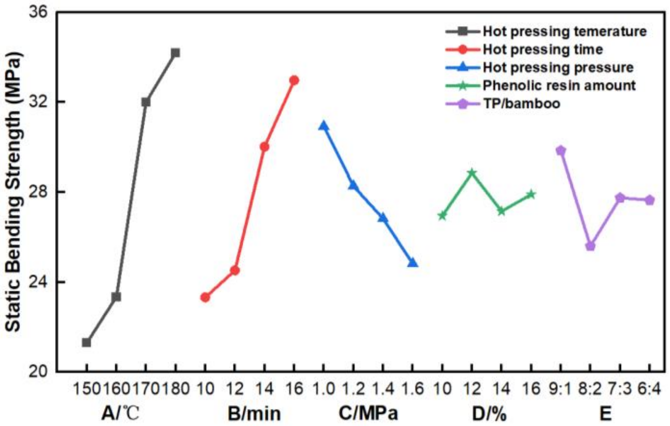

Fig. 3. Effects of influencing factors on the static bending strength of TP/bamboo composite

Internal adhesive bonding strength analysis

The range analysis of the internal adhesive bonding strength is shown in Table 5. The most important factor for the internal adhesive bonding strength of the composites was hot-pressing temperature, and the least important factor was phenolic resin amount. The important sequence of each factor on the composite properties according to range analysis was A (hot- pressing temperature) > B (hot-pressing time) > C (hot-pressing pressure) > E (TP/bamboo) > D (phenolic resin amount). The optimal hot-pressing parameters were hot-pressing temperature 180 °C, hot-pressing time 16 min, hot-pressing pressure 1.0 MPa, the phenolic resin amount 16%, and the ratio of Tetra Pak/bamboo 8:2.

Table 5. Range Analysis of Internal Adhesive Bonding Strength

	A	B	C	D	E
K_1	1.99	2.22	2.73	2.14	2.44
K_2	2.68	2.35	2.59	1.86	2.93
K_3	2.63	2.49	2.36	2.98	2.46
K_4	2.94	3.18	2.56	3.26	2.41
k_1	0.4975	0.555	0.6825	0.535	0.61
k_2	0.67	0.5875	0.6475	0.465	0.7325
k_3	0.6575	0.6225	0.59	0.745	0.615
k_4	0.735	0.795	0.64	0.815	0.6025
R	0.2375	0.24	0.0925	0.35	0.13
Influence Order	A > B > C > E > D				
Optimal Level	A4	B4	C1	D2	E1

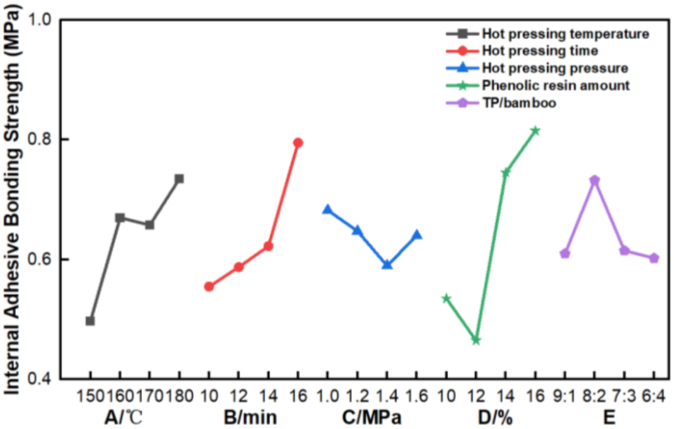

Fig. 4. Effects of influencing factors on the internal adhesive bonding strength of TP/bamboo composite

The effects of influencing factors on the internal adhesive bonding strength of TP/bamboo composite are shown in Fig. 4. The effects of the hot-pressing temperature and hot-pressing time on the internal adhesive bonding strength of TP/bamboo composites were similar with those observed in the elastic modulus and the static bending strength, although its linearity was not as obvious as those two indexes. The adhesive bonding strength of the composite initially decreased, and then it increased as the hot-pressing pressure increased, which also demonstrated that higher hot-pressing pressure could not ensure the heat energy evenly distributed in the composites, and maybe the composites were extremely compact at 1.6 MPa, as the result, the adhesive bonding strength of the composite could be improved. The effects of the phenolic resin amount on the adhesive bonding strength of the composite were much more obvious than those observed in the elastic modulus and the static bending strength, and the adhesive bonding strength would be initially decreased, then increased sharply as the phenolic resin increased. The results demonstrated that the amount of the phenolic resin was critical for the performance of the adhesive bonding strength of the composites, which was consistent with results observed in the glued hexagonal pre-shaped bamboo with the phenolic resin adhesive exhibited the best mechanical performance (Ji et al. 2023). The effects of the ratio of TP/bamboo on the adhesive bonding strength were also different from those obtained from the results of the elastic modules and the static bending strength, in which the adhesive bonding strength would be initially increased, and then decreased, while the change was not particularly obvious.

24 h thickness swelling rate analysis

The range analysis of the 24 h thickness swelling rate is shown in Table 5. The most important factor for the 24 h thickness swelling rate of the composites was hot-pressing pressure, and the least important factor was hot- pressing temperature. The significance sequence of each factor on the composite properties was C (hot-pressing pressure) > D (phenolic resin amount) > E (TP/bamboo) > B (hot-pressing time) > A (hot-pressing temperature). The optimal hot-pressing conditions were hot pressing temperature 150 °C, hot-pressing time 10 min, hot-pressing pressure 1.0 MPa, the phenolic resin amount 10%, and the ratio of Tetra Pak/bamboo 9:1.

Table 6. Range Analysis of 24 h Thickness Swelling Rate

	A	B	C	D	E
K1	40.7	39.4	38.3	37.5	40.4
K2	41.2	45.4	38.5	51.3	40.8
K3	44.8	42.6	42.1	41.5	50.6
K4	45.6	44.9	53.4	42	40.5
k1	10.175	9.85	9.575	9.375	10.1
k2	10.3	11.35	9.625	12.825	10.2
k3	11.2	10.65	10.525	10.375	12.65
k4	11.4	11.225	13.35	10.5	10.125
R	1.225	1.5	3.775	3.45	2.55
Influence Order	C > D > E > B > A				
Optimal Level	A1	B1	C1	D1	E1

The effects of influencing factors on the 24 h thickness swelling rate of TP/bamboo composites are shown in Fig. 5, and it seemed that the values varied less than 4% among different groups. The 24 h thickness swelling rate of TP/bamboo composites was also affected by hot-pressing temperature and hot-pressing time, which could obtain better results at higher temperatures and longer duration. The hot-pressing pressure was shown to be one of the critical factors for the dimensional stability for the composites, in which the 24 h thickness swelling rate would increase as the hot-pressing pressure increased, especially when the hot-pressing pressure was increased from 1.4 to 1.6 MPa. This was attributed to the hot-pressing pressures (1.4 to 1.6 MPa) being more prone to promote heat energy to distribute evenly in the composites and force the water and air in the composites to migrate outside in a shorter time (Zhou and Hua 2016). The trends of the effect of phenolic resin amount and the ratio of TP/bamboo on the composites were similar, and the values would initially increase, then decrease sharply, which may be caused by the complicated reactions among different constituents in the composites.

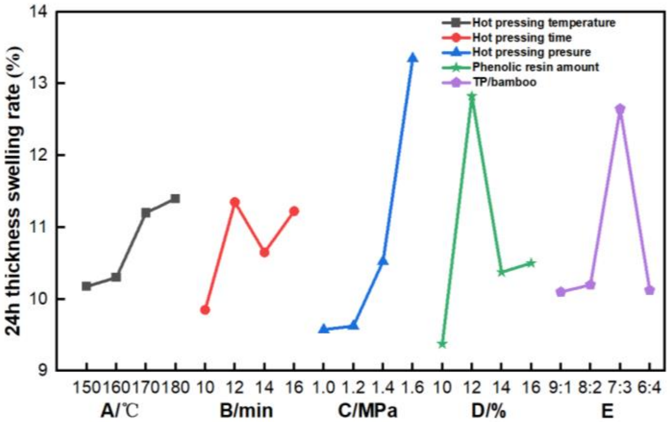

Fig. 5. Effects of influencing factors on the 24 h thickness swelling rate of TP/bamboo composite

Verification of the Optimal Process Conditions

Based on the range analysis of the orthogonal test, the optimal hot-pressing parameter combinations obtained from the evaluation indexes of the elastic modulus, static bending strength, internal adhesive bonding strength, and 24 h thickness swelling rate, as well as L15 and L16 were selected and compared, as shown in Table 7. The results showed that according to GB/T 11718 (2021), the main dimensional and mechanical properties of TP/bamboo composite prepared with the hot-pressing parameters of $A_4B_4C_1D_2E_4$ could meet the requirements for the ordinary and building MDF, but its internal adhesive bonding strength could not meet the requirements for furniture MDF. The bending strength and the internal adhesive bonding strength of TP/bamboo composite prepared with the hot-pressing parameters of$A_1B_1C_1D_1E_1$ could not meet the requirements for any MDF application. The main dimensional and mechanical properties of TP/bamboo composites prepared with the hot-pressing parameters of $A_4B_4C_1D_2E_1$ and $A_4B_4C_1D_4E_2$ could meet the requirements for MDF in different states, as shown in Table 2. Compared with the hot-pressing parameter combinations of $A_4B_4C_1D_2E_1$, $A_4B_4C_1D_4E_2$, L15, and L16, the differences in the hot-pressing pressure and hot-pressing time were not obvious. Reductions in phenolic resin amount resulted in a more environmentally friendly and economical MDF (Zhou and Hua 2016). The more the Tetra Pak materials were added, the higher the waste utilization rate. Evidently, the optimal hot-pressing parameters for TP/bamboo composite were hot-pressing temperature 180 ℃ (A_4), hot-pressing time 16 min (B_4), hot-pressing pressure 1.0 MPa (C_1), the phenolic resin amount 12% (D_2), and the ratio of Tetra Pak/bamboo 9:1 (E_1).

Table 7. Verification Experimental Results of the Optimal Process Conditions

Optimal Combinations	Elastic Modulus (MPa)	Bending Strength (MPa)	Internal Adhesive Bonding Strength	24 h Thickness Swelling Rate (%)
$A_4B_4C_1D_2E_4$	7290	39.3	0.67	13
$A_4B_4C_1D_2E_1$	7670	40.0	0.86	10.6
$A_4B_4C_1D_4E_2$	7310	37.6	1.33	9.9
$A_1B_1C_1D_1E_1$	2510	21.5	0.32	6.0
$A_4B_3C_2D_4E_1$ (L15)	5280	39.4	0.87	9.2
$A_4B_4C_1D_3E_2$ (L16)	5890	40.0	1.13	9.7

CONCLUSIONS

In this study, the orthogonal test method was used to explore the influence of different hot-pressing parameters on the main mechanical properties and dimensional stability of TP/bamboo composites, and based on the results, the most optimal combination of hot-pressing parameters for the composites was obtained.

1. The elastic modulus, static bending strength, internal adhesive bonding strength, and 24 h thickness swelling rate of TP/bamboo composites would be affected by different factors during the hot-pressing process. The hot-pressing temperature was the most important factor for the elastic modulus, static bending strength and internal adhesive bonding strength of the composites, and the hot-pressing pressure was the most important factor for the 24 h thickness swelling of the composites. While for the regular property of the composites, different influencing factors had different change trends during the hot-pressing process.
2. Based on the optimal process conditions obtained in the orthogonal test and range analysis, the most optimal hot-pressing parameters of TP/bamboo composites were hot-pressing temperature 180 ℃, hot-pressing time 16 min, hot-pressing pressure 1.0 MPa, the phenolic resin amount 12%, and the ratio of Tetra Pak/bamboo 9:1, in which the main mechanical properties and dimensional stability of the composite could satisfy the requirements for different applications according to GB/T 11718 (2021). Therefore, it can be used for various industrial applications in future, especially for decorative and furniture materials. In such structures, the incorporation of bamboo and waste Tetra Pak fibres can significantly enhance the mechanical performance of biocomposites, making them more suitable for these applications where better strength and machinability are required. Especially, they could be suitable for the packaging industry as biodegradability and the lowest cost are the critical criteria for such applications.

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