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Optimizing the Preparation Process of Bamboo Scrimber with Bamboo Waste Bio-Oil Phenolic Resin Using Response Surface Methodology

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Abstract: Bamboo scrimber is a new type of biomass fiber-based composite material with broad application. In this study, self-developed bio-oil phenolic resin (BPF) was used to prepare bamboo scrimber. The effects of hot-pressing temperature, hot-pressing time, and BPF resin solid content on the modulus of rupture (MOR) and modulus of elasticity (MOE) were systematically investigated through single-factor experiments and response surface methodology (RSM). According to the Box-Behnken design (BBD) experiment of the RSM, the effects of all three factors on MOR and MOE are significant. The effects of the main factors affecting the MOR and MOE decreased in the order of resin solid content, hot-pressing temperature, and hot-pressing time. Based on BBD, the optimal conditions for the preparation of bamboo scrimber were determined as follows: a hot-pressing temperature of 150 °C, a hot-pressing time of 27.5 min, and a resin solid content of 29%. Under these conditions, the MOR is 150.05 MPa and the MOE is 12,802 MPa, which are close to the theoretical values, indicating that the optimization results are credible. This study helps to promote the full utilization of bamboo components and provides a reference for the development of high-quality bamboo scrimber.

Keywords: bamboo scrimber; bio-oil phenolic resin; response surface methodology; regression model; MOR; MOE



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1. Introduction

As a green and biodegradable biomass material, bamboo is characterized by abundant resources, a short growth cycle (3–5 years to maturity), excellent performance, and having a wide range of applications in the fields of construction, home furnishing, papermaking, and textile [1–3]. Moreover, it can absorb a large number of carbon dioxide during the growth process and has a carbon sequestration capacity in the ecosystem, which gives it great potential to address climate change, energy conservation, and emission reduction [4–6]. In the context of low-carbon development and the “Bamboo as a Substitute for Plastic” initiative, the demand for bamboo products is gradually increasing, and the research on the high-value utilization of bamboo has also received widespread attention. At present, a large number of bamboo-based materials have been developed, including bamboo scrimber, plybamboo, and laminated bamboo [7–9].

Among them, bamboo scrimber is a bamboo-based composite material obtained from bundles by defiberizing, impregnating adhesive, oriented assembling, drying, and hot-pressing. In contrast to other composites, bamboo scrimber has a greater usage rate because it can be made from raw materials such as small-sized bamboo and waste [10]. Because it maintains the bamboo fibers’ inherent orientation and traits, they have notable mechanical properties [11]. It also has a beautiful texture and is commonly applied in decorative materials, indoor and outdoor flooring, and engineering structural materials [12].

Phenolic (PF) resin is the most common adhesive for the production of bamboo scrimber, which can bring good mechanical properties and dimensional stability to bamboo boards. For example, with a resin content of 25 wt%, the water-absorbing width and thickness expansion of bamboo scrimber were 3.74% and 3.72%, respectively [13]. With a density of 1.0 g/cm³ and a PF content of 16%, the moso bamboo (*Phyllostachys heterocycla*) scrimber had a modulus of rupture (MOR) of 271.05 MPa and a modulus of elasticity (MOE) of 23.7 GPa [14]. However, PFM resin also has drawbacks such as high brittleness and a long curing time [15]. At the same time, with the increasing global attention to sustainable development, people are committed to using green materials to replace phenol to synthesize PF resin. There are many natural polymers in nature that contain phenolic substances including tannin [16], lignin [17], and biomass-derived products such as cardanol [18] and bio-oil [19].

Bio-oil can be obtained by pyrolysis of wood or bamboo processing wastes such as sawdust and small chips [20,21]. Bio-oil contains a high content of phenolic substances and exhibits good reactivity. It can be added to phenolic resin to increase the mechanical strength, toughness, and aging resistance of the resin [22]. Additionally, it can reduce the consumption of petrochemical resources and lower production costs [23]. A relevant study demonstrated that bamboo scrimber prepared using bio-oil phenolic resin (BPF) had good mechanical and anti-mildew properties. Among them, the MOR was 143 MPa and the MOE was 9269 MPa. According to tests on mildew resistance, the anti-mildew level increased from slight to high due to BPF resin [24].

During the preparation of bamboo scrimber, many factors have a strong influence on the quality and performance of products. For example, Lu et al. studied the effects of various hot-pressing temperatures on bamboo scrimber [25]. Ji et al. investigated the effects of density and PF resin adhesive solid content on the water resistance of bamboo scrimber [26]. However, few previous studies have systematically investigated the impact of multiple factors on bamboo scrimber. Finding the optimal process parameters based on the interactions of the factors can provide important guidance for the high-quality production of bamboo scrimber. The response surface methodology (RSM) is an accurate and effective statistical and mathematical tool for optimizing experimental processes [27]. The theoretical optimal process parameters also can be corrected and reconfirmed according to the experimental data, which can greatly improve work efficiency and save resources [28].

In this study, BPF resin was synthesized from bamboo waste bio-oil and was used to prepare bamboo scrimber. The effects of hot-pressing temperature, hot-pressing time, and the adhesive solid content of BPF resin on the properties of bamboo scrimber were evaluated by statistical modeling using RSM. According to the actual application scenario of bamboo scrimber, MOR and MOE were selected as the response values to evaluate the quality of the boards. High-performance bamboo scrimber was obtained through the optimization of process parameters. Based on this method, bamboo scrimber can achieve the full utilization of bamboo components. These results can offer a technical and theoretical foundation for the bamboo scrimber's quality control and preparation process.

2. Materials and Methods

2.1. Materials

Thirty-five-centimeter moso bamboo (*Phyllostachys heterocycla*) bundles were supplied by Fujian Youzhu Technology Co., Ltd., Yongan, China. A bio-oil phenolic resin with a solid content of 40% and a viscosity of 68 mPa·s was self-developed. Bamboo waste bio-oil, an acid liquid (pH 3.5), was obtained by quickly pyrolyzing moso bamboo waste in a fluidized bed at 550 °C in the Laboratory of Beijing Forestry University [24]. Phenol was produced by Shanghai McLean Biochemical Technology Co., Ltd., Shanghai, China. Sodium hydroxide was produced by Beijing Chemical Factory, Beijing, China. 37% formaldehyde was obtained by Shanghai Aladdin Biochemical Technology Co., Ltd., Shanghai, China. All reagents used were analytically pure.

2.2. Preparation of Bamboo Scrimber

Firstly, according to Table 1, the BPF resin was diluted into different solid contents, and the bamboo bundles were soaked in the adhesive at atmospheric pressure for 8 min, aged for 2 days, and dried naturally to a moisture content of 8%. Then, according to the set board density (1.05 g/cm^3), the board was assembled with a length $\times$ width $\times$ thickness of $35 \text{ cm} \times 35 \text{ cm} \times 5 \text{ mm}$, and the board was put into the hot press (QD, SWPM, Shanghai, China) for hot-pressing according to Table 1, and the hot-pressing pressure was set to 5.0 MPa. Finally, the pressed bamboo scrimber boards were kept at constant room conditions (20°C and 65% RH) for 2 days and then trimmed, sanded, and sawn for samples (Figure 1).



Figure 1. Detailed preparation process of bamboo scrimber.

2.3. Experimental Design

2.3.1. Single-Factor Experiment Design

The effects of hot-pressing temperature, hot-pressing time, and resin solid content on the MOR and MOE of bamboo scrimber were studied by single-factor experiments to clarify the optimization level range of influencing factors. The number of MOR and MOE test samples was six, and the test results were averaged. The error bars were represented as a standard deviation to reflect the fluctuations in the data for each sample. According to the relevant studies [24,25], the levels of each factor are shown in Table 1.

Table 1. Factors and levels of single-factor experiment design.

Factors	Level
Hot-pressing temperature ($^\circ\text{C}$)	120, 130, 140, 150, 160, 170
Hot-pressing time (min)	15, 20, 25, 30, 35, 40
Solid content (%)	15, 20, 25, 30, 35, 40

2.3.2. Multi-Factor Experiment Design

Based on a single-factor experiment, the Box-Behnken design (BBD) scheme in RSM was used to design the central composite experiment. Three variables and their actual experimental scope and coding level are shown in Table 2. A total of 17 runs were made in random order. In the optimization level interval, the optimal process for the preparation of bamboo scrimber was found and three confirmatory tests were conducted. The test results

were averaged, and there were six specimens for each performance test. The experimental results of the optimized samples were compared to match the predictions.

Table 2. Actual and coded experimental factors and corresponding levels in BBD.

Factors	Code	Level		
		Low (−1)	Middle (0)	High (1)
Hot-pressing temperature (°C)	A	120	145	170
Hot-pressing time (min)	B	20	27.5	35
Solid content (%)	C	15	25	35

The independent variables (x_1 : hot-pressing temperature (°C), x_2 : hot-pressing time (min), x_3 : resin solid content (%)) were at three levels, exploring the impact of each factor on the response values in terms of MOE and MOR. The specific model of the quadratic multinomial regression equation was as follows: y represents the model prediction response value. The coefficient for constant regression was denoted as β_0 , while the coefficients for linear regression were β_1 , β_2 , and β_3 . The quadratic coefficients were β_{11} , β_{22} , and β_{33} , while the interaction coefficients were β_{12} , β_{13} , and β_{23} . These coefficients were determined in the second-order model using Design-Expert software V.8.0.6 (Stat-Ease, Inc., Minneapolis, MN, USA). An analysis of variance (ANOVA) was used to assess the model's statistical significance based on p values less than 0.05. The quality of the created model was assessed using the model regression R^2 and the lack of fit from the ANOVA [29].

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \quad (1)$$

2.4. Performance Testing

Before testing, all specimens were kept in a climate chamber (20 °C and 65% RH) until the mass was constant. Each group of experiments was replicated three times. The number of each performance test specimen was six, and the test results were averaged. There were 18 groups in the single-factor experiment, and a total of 324 samples were prepared. There were also 17 groups in the multi-factor experiment, and a total of 306 samples were prepared. There were 3 groups in the optimal process validation experiment, and a total of 108 samples were prepared. The standard deviation was used to describe the level of errors in samples. The tests of MOR, MOE, and water-absorbing expansion were carried out in accordance with the Chinese national standard GB/T 17657-2022 [30]. The water-absorbing expansion tests were conducted in a water bath at (20 ± 1 °C) and pH (7 ± 1) using the indoor test method. Among them, a universal testing machine (MMW-50, NAIER, Jinan, China) was used to measure the MOE and MOR at a constant speed of 10 mm/min. The cross-sectional microstructure of bamboo scrimber was observed using scanning electron microscopy (Regulus8100, HITACHI, Tokyo, Japan), and samples were gold-plated in a vacuum for 5 min before observation using ion sputter (MC1000, HITACHI, Tokyo, Japan). The experimental conditions for electron microscopy were a vacuum environment and an excitation voltage of 3.0 kV. The sample size was 10 mm × 10 mm × 5 mm. The size of the samples for measuring MOR and MOE was 15 cm × 5 cm × 5 mm. The size of the samples for measuring thickness swelling rate (TSR) and width swelling rate (WSR) was 5 cm × 5 cm × 5 mm. The equations are shown in (2) and (3), respectively:

$$TSR = \frac{t_2 - t_1}{t_1} 100\% \quad (2)$$

$$WSR = \frac{d_2 - d_1}{d_1} 100\% \quad (3)$$

In the formula, t_1 is the initial thickness of the bamboo scrimber specimen in mm; t_2 is the final thickness of the bamboo scrimber specimen in mm. d_1 is the initial width of the

bamboo scrimber specimen in mm; d_2 is the final width of the bamboo scrimber specimen in mm (Figure 2).



Figure 2. (a) MOR and MOE testing, (b) scanning electron microscope and (c) dimensional stability test.

3. Results and Discussion

3.1. Single-Factor Experiment

3.1.1. Effect of Hot-Pressing Temperature

The effect of hot-pressing temperature on MOR and MOE is shown in Figure 3. From Figure 3a,b, it can be observed that as the hot-pressing temperature increased from 120 °C to 140 °C, the increase in MOR of the bamboo scrimber was relatively small, with a maximum increase of 35.1%; while the increase in MOE was more significant, with a maximum increase of 84.8%. This indicates that within the temperature range of 120 °C to 170 °C, there is difference in the curing degree of the adhesive. The MOR and MOE of the bamboo scrimber gradually improved as the temperature increased from 120 °C to 140 °C. However, after reaching 140 °C, the mechanical properties gradually decreased. This may be due to the high temperature causing thermal degradation of the bamboo surface or curing of the adhesive [31].

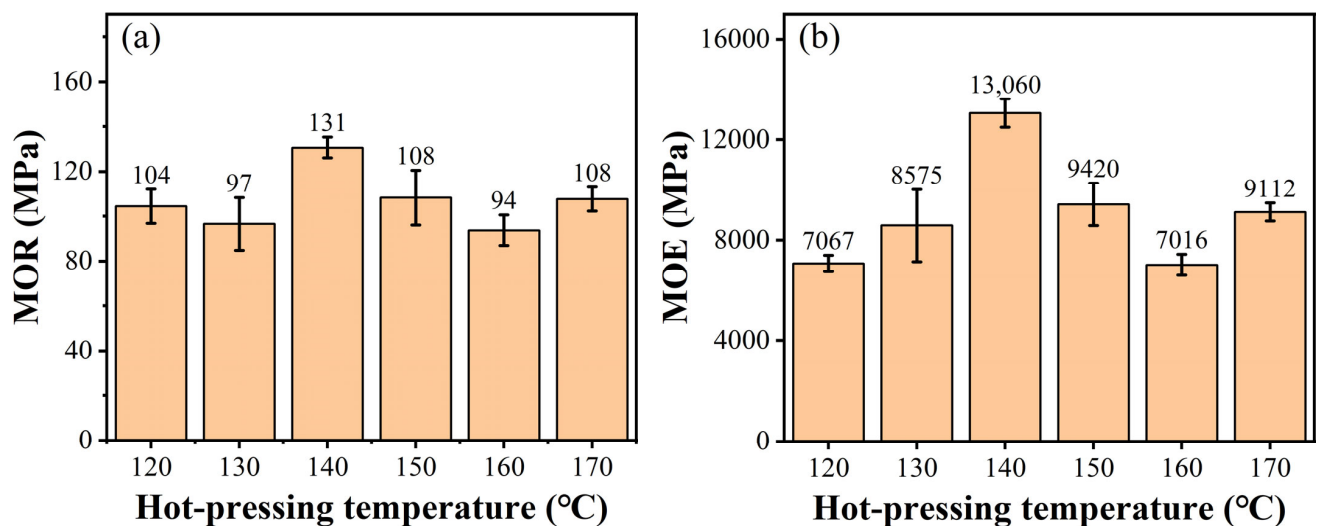


Figure 3. Effect of hot-pressing temperature on the (a) MOR and (b) MOE of bamboo scrimber.

3.1.2. Effect of Hot-Pressing Time

The effect of hot-pressing time on MOR and MOE is shown in Figure 4. From Figure 4a,b, it can be seen that the influence of hot-pressing time on the MOR and MOE of bamboo scrimber was greater compared to the hot-pressing temperature. Within the certain experimental range, both performance indicators increased with the extension of hot-pressing time. When the hot-pressing time was 15 min, the MOR was 84 MPa

and the MOE was 7247 MPa, both of which did not meet the minimum requirements of GB/T 40247-2021 (The MOE is 9000 MPa and the MOR is 80 MPa) [32], indicating that the hot-pressing time was too short and the resin had not fully cured. However, as the hot-pressing time increased, the curing of the PF resin in the bamboo scrimber surface formed a hard shell easily, which was not conducive to the conduction of pressure [33]. When the hot-pressing time was 40 min, although both performance indicators would meet the national standards, excessive curing could make the board brittle, leading to a decrease in MOR and MOE. From an economic perspective, this would reduce production efficiency and increase production costs. Therefore, while ensuring performance requirements, a shorter hot-pressing time should be chosen.

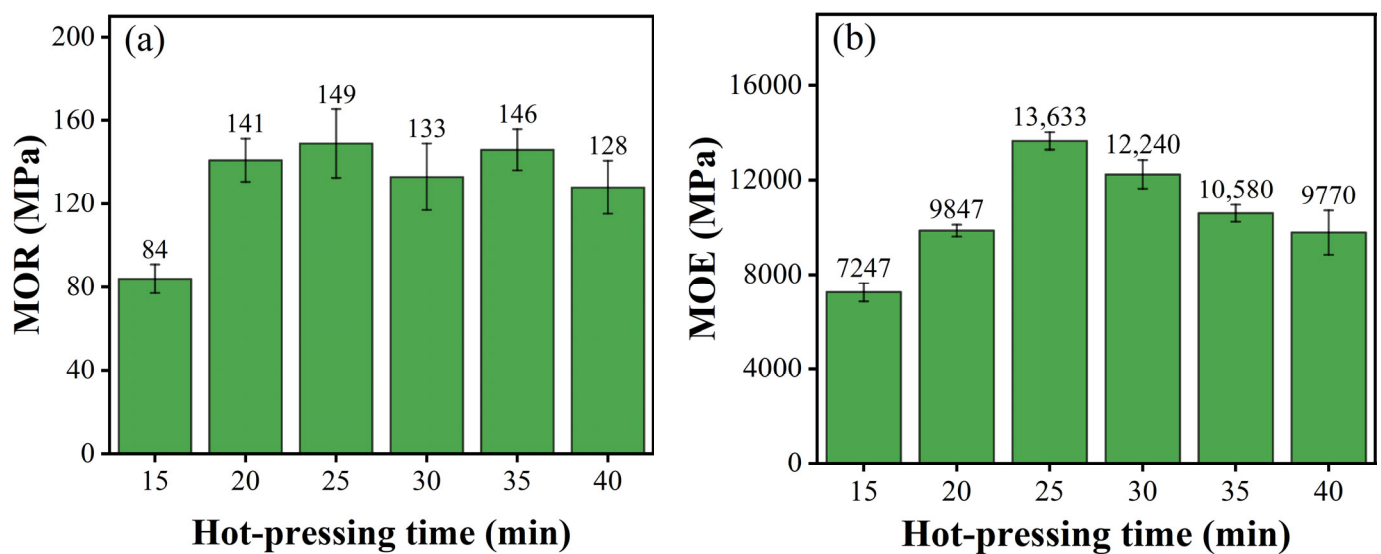


Figure 4. Effect of hot-pressing time on the (a) MOR and (b) MOE of bamboo scrimber.

3.1.3. Effect of Adhesive Solid Content

Figure 5 shows the influence of adhesive solid content on MOR and MOE, carried out under similar conditions with a hot-pressing temperature of 145 °C and a time of 20 min. From Figure 5a,b, it can be observed that the MOR and MOE of bamboo scrimber were relatively less affected by the solid content of the diluted phenolic resin. When the solid content increased from 15% to 40% (undiluted resin solid content), there was an overall trend of first increasing and then decreasing. When the solid content increased from 15% to 25%, the MOR increased by 19.1% and the MOE increased by 26.6%. This indicates that as the solid content increases, more resin macromolecules enter the bamboo scrimber. However, when the solid content increased from 25% to 40%, both indicators showed an overall decreasing trend, indicating that excessive solid content hindered the entry of resin molecules into the bamboo and affected the cross-linking of bamboo and resin [11]. Moreover, when the solid content reached 40%, the resin adhering to the bamboo surface would experience “resin exudation” during hot-pressing, significantly impacting product quality and production efficiency.

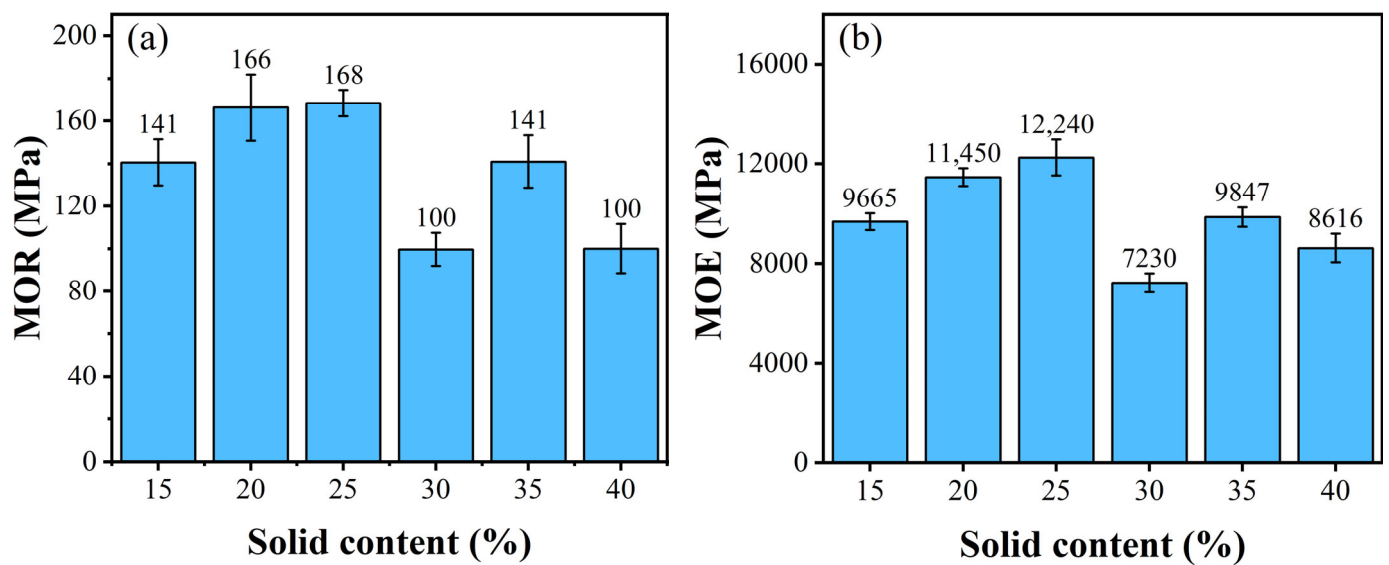


Figure 5. Effect of adhesive solid content on the (a) MOR and (b) MOE of bamboo scrimber.

3.2. Multi-Factor Experiment

3.2.1. Variance Analysis

The test protocol and results of the BBD are shown in Table 3. The larger the multi-variate correlation coefficient R^2 , the better the correlation [34]. The coefficient of variation (CV) < 10%, indicates high confidence and precision of the experiment [35]. As can be seen in Table 4, the fitted regression equation conformed to the above test principles and had good adaptability.

Table 3. Experiment scheme and results of Box-Behnken design.

Run	A	B	C	MOR (MPa)	MOE (MPa)
1	0	1	−1	117.35	7300
2	0	0	0	151.56	12,733
3	1	0	1	131.76	12,155
4	1	1	0	133.73	8960
5	1	0	−1	107.57	9112
6	−1	0	−1	104.40	7067
7	−1	−1	0	113.69	7613
8	−1	0	1	115.74	10,488
9	0	0	0	156.60	13,030
10	0	1	1	145.45	10,580
11	0	0	0	145.32	11,327
12	0	0	0	158.52	12,828
13	0	0	0	142.04	13,260
14	1	−1	0	129.69	11,380
15	0	−1	−1	140.52	9665
16	−1	1	0	137.13	8296
17	0	−1	1	140.92	9847

Table 4. Model Adequacy Indicators for Each Modeled Response of bamboo scrimber.

Response Variables	R^2 -Value	CV (%)
MOR	0.9136	6.18
MOE	0.9492	6.84

Variance Analysis of MOR

The results of the ANOVA of MOR are shown in Table 5. The effects of hot-pressing temperature (A), hot-pressing time (B), and resin solid content (C) on MOR were significant ($p < 0.05$) and lack of fit was not significant ($p > 0.05$). A^2 and C^2 had an extremely significant effect ($p < 0.01$), while B^2 had no significant effect ($p > 0.05$). The results show that the hot-pressing temperature, hot-pressing time, and solid content had significant effects on MOR, and their influences decreased in the order of resin solid content, hot-pressing temperature, and hot-pressing time. The regression equation for MOR is as follows:

$$\text{MOR} = -716.02489 + 10.62728 \times A + 2.10551 \times B + 3.50796 \times C - 0.025864 \times AB + 0.012850 \times AC + 0.092333 \times BC - 0.034753 \times A^2 - 0.009387 \times B^2 - 0.142200 \times C^2 \quad (4)$$

Table 5. Analysis of Variance for MOR Regression Equation.

Source	Sum of Square	DF	Mean Square	F-Value	Prob > F	Significance
Model	3985.76	9	442.86	6.48	0.0111	significant
A	126.34	1	126.34	1.85	0.2160	
B	9.76	1	9.76	0.14	0.7166	
C	512.48	1	512.48	7.50	0.0289	
AB	94.07	1	94.07	1.38	0.2789	
AC	41.28	1	41.28	0.60	0.4623	
BC	191.82	1	191.82	2.81	0.1377	
A^2	1986.44	1	1986.44	29.09	0.0010	
B^2	1.17	1	1.17	0.017	0.8994	
C^2	851.40	1	851.40	12.47	0.0096	
Residual	478.05	7	68.29			not significant
Lack of Fit	277.46	3	92.49	1.84	0.2795	
Pure Error	200.58	4	50.15			
Cor Total	4463.80	16				

Variance Analysis of MOE

The results of the ANOVA of MOE are shown in Table 6. The effects of three factors on MOR were significant ($p < 0.05$), and lack of fit was not significant ($p > 0.05$). F_C , F_A , and F_B indicated that the effects decreased in the order of C, A, B, A^2 , B^2 , and C^2 and had an extremely significant effect on MOE ($p < 0.01$). The regression equation for MOE is as follows:

$$\text{MOE} = -94372.34631 + 910.01887 \times A + 2207.34556 \times B + 555.98917 \times C - 4.13733 \times AB - 0.37800 \times AC + 10.32667 \times BC - 2.57268 \times A^2 - 34.94089 \times B^2 - 13.22175 \times C^2 \quad (5)$$

Table 6. Analysis of Variance for MOE Regression Equation.

Source	Sum of Square	DF	Mean Square	F-Value	Prob > F	Significance
Model	6.529×10^7	9	7.254×10^6	14.52	0.0010	significant
A	8.289×10^6	1	8.289×10^6	16.59	0.0047	
B	1.419×10^6	1	1.419×10^6	2.84	0.1358	
C	1.232×10^7	1	1.232×10^7	24.65	0.0016	
AB	2.407×10^6	1	2.407×10^6	4.82	0.0642	
AC	3.572×10^4	1	3.572×10^4	0.072	0.7969	
BC	2.399×10^6	1	2.399×10^6	4.80	0.0645	
A^2	1.089×10^7	1	1.089×10^7	21.79	0.0023	
B^2	1.626×10^7	1	1.626×10^7	32.56	0.0007	
C^2	7.361×10^6	1	7.361×10^6	14.73	0.0064	
Residual	3.497×10^6	7	4.996×10^5			not significant
Lack of Fit	1.192×10^6	3	3.975×10^5	0.69	0.6040	
Pure Error	2.304×10^6	4	5.761×10^5			
Cor Total	6.879×10^7	16				

3.2.2. Effects of Interactions between Factors

In order to predict and optimize the response values and to analyze the interaction of two factors, the regression equations for the response values were used to obtain the corresponding response surfaces and contour plots. A contour consists of multiple response value lines that are connected by closed curves of points with the same response value. Response surface plots are three-dimensional forms of contour lines [36]. Response surfaces and contour plots provide a visual response to the extent to which the interaction affects the response values. The steeper the surface and the denser the contours, the more significant the effect, and the closer the contours are to an oval, the stronger the interaction between the two factors [37].

Effect of the Interactions on MOR

The three-dimensional response surfaces and two-dimensional contour plots of MOR by the interaction of different factors from the regression equation are shown in Figure 6. The contour lines in Figure 6d were close to the ellipse, indicating that the interaction between the hot-pressing temperature and the solid content is the most significant of the three factors; Figure 6b had a smaller number of contour lines and slower change compared with Figure 6f, indicating that the interaction between the hot-pressing temperature and the solid content was weaker, which was consistent with $F_{BC} > F_{AB}$ in Table 4.

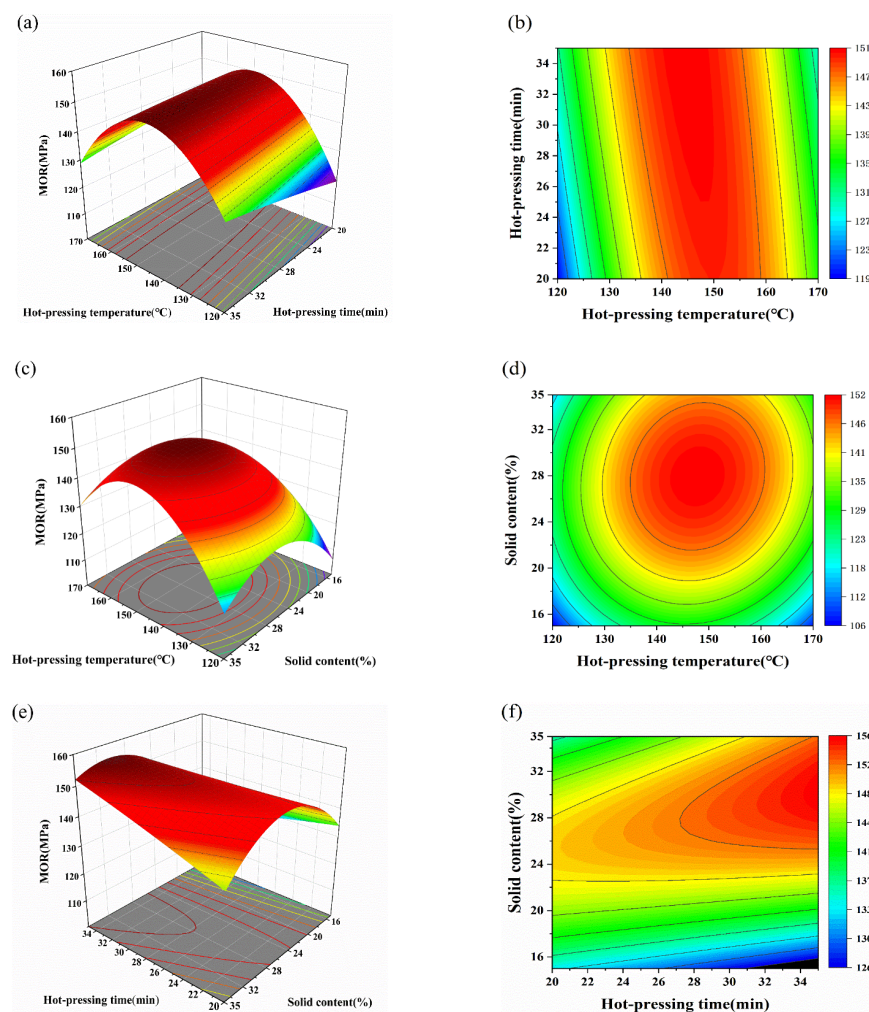


Figure 6. Contour plots and 3D surface for MOR of bamboo scrimber: (a,b) hot-pressing temperature and hot-pressing time; (c,d) hot-pressing temperature and solid content; (e,f) hot-pressing time and solid content.

In Figure 6a, there was a prominent “arch” surface where the hot-pressing time was mostly a gentle straight line. The hot-pressing temperature was an “arch” line with a larger surface inclination and curvature. This suggests that the effect of hot-pressing temperature on MOR was more significant, which was consistent with the result that the F-value for hot-pressing temperature was more significant than that for hot-pressing time (Table 4). As shown in Figure 6b, when both the hot-pressing temperature and the hot-pressing time were increased simultaneously, the MOR first increased and then decreased. The optimum range of hot-pressing temperatures was about 140 °C to 160 °C. With the increase of hot-pressing temperature, the MOR first increased and then slowly decreased, and the curve reached the highest response value at roughly 150 °C. When the hot-pressing temperature was lower, the flowability and bonding of the adhesive were weak and a strong bonding interface could not be formed [33]. When the temperature increased, the cementing performance was improved and the adhesive could penetrate into the bamboo bundle cells to form a good bonding interface. At this time, the macroscopic manifestation was the increase of MOR [11]. At the same time, the high temperature accelerated the evaporation of water in the adhesive, which reduced the fluidity of the adhesive and prevented the adhesive from entering the interface cells to form the interface. As the hot-pressing time continued to increase, the MOR gradually decreased because the longer the time, the longer the adhesive would be aging, which would also lead to a decline in adhesive performance. In the actual production process, the longer the hot-pressing time, the greater the increase in energy consumption and decrease in productivity. As shown in Figure 6c, the change rule for the hot-pressing temperature was consistent with Figure 6a, which still rose first and then decreased. As the solid content of the BPF resin adhesive increased, the MOR first rose and then slowly decreased, and the curve reached the maximum response value at around 29%. When the solid content was low, the flowability of the adhesive was strong, and it could easily enter the interstices of the bamboo bundle cells and the gaps between the bundles, and the gluing effect is manifested in the increase of MOR [26]. However, too high a solid content will reduce the flowability of the adhesive and prevent the resin from entering the bamboo material. As shown in Figure 6e, the slope of the hot-pressing time-MOR curve was smaller than that of the solid content-MOR curve. Within the set parameter range, the hot-pressing time was less than the effect of solid content on the MOR. The top and bottom contour lines of the contour plot shown in Figure 6f were asymmetric, with a slightly larger color change in the lower part; the contour line at about 150 MPa was an elliptical shape. There was a tendency for the red area on the right side to expand, indicating that there was a significant interaction between hot pressing time and the solid content on the MOR of the bamboo scrimber. The optimum range of solid content was 26%-35%, and the MOR gradually increased whenever the hot-pressing time was prolonged and the BPF was fully cured in the bamboo bundle. For the MOR of bamboo scrimber, the adhesive solid content had the greatest influence, followed by the hot-pressing temperature, and the hot-pressing time had the least influence.

Effect of the Interaction on MOE

The three-dimensional response surfaces and two-dimensional contour plots of MOE by the interaction of different factors from the regression equation are shown in Figure 7. The contours of Figure 7b,f were both close to an elliptical shape, and the contour of Figure 7d was close to a circular shape, indicating that the interaction between the hot-pressing temperature and the solid content was weak, which was consistent with $F_{AB} > F_{BC} > F_{AC}$ in Table 4. As can be seen from Figure 7, the effects of adhesive solid content, hot-pressing temperature, and hot-pressing time on the MOE of bamboo scrimber were basically the same as those on the MOR. In Figure 7a,b, when the hot-pressing temperature and hot-pressing time were increased simultaneously, the MOE of the bamboo scrimber showed an obvious pattern of increasing first and then decreasing. The curve of hot-pressing time with MOE showed a tendency to first increase and then decrease, and the maximum appeared at about 26 min. As the hot-pressing temperature increased, the MOE first increased and

then slowly decreased, and the curve reached its maximum at about 155 °C. Figure 7c,d showed that the hot-pressing temperature and MOE change rule were still the first rise and then decline, with the curve reaching the maximum response value at about 155 °C. With the increase in the solid content of BPF resin adhesive, MOE first rose and then slowly decreased; the curve reached the maximum response value at about 29%. As shown in Figure 7e,f, the change rule curve of hot-pressing time and MOE reached the maximum response value at about 27 min. As the solid content of BPF resin adhesive increased, the MOE first increased and then slowly decreased, and the curve reached the maximum response value at about 29%. For the MOE of bamboo scrimber, the adhesive solid content had the greatest influence, followed by the hot-pressing temperature, and the hot-pressing time had the least influence, and its law was consistent with the MOE.

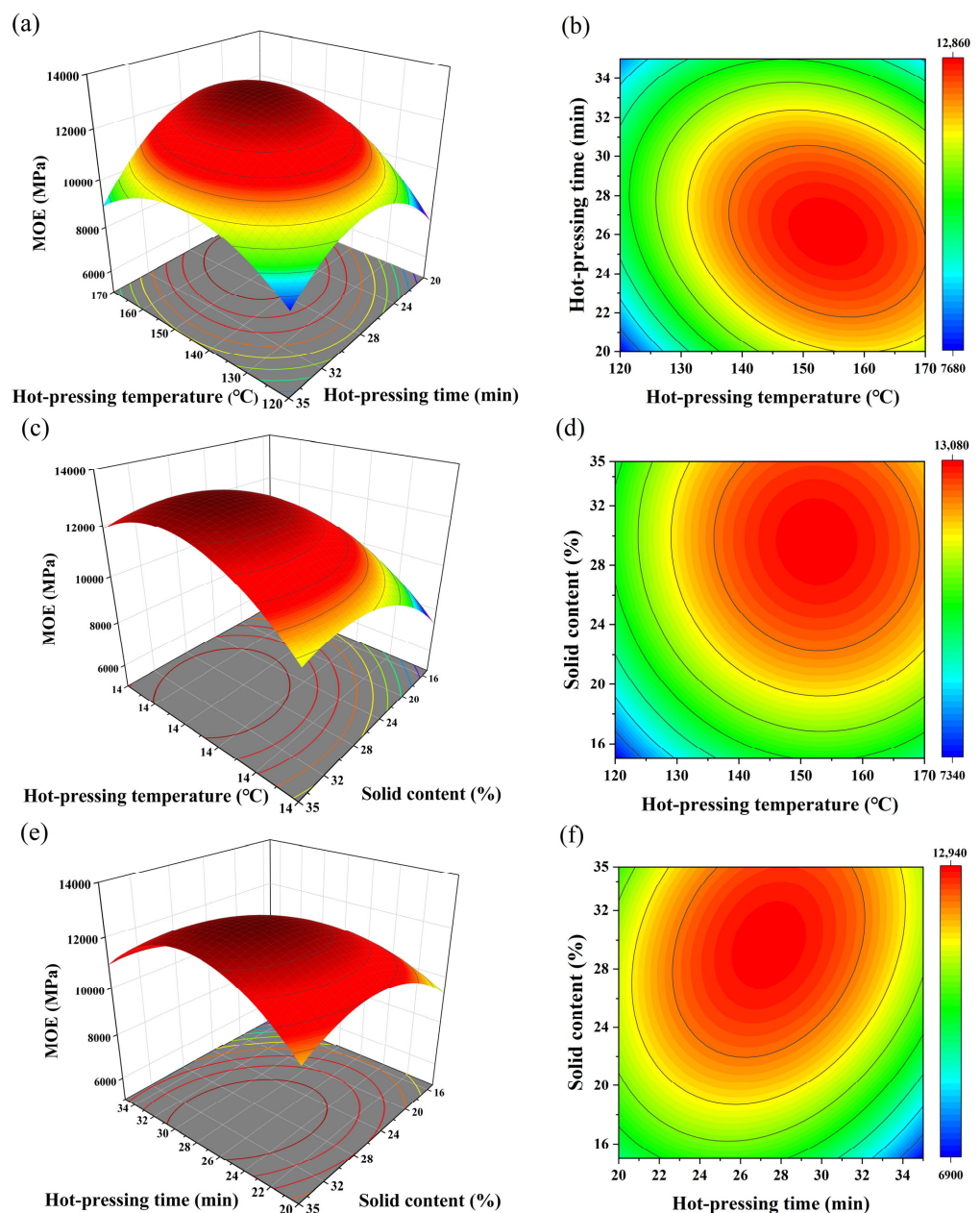


Figure 7. Contour plots and 3D surface for MOE of bamboo scrimber: (a,b) hot-pressing temperature and hot-pressing time; (c,d) hot-pressing temperature and solid content; (e,f) hot-pressing time and solid content.

3.3. Optimization and Validation

The optimal process was obtained by Design-Expert software: a hot-pressing temperature of 149.62 °C, a hot-pressing time of 27.65 min, and a resin solid content of 28.76%. Taking into consideration the laboratory conditions and practical feasibility, the process was adjusted to a hot-pressing temperature of 150 °C, a hot-pressing time of 27.5 min, and a resin solid content of 29%. Three confirmatory tests were carried out, and the MOR and MOE results are shown in Table 7. The average MOR was 150.05 MPa and the MOE was 12,802 MPa, which met the requirement of 120 E_b level according to the Chinese national standard (GB/T 40247-2021) [38]. Moreover, the difference between the theoretical values of MOR of 152.08 MPa and MOE of 13,036 MPa was not much, which was within the error range of 5%. It showed that the equation fits well with the actual situation, and the model was correct. Meanwhile, MOR and MOE were higher than the values of other studies [24,38], indicating that the optimized process has a beneficial effect on the enhancement of mechanical properties with bamboo scrimber. Figure 8 shows the morphological characteristics of the bamboo scrimber cross-section under optimal and non-optimal preparation process parameters. Figure 8a,b shows that the cross-sectional surface of bamboo scrimber was flat and evenly filled with BPF resin compared to Figure 8c,d. The TSR and WSR of the samples after a 24-h immersion period in room-temperature water are displayed in Table 7. According to the Chinese national standard (GB/T 40247-2021), the average WSR of bamboo scrimber was 1.96%, which met the requirement of a W2.0 level; the average TSR was 8.68%, which met the requirement of a T9.0 level. This result showed that the optimized bamboo scrimber has good water resistance and can be used as flooring or desktop decorative panels in the indoor environment.

Table 7. MOR, MOE, WSR, and TSR of optimized bamboo scrimber.

Sample	MOR (MPa)	MOE (MPa)	WSR (%)	TSR (%)
1	150.40 ± 11.95	11,547 ± 378.00	2.19 ± 0.26	11.72 ± 1.11
2	153.04 ± 15.70	13,560 ± 153.04	1.86 ± 0.12	6.18 ± 1.15
3	146.70 ± 7.11	13,300 ± 146.70	1.82 ± 0.09	8.14 ± 0.91

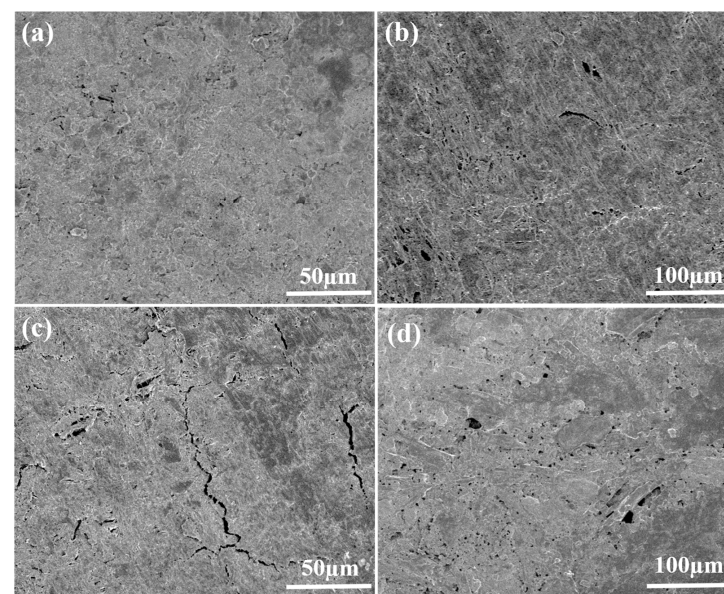


Figure 8. SEM images of bamboo scrimber cross-section, (a,b) bamboo scrimber prepared under optimized conditions, (c,d) bamboo scrimber prepared under non-optimized conditions. Among them, (a,c) represent images magnified by ×500 times, and (b,d) represent images magnified by ×1000 times.

4. Conclusions

Bamboo scrimber was prepared successfully using bio-oil phenolic resin. The RSM was used to optimize the hot-pressing process of bamboo scrimber, which could effectively predict the optimal process conditions. Combined with the optimization scheme given by the Design-Expert software and the actual production situation, the optimized process conditions are as follows: a hot-pressing temperature of 150 °C, a hot-pressing time of 27.5 min, and a solid content of impregnated bio-oil phenolic resin of 29%. Under these conditions, the MOR and MOE of bamboo scrimber were 150.05 MPa and 12,802 MPa, respectively. The order of influence of each variable on MOR and MOE was resin solid content, hot-pressing temperature, and hot-pressing time. Among them, the hot-pressing temperature and time, as well as the hot-pressing time and resin solid content, had significant interactive effects on the MOR and MOE. It demonstrated that RSM is applicable for regression analysis and parameter optimization of the process in the preparation of bamboo scrimber. The preparation of bamboo scrimber using bamboo waste bio-oil phenolic resin promotes the full use of bamboo components, and the optimized process has a certain guiding significance for the actual production in the bamboo industry.

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