Optimization of Parameters for Vacuum Heat Modification of *Cupressus funebris* Wood

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A full factorial experiment was conducted to analyze the main and interaction effects on the physical and mechanical properties of *Cupressus funebris* Endl. wood subjected to vacuum heat modification. The response variables evaluated were mass loss rate (ML, %), moisture resistance (MR, %), and modulus of rupture in bending (MOR, MPa). The results reveal significant variations in the effects of modification time, holding temperature, and vacuum pressure as independent factors, along with varying degrees of interaction effects among them. Simplifying the analysis model, a regression equation was derived to describe the relationship between the response variable (mass loss rate) and the factors: The model achieved an R-squared value of 96.0% and an R-squared (predicted) value of 73.7%, indicating good overall predictive performance. Optimal process parameters for mid-temperature vacuum heat modification of cypress were determined based on the mass loss rate and modulus of rupture (MOR), resulting in a modification temperature of 120 °C, holding time of 5 h, and a pressure intensity of 0.1. The reliability of the full factorial experiment was further confirmed through orthogonal testing.

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INTRODUCTION

Wood, as the only natural polymer among the four major construction materials (structural steel, concrete, plastic, and wood), possesses favorable environmental characteristics, in addition to favorable visual aesthetics, tactile properties, auditory characteristics, as well as temperature and humidity control capabilities. However, its biological nature leads to inherent drawbacks such as low dimensional stability and susceptibility to decay. Among various wood preservation methods, thermal modification emerges as an environmentally friendly approach, utilizing physical means to enhance wood functionality. Heat modification reduces the equilibrium moisture content, moisture absorption, and improves dimensional stability (Cao *et al.* 2012; Bytner *et al.* 2021) and weather resistance (Dahali *et al.* 2020). These changes broaden the application possibilities of wood, helping to address the supply-demand imbalance and increase its value. Heat-modified wood demonstrates superior performance in architecture and furniture, presenting significant potential for utilization.

Cupressus funebris, a native species in China belonging to the Cupressaceae family, is an evergreen, tall tree. Abundant cypress resources are found in the southwestern region of China. It holds a prominent position in the wood industry due to its high grade and favorable mechanical properties. *Cupressus funebris* Endl. wood (CFW) is widely used as a primary material in various forms such as sawn materials, veneers, plywoods, particleboards, and fiberboards. Additionally, it serves as a secondary material for applications such as parquet flooring, carpentry products, and furniture. However, *Cupressus funebris* exhibits limitations in terms of decay resistance and dimensional stability. Therefore, efficient utilization of cypress resources is crucial (Kaya 2023).

Cupressus funebris Endl. wood, commonly known as Chinese weeping cypress, exhibits distinct features that make it relevant for scientific investigation (Lyu *et al.* 2023). Understanding its physical and mechanical properties, as well as the effects of various treatments, can contribute to the development of improved wood-based products and enhance our knowledge of wood science and engineering. Therefore, it is essential to conduct further research on *Cupressus funebris* Endl. wood to unlock its full potential and explore its suitability for different applications.

To fulfill the application-specific modifications and meet performance requirements for wood, the vacuum heat modification method offers effective control over the loss of mechanical properties while ensuring reduced moisture absorption and improved dimensional stability. Previous studies have demonstrated that the mechanical properties of wood achieve optimal results in nitrogen and vacuum environments, compared to media such as steam or air (Rautkari *et al.* 2014; Yang *et al.* 2016; Lee *et al.* 2018; Qi *et al.* 2021). Using vacuum instead of N_2 as the medium for heat modification at the same temperature significantly reduces the degradation of wood polysaccharides and the formation of internal recondensed compounds within the wood structure, leading to less degradation of mechanical properties in wood samples (Candelier *et al.* 2013). The vacuum environment protects wood from the effects of oxygen and aids in the removal of volatile compounds that promote polysaccharide degradation, resulting in reduced degradation compared to other mediums (Bailing *et al.* 2013). Studies have also shown that pressure impacts the thermal degradation reaction in a closed system, with temperature, pressure, and relative humidity parameters being interdependent and collectively influencing wood degradation (Zaman *et al.* 2000; Altgen *et al.* 2016b; Hazir 2021). Therefore, the key process parameters influencing the vacuum heat modification of wood are heating time, holding temperature, and chamber pressure. While extensive research exists on the physical and mechanical properties of wood after high-temperature heat modification based on these three main factors, limited research has been conducted on predictive models for the physical and mechanical properties of wood after medium-temperature heat modification and the interaction effects among these factors.

Minitab software, an efficient statistical and analysis tool, can be utilized for experimental design, analyzing factor effects, and parameter design. However, its application in the field of wood modification is limited. A full factorial design (FFD) allows for a comprehensive evaluation of the influence of factors and their interactions on experimental outcomes by considering all possible combinations of the factors. Although this approach may result in a large number of experiments, it minimizes ambiguity in result interpretation (Taguchi *et al.* 2005).

In this study, Minitab software was used to conduct a full factorial design and analyze the physical and mechanical properties of CFW after medium-temperature heat modification. The mass loss rate was used as a measure of degradation extent and a significant process condition. The objective was to explore and quantify the effects of influential factors and their interactions on wood performance, eliminate non-essential factors, and identify key parameters for modeling the wood heat modification process. Ultimately, a predictive model for assessing the quality of heat-treated CFW based on process parameters was established.

EXPERIMENTAL

Materials

Cupressus funebris wood was sourced from Deyang City, Sichuan Province. Wood specimens were carefully chosen based on clear grain patterns, uniform color, and absence of defects such as knots and decay. The wood was then processed into lamellas measuring 300 mm × 20 mm × 20 mm, and cubes measuring 20 mm × 20 mm × 20 mm. The initial moisture content of the wood ranged from 11% to 13%. To facilitate experimental conditions, each specimen was assigned a unique numerical identifier. Eight replicates were treated at each heating temperature.

Experimental Equipment

The experimental equipment comprised various instruments, including a computer-controlled universal mechanical testing machine (RGM-4100), an electric heating constant temperature convection drying oven (101-3A), a precision sliding table saw (CDOWADA3200), an electronic balance (JA5003A), an intelligent electric heating vacuum drying oven (DZF-6050AB), an electronic digital caliper, and a constant temperature and humidity test chamber.

Full Factorial Design

Previous studies have indicated the potential benefits of long-term low-temperature heat modification for wood used in outdoor applications such as furniture, perches, and decorative projects (Durmaz *et al.* 2019). Building upon existing research on medium to high-temperature heat modification of wood (Wang 2017; Wu 2020), a full factorial experimental design approach was employed in this study. The three key factors were coded at high and low levels, and their specific experimental factors and level codes are presented in Table 1. To enhance the analysis of variance and minimize errors, a total of 11 experimental runs were designed, including three additional center point tests (runs: 3, 7, 10) for replication. The design variables included holding temperature (A °C), heating time (B, h), and vacuum pressure (C, MPa), while the physical and mechanical properties of cypress wood served as the response variable. The factor and parameter inputs were entered into the Minitab software, which generated 11 sets of randomly ordered experiments.

Table 1. Coding Levels of Test Factors

Factor		Encoding	Level	
			Low	High
Holding Temperature (°C)	H_1	A	120	180
Heating Time (h)	T_2	B	1	5
Vacuum Pressure (MPa)	V_3	C	0.10	0.02

Vacuum Heat Modification

To ensure similar moisture content between the treated and control specimens, the specimens were initially placed in an electric heating constant temperature convection drying oven and dried for 10 h until moisture equilibrium was achieved. After stress relief, the specimens were transferred to an intelligent electric heating vacuum drying oven, and the chamber door was sealed. The air within the drying chamber was evacuated, and a negative pressure vacuum carbonization modification was conducted following a predetermined process. It took 2 to 3 min for the chamber's internal pressure to reach the desired value. Subsequently, the temperature was increased gradually at a rate of 1.5 °C per min until reaching the target temperature, which was maintained throughout the modification. After the specified intermediate temperature modification duration, the heater was deactivated, and the vacuum was sustained until the chamber temperature dropped to approximately 60 °C. The vacuum pressure was then released to restore atmospheric pressure, and the specimens were promptly removed and stored in a drying cabinet to cool down to room temperature.

Determination of Mass Loss Rate

Wood density was determined in accordance with the GB/T 1933 (2009) standard. The mass loss was determined by comparing the oven-dry mass of the specimens before and after heat modification. Prior to placement in the intelligent electric heating vacuum drying oven, the specimens were weighed, and the initial oven-dry mass (m_0) in grams was calculated based on the specimen's moisture content. After the completion of vacuum heat modification, depressurization, and cooling, the specimens were further dried in a drying cabinet until they reached an oven-dry state. The final oven-dry mass (m_1) in grams of the specimens after vacuum heat modification was then measured. The mass loss percentage (m_L) was calculated using the following Eq. 1.

$$m_L=(m_0-m_1)/m_0 \times 100\% \tag{1}$$

Determination of Moisture resistance

Both untreated wood and wood subjected to vacuum heat modification were divided into groups, and their oven-dry mass (M_0) in grams and tangential dimension (L_0) in millimeters were measured. The specimens were then subjected to humidity conditioning at a temperature of 20 ± 2 °C and a relative humidity of 40 ± 5%. Mass and dimension measurements were taken at regular intervals to track changes in moisture content. The percent moisture absorption (A) was recorded as the wood's moisture content varied. Equilibrium moisture content was considered reached when the time interval between two consecutive measurements was not less than 1 day, and the differences in dimension and mass were both within 0.02 mm and 0.01 g, respectively. At this point, the moisture absorption (A) and moisture resistance (R_M) were calculated using Eqs. 2 and 3, respectively,

$$A = (M-M_0)/M_0 \times 100\% \tag{2}$$

$$R_M = (A-A_0)/A_0 \times 100\% \tag{3}$$

where M_0 indicates the final oven-dry mass in grams of the specimens, A_0 indicates the hygroscopic rate of untreated wood, and A stands for the hygroscopic rate of heat-treated wood.

Determination of Modulus of Rupture

The modulus of rupture of the specimens was determined using the three-point bending method following GB/T 1936.1. (2009). Before testing, the treated specimens underwent one week of constant temperature and humidity conditioning at (20±2)°C and a relative humidity of (65±5)%. Moisture content in wood plays a crucial role in fiber bonding and strongly influences the mechanical properties. The measured moisture content (W) in percentage was subsequently converted to the MOR at 12% moisture content using the Eq. 4,

$$\delta_{b12}=\delta_{bw}[1+0.04(W\text{-}12)] \quad (4)$$

where δ_{bw} represents MOR at a specific moisture content W, and δ_{b12} represents MOR at a moisture content of 12%.

The mechanical performance testing was carried out using a computer-controlled universal mechanical testing machine with a span of 260 mm and a loading rate of 2 mm/min. Six replicates were performed for each modification, and the average values were calculated. Table 2 displays the results and the experimental design, which followed a 23+3 full factorial design and was generated using Minitab software.

Table 2. Full Factorial Design (2^4+3) and Test Results

Standard	Run	Temperature (°C)	Time (h)	Pressure (MPa)	Mass Loss Rate (%)	EMC (%)	MR (%)	MOR (MPa)
1	1	120	1	0.02	1.68	9.95	6.55	75.9
7	2	120	5	0.10	1.66	9.50	11.64	107.8
9	3	150	3	0.06	1.75	9.48	11.85	92.3
5	4	120	1	0.10	1.02	9.76	8.64	88.0
8	5	180	5	0.10	3.96	9.57	10.81	92.2
3	6	120	5	0.02	1.31	9.98	6.21	89.5
10	7	150	3	0.06	1.91	9.70	9.27	101
6	8	180	1	0.10	2.09	9.79	8.28	104
4	9	180	5	0.02	2.97	8.18	29.56	68.8
11	10	150	3	0.06	2.33	9.71	9.19	95.2
2	11	180	1	0.02	2.61	9.05	17.21	89.2

Note: The average equilibrium moisture content of the control specimens was 10.60%, while the modulus of rupture (MOR) measured 93.04 MPa.

RESULTS AND DISCUSSION

Mass Loss Rate Variations

The effects of the mid-temperature heat modification variables (heating time, holding temperature, and pressure), along with their interactions, on mass loss rate, moisture resistance, and flexural strength were analyzed using Minitab software. Auxiliary plots were generated to visualize these effects. The standardized Pareto effect plot, which performs t-tests on each factor and calculates the critical value of t based on a predetermined significance level (α = 0.05), was employed to assess the significance of each factor on the response variables. Figure 1 displays the standardized effects Pareto plot generated by Minitab software.

From the mass loss rate effect plot, it is evident that the critical value of *t* was 2.776, and the absolute values of the effects of factor A, factor B, and the two-factor interaction BC surpassed this critical value. The analysis reveals that the heating temperature and the interaction between holding time and pressure had significant effects, with the influence of holding time decreasing progressively. This finding is further supported by the analysis of variance presented in Table 3. The primary cause of mass loss under medium to high-temperature conditions is the thermal decomposition of low molecular weight extractives and hemicellulose (Todorović *et al.* 2015; Zhang *et al.* 2015). Hemicellulose structures contain numerous aldehyde and hydroxyl groups, making them susceptible to thermal degradation at medium to high temperatures. Experimental studies conducted by Čabalová *et al.* (2018) have confirmed that the thermal decomposition temperature of hemicellulose falls within the range of 160 to 180 °C. In contrast, lignin and cellulose structures, being more complex and stable, exhibit greater resistance to degradation at lower temperatures. Some researchers have reported that hemicellulose degradation occurs at temperatures exceeding 120 °C, with the degree of degradation influenced by the duration of the thermal process (İmirzi *et al.* 2014; Cao *et al.* 2022). However, the density of cypress wood remained relatively stable before and after heat modification, with a basic density of approximately 0.56 g/cm³ and an air-dry density of about 0.53 g/cm³. These findings align with the significant influence of insulation time observed in the present study. The strong interaction between insulation time and pressure within the vacuum chamber can be attributed to the impact of pressure on the thermal conductivity of CFW and the evaporation of internal moisture. Under high-pressure conditions, the internal gas pressure within CFW decreases, thereby amplifying the influence of modification time and subsequently affecting the wood's quality. The normalized effect normal plot reveals that all estimated significant effects align with the lower right of the regression line, indicating a positive relationship. Specifically, the response variable, volume-mass loss rate, increases with higher levels of the factors.

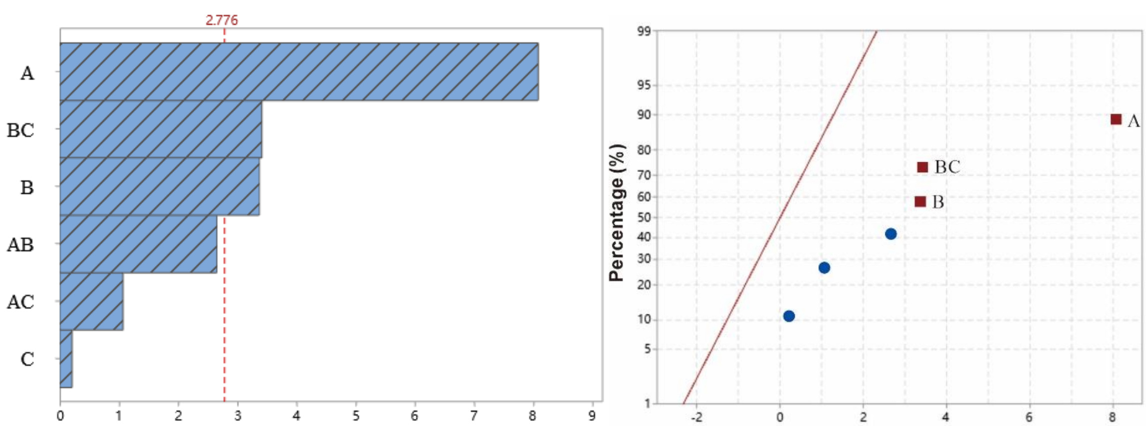

Fig. 1. Pareto chart of standardized effects for mass Loss rate

Figure 2 illustrates the range of mass loss rate falling between 1.02% and 3.96%. When pressure and insulation time were held constant, an increase in heating temperature led to a significant increase in ML. At higher temperatures, the effect of time on ML became more pronounced, whereas this difference was not significant at lower temperatures. The impact of heating temperature on ML surpassed that of holding time, consistent with the previous research results (Boonstra *et al.* 2007; Esteves and Pereira

2009; Ebadi *et al.* 2021). Under high-pressure conditions, shorter heating times result in higher ML, while longer heating times lead to higher ML under low-pressure conditions. These outcomes indicate that the highest ML for *Cupressus funebris* wood was achieved under the experimental conditions when the heating temperature was 180 °C, the holding time was 5 h, and the pressure was 0.1 MPa.

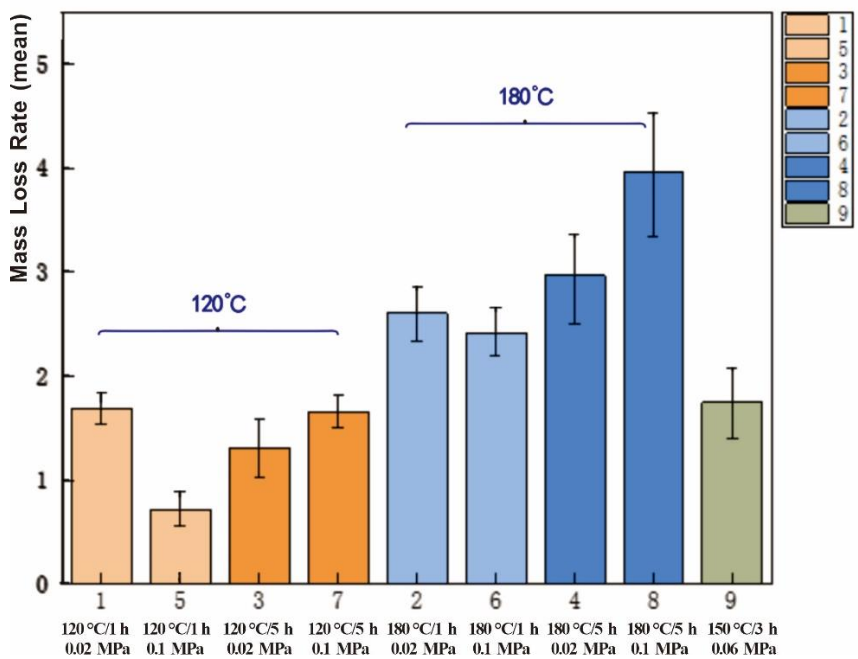

Fig. 2. Variation in mass loss rate

Moisture Resistance Variations

Table 2 presents the variation in moisture resistance of wood under different vacuum heat modification conditions. The table reveals that, compared to the control group, the improvement in moisture resistance ranged from 6.5% to 29.6%. The optimal treatment parameters were as follows: modification temperature of 180 °C, insulation time of 5 h, and pressure maintained at 0.02. In the Pareto chart, the vertical lines indicate the statistical significance of the effects on moisture resistance at a 5% significance level (Taguchi 2005).

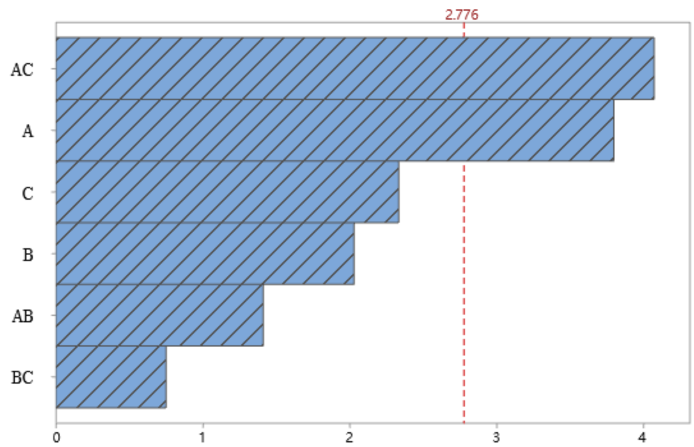

Fig. 3. Pareto chart of standardized effects for moisture resistance

Analyzing the Pareto chart in Fig. 3 and the analysis of variance, the factors are ranked in terms of their influence strength as follows: modification temperature > pressure > insulation time. The interaction between temperature and pressure, as well as the main effect of temperature on moisture resistance, exhibited statistically significant effects at the 5% level.

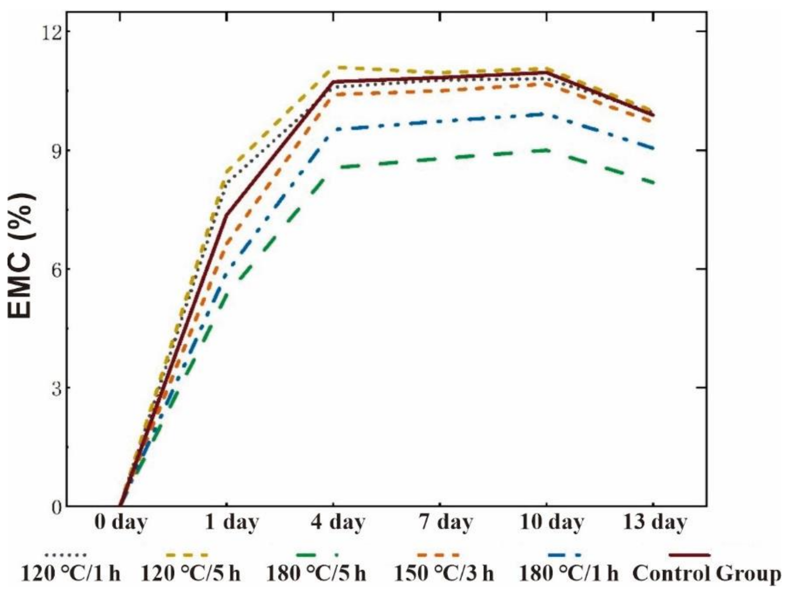

Fig. 4. Moisture sorption process of completely dry wood

The influence of factors in the medium-temperature thermal modification (on equilibrium moisture content is depicted in Fig. 4. Following 13 days of constant temperature and humidity drying, the EMC ranged from 8.18% to 9.98%. As the temperature increased from 120 to 180 °C, the EMC decreased. The lowest EMC of 8.18% was attained after modification at 180 °C under lower pressure for 5 h. This observed trend aligns with the findings reported by previous researchers (Zhang *et al.* 2017; Kozakiewicz *et al.* 2019; Priadi *et al.* 2019; Nourian and Avramidis 2021). Nevertheless, both treated and untreated specimens exhibited consistent water absorption trends at different factor levels. Initially, within the first 5 days, a higher rate of water absorption was observed, which then gradually decreased. The reduction in EMC and the improvement in moisture resistance can be attributed to factors such as the reduction of extractives in the cell structure, decrease in -OH groups, increase in cellulose crystallinity, and lignin cross-linking. These factors collectively contribute to the reduced availability of hydroxyl groups to water molecules, extending the lag period for moisture absorption, and ultimately enhancing the dimensional stability of the wood (Yuliansyah and Hirajima 2012; Salim *et al.* 2013; Talaei *et al.* 2013).

Modulus of Rupture Variations

The influence of factors C and the interaction AB on the modulus of rupture in the medium-temperature thermal modification environment is apparent from the Pareto chart and standardized effect normal plot of MOR. These factors exhibit statistical significance at the 5% level. In the temperature range of 120 to 180 °C, pressure is the most influential factor affecting MOR. This finding aligns with previous reports that, within a closed system, modified pressure exerts a greater impact on the chemical structure and mechanical properties compared to temperature (Altgen *et al.* 2016a; Hofmann *et al.* 2016; Wentzel *et al.* 2018). The effect of medium-temperature thermal modification on mechanical properties is associated with the primary chemical constituents and crystallinity of the wood. At lower modification temperatures, pressure exerts a more pronounced influence on internal thermal decomposition and wood density. The interaction effect of temperature and time is positioned in the upper-left region of the regression line, indicating a negative effect where the response decreases with an increase in the interaction between these two factors.

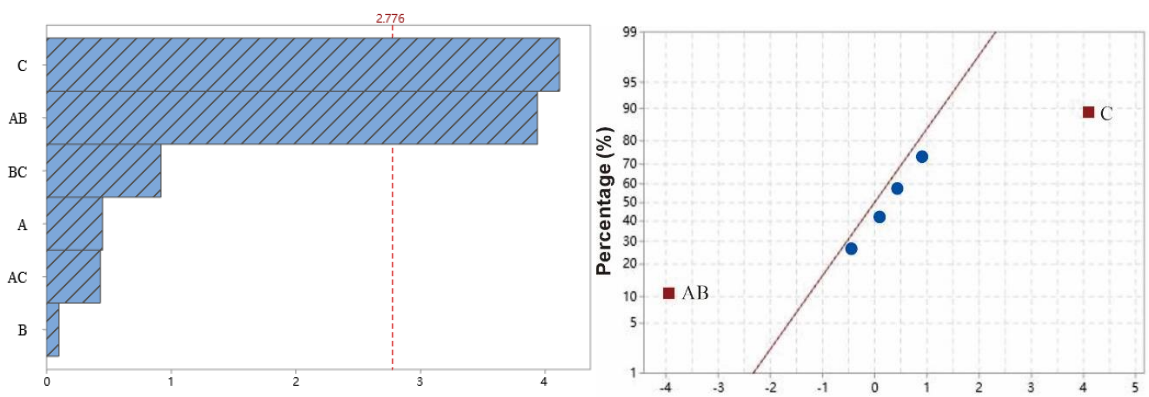

Fig. 5. Pareto plot and normal plot of standardized effects for moisture resistance modulus of rupture

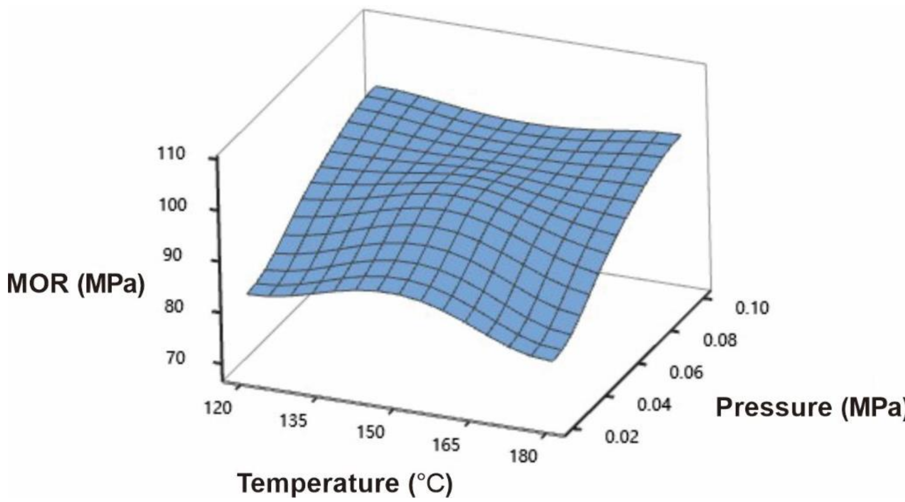

Fig. 6. Surface plot of modulus of rupture variation

The surface plot illustrates variations in modulus of rupture and the data from Table 2 reveal that, within a specific temperature range (120 to 180 °C), MOR demonstrated an increasing trend with higher pressure. In comparison to untreated wood, the samples exhibited enhanced MOR in environments with lower heating temperatures (120 to 150 °C), and a significant reduction in MOR loss was observed at 180 °C. The highest MOR value of 107.8 MPa was achieved when the heating temperature is 120 °C, the holding time is 5 h, and the pressure is 0.1 MPa. This finding is consistent with the research conducted by Zhang (2015). Throughout the heat modification process, the depletion of hydroxyl groups in the hemicellulose molecular chain resulted in moisture loss from the amorphous region of cellulose and the surface of neighboring cellulose, potentially leading to a denser arrangement of cellulose molecular chains and the formation of new hydrogen bonds. An increase in the crystallinity index contributes to the improved mechanical strength of the wood. Furthermore, the reduction in cellulose and hemicellulose polysaccharide components results in a relative increase in lignin content, which also enhances the mechanical properties of the samples (Hill 2007; García-Iruela *et al.* 2021; Birinci *et al.* 2022).

Developing a Predictive Model

A predictive model was developed using Minitab software based on the obtained relationship model between the mass loss rate of specimens and the factors. The model demonstrated a high R-sq (predicted) value, indicating its effectiveness. To enhance the model's accuracy, identify significant factor effects, and simplify the model, insignificant factors were eliminated, and the data were reanalyzed. Figure 5 presents the Pareto chart of standardized effects generated in Minitab after eliminating insignificant factors. The critical value of t was observed to be 2.571. Factors A and B exhibited significant effects, while the two-factor interactions of B and C, as well as A and B, were prominent. The R-sq value and R-sq (predicted) value were calculated as 96.0% and 73.7%, respectively. These values indicate a strong explanatory power of the independent variables on the response variable, explaining over 96% of the variation in the mass loss rate. Furthermore, within the experimental range, the combination of any levels of factors demonstrates robust simulation and predictive capabilities. Additionally, the Minitab software generates a regression equation with the experimental effects as the response variable,

$$Y = 0.440 + 0.01259A - 0.693B - 11.33C + 0.00408A \times B + 3.94B \times C$$

where A indicates the holding temperature, B indicates the heating time, C stands for the vacuum pressure.

Table 3 presents the simplified model's analysis of variance (ANOVA). From the table, it can be observed that the p-value of the lack-of-fit term was 0.425, which is greater than the significance level of 0.05.

Table 3. Analysis of Variance (ANOVA) Table

Source	Degrees of freedom	Adj SS	Adj MS	F-alue	P-value
Model	5	6.498	1.300	18.515	0.003
Linear	3	5.224	1.741	24.806	0.002
Temperature	1	4.445	4.445	63.329	0.001
Time	1	0.775	0.775	11.048	0.021
Pressure	1	0.003	0.003	0.043	0.845
2-Factor Interaction	2	1.274	0.637	9.078	0.022
Temperature * Time	1	0.480	0.480	6.844	0.047
Time * Pressure	1	0.794	0.794	11.312	0.020
Error	5	0.351	0.070		
Bending	1	0.060	0.060	0.826	0.415
Mismatch	2	0.107	0.053	0.580	0.633
Pure Error	2	0.184	0.092		
Total	10	6.849			

This indicates that there is no lack-of-fit phenomenon in the model, and the model is overall effective. The p-value of the curvature term is 0.634, also exceeding the significance level of 0.05. Therefore, it suggests that the curvature term in the model is not significant. This implies that the linear effects of the factors on the response variable are more important, and when optimizing process parameters, it is essential to focus on the linear effects of the factors to achieve the desired optimization of the response variable. Furthermore, the predicted values of the mass loss rate obtained using this model are compared with the actual values and shown in Fig. 7. The coefficient of determination (R^2) for ML was 96.3%, and the actual values were mostly distributed within the 95% confidence interval. This demonstrates good consistency between the experimental values and the model predictions.

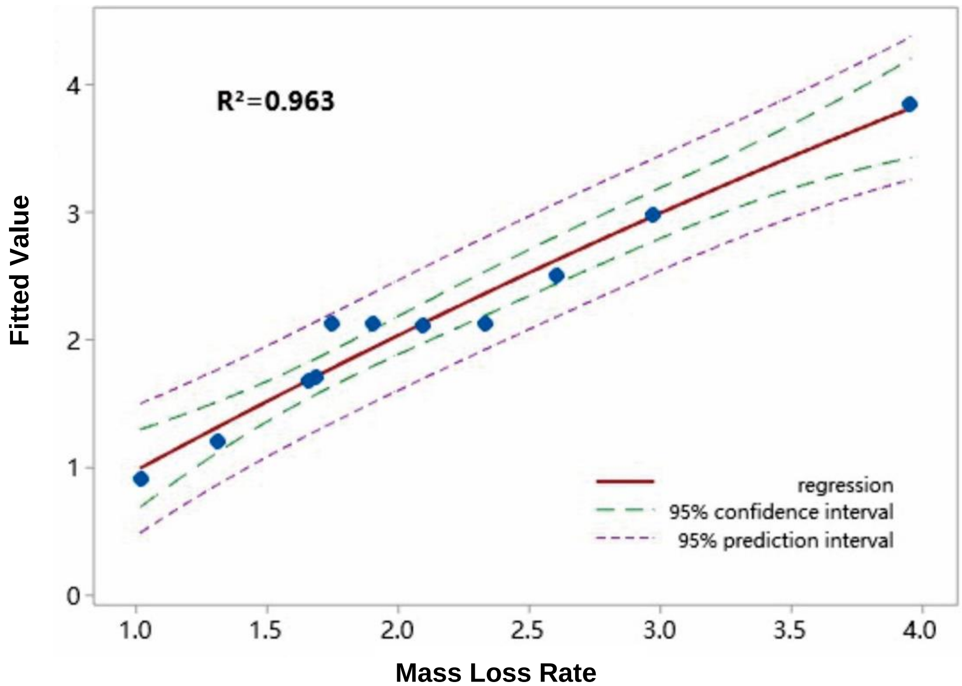

Fig. 7. Comparison of Experimental and Model Data for Mass Loss Rate

Optimization of Experimental Design

The variance analysis table reveals that the curvature term of the model was not significant, allowing for parameter optimization and design using the response optimizer in Minitab software. Figure 8 presents the main effects plot for the mass loss rate and modulus of rupture, where the horizontal axis represents the different levels of the factors, and the vertical axis represents the mean values of the response. Smaller slopes on the horizontal axis indicate minimal differences in the effects between different levels. Based on the factor effect relationships of the mass loss rate and the results from the response optimizer, the optimal experimental design based on a full factorial design approach is determined to be a modification temperature of 120 °C, a holding time of 5 h, and a pressure level of 0.1 MPa, corresponding to the experimental set of the 7^{th} standard sequence. Similarly, based on the factor effect relationships of the MOR and the response optimizer results, the optimal experimental design based on a full factorial design approach is a modification of 120 °C, a holding time of 5 h, at 0.1 MPa pressure. Compared to the control group, this design exhibits a 9.40% increase in MOR and a smaller mass loss rate.

During the process of mid-temperature vacuum thermal modification of poplar wood, some hemicelluloses and extractable organic compounds in the wood decompose, resulting in the removal of a portion of moisture and other volatile substances from the wood, leading to a reduction in the mass loss rate. These decomposition products fill the microvoids left by the decomposed substances, making the wood more compact and thereby increasing the bending strength. Based on a full-factor experimental design analysis, for mid-temperature vacuum thermal modification of poplar wood, a temperature of 120 °C, a duration of 5 h, and a pressure of 0.1 MPa have been found to play a crucial role in improving the strength properties of the treated samples while minimizing the overall mass loss. This approach optimizes the performance of mid-temperature thermally modified wood.

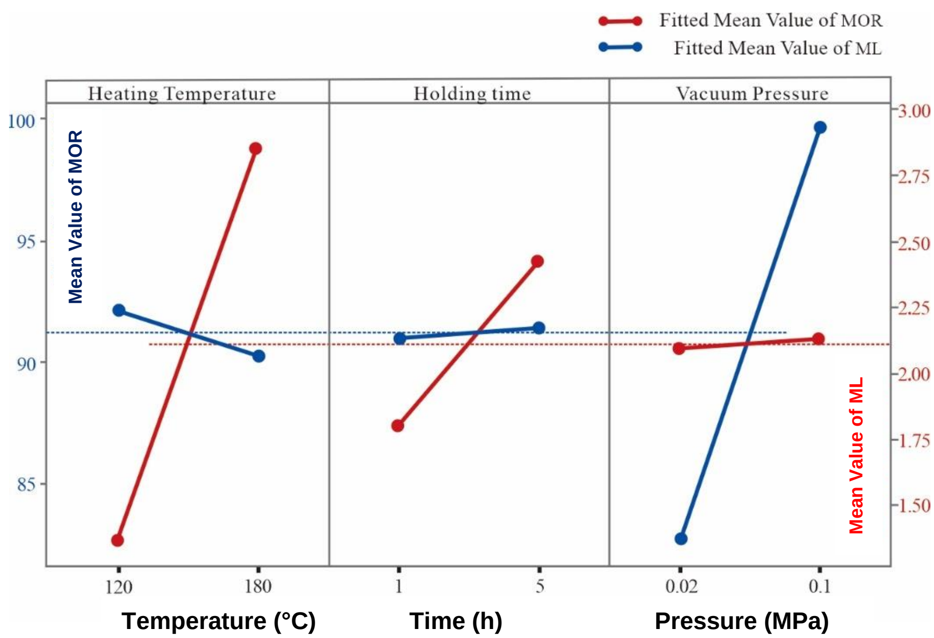

Fig. 8. Main Effects Plot of Mass Loss Rate and MOR

Orthogonal Experimental Validation

To validate the main effect results obtained from the experimental analysis, an orthogonal experimental design was conducted with mass loss rate as the response variable to investigate the influence of each factor. As shown in Table 4, the results aligned with the trends observed in the significant factors of the main effects from the full factor design, thereby verifying the reliability of the main effect considerations in the Minitab full-factor experimental design. This further emphasizes the importance of considering the interactions among the factors when determining the process parameter settings.

In the middle-temperature range of heat modification (120 to 180 °C), the holding temperature had the greatest impact on the wood mass loss rate, with the following order of influence strength: temperature > holding time > pressure. Furthermore, the temperature inside the vacuum heat modification chamber and the holding time had a highly significant effect on the mass loss rate of cypress wood. The optimal combination with the lowest mass loss rate is consistent with the process parameter optimization results obtained from the response optimizer in Minitab software, which is a temperature of 120 °C, a holding time of 5 h, and a pressure of 0.1 MPa.

Table 4. Range Analysis of Variance for Mass Loss Rate

Number	Temperature (°C)	Time (h)	Pressure (MPa)	Blank Columns	Mass Loss Rate (%)
1	120	1	0.02	1	0.775
2	120	3	0.06	2	2.628
3	120	5	0.1	3	1.051
4	150	1	0.06	3	3.215
5	150	3	0.1	1	3.848
6	150	5	0.02	2	4.086
7	180	1	0.1	2	2.662
8	180	3	0.02	3	5.338
9	180	5	0.06	1	2.846
K1	4.454	6.652	10.199	7.469	
K2	11.149	11.814	8.689	9.376	
K3	10.846	7.983	7.561	9.604	
Range R	2.232	1.721	0.879	0.712	
Primary and Secondary Factors	A > B > C				
Optimal Level	A1	B1,B3	C3		
Optimal Combination	A1B1(B3)C3				

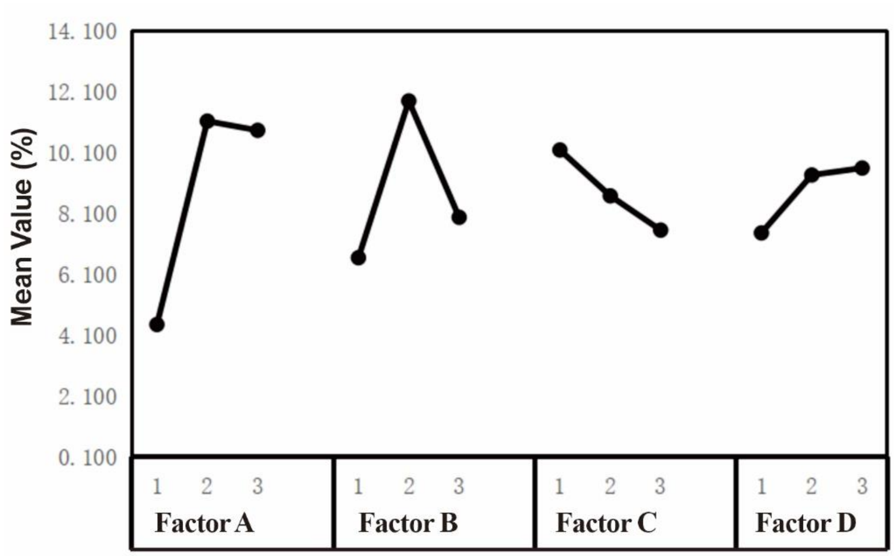

Fig. 9. Factor and Indicator Trends of Mass Loss

Future research should focus on developing a comprehensive model and system that compares heat modification parameters with various performance indicators. This will enable the prediction and control of treatment effects on industrial products, leading to greater efficiency and clarity in medium temperature heat treatment processes. Comprehensive utilization of various microanalytical instruments should be employed to delve deeper into the micro-modification mechanism of medium temperature heat treatment. This will facilitate optimization of the modification process and enhancement of heat treatment material quality. It is essential to establish a standardized evaluation criterion for heat treatment materials and regulate the market for heat treatment products.

CONCLUSIONS

1. Based on the full factorial experimental design, it can be concluded that within the experimental range, the main factors influencing the mass loss rate of *Cupressus funebris* Endl wood in the middle-temperature vacuum heat modification were the modification temperature and holding time. The interaction between holding time and pressure was significant. The mass loss percentage significantly increased with the increase in heating temperature, and the influence of holding time on ML became more pronounced with the rise of temperature.
2. In the mild reaction environment of 120 to 180 °C during the heat modification, the main factor affecting the moisture resistance rate was the modification temperature. Under constant time and pressure, the equilibrium moisture content of the wood significantly decreased with increasing heating temperature. The interaction between temperature and pressure was also significant. On the other hand, pressure was the primary factor influencing the MOR loss rate, while the interaction between temperature and time was also a statistically significant factor.
3. After optimizing the model, an effective regression equation for the mass loss rate was obtained: $Y = 0.440 + 0.01259A - 0.693B - 11.33C + 0.00408A \times B + 3.94B \times C$. The R-squared value reached 96.0%, and the R-squared (predicted) value reached 73.7%, indicating a good predictive capability of the model. Based on the main effects plot of the mass loss rate and MOR, as well as the response optimizer results, the optimal parameters for the mid-temperature vacuum heat modification were determined as follows: modification temperature of 120 °C, holding time of 5 h, and pressure level of 0.1 MPa. The findings inform wood modification practices and highlight the importance of comprehensive performance assessment.
4. The reliability of the Minitab full-factor experiment was verified using orthogonal testing. The results of variance analysis and range analysis for the response variable, mass loss rate, were consistent with the analysis results of the full factor experiment. This study confirmed the feasibility of using Minitab software for modified wood and provides process references for mid-temperature vacuum heat modification of modified wood, effectively improving the utilization of modified wood. It also improved the understanding of wood properties and offers the potential to improve industrial applications, such as construction and furniture.

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