Effect of Climate and Wood Type on Elastic Modulus of Heat-treated Wood and its Optimization by the Taguchi Method

Mehmet Gunes,[a,]* Cagatay Ersin,[b] and Mustafa Altunok [c]

Wood, as the oldest building material, provides some of the basic needs of human beings, including shelter and protection. Wood is used in exterior cladding, carrier systems, joinery, ceiling-floor coverings, windows, doors, and furniture production. When wooden material is exposed to external weather conditions, due to its hygroscopic structure, its physical and mechanical properties deteriorate from exposure to moisture, temperature, and biological organisms. The bending modulus of elasticity of Scots pine (*Pinus sylvestris* L.), oak (*Quercus petraea* L.), and chestnut (*Castanea sativa* M.) wood that was tannin-impregnated and heat-treated at 160 °C, was investigated using Taguchi L9 (3^3). The sequence was optimized. After heat treatment, the carrier elements were subjected to artificial climate conditions. In the optimization of the data obtained, it was understood that the highest impact factor was the tree type. In contrast, the climate on the elastic modulus was the lowest impact factor. In Taguchi analysis, a mathematical prediction model was created using actual and predicted data using the S/N ratio's biggest-best equation. The R^2 of the model can be predicted with an accuracy rate of 98.6%.

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*Contact information: a: Design Department, Vocational School, Cankiri Karatekin University, Cankiri, Turkey; b: Electronics and Automation Department, Vocational School, Cankiri Karatekin University, Cankiri, Turkey; c: Wood Product Industrial Engineering, Faculty of Technology, Gazi University, Ankara, Turkey *Corresponding author: mehmetgunes@karatekin.edu.tr*

INTRODUCTION

Throughout history, humanity has effectively used natural, renewable, and sustainable materials, such as wood in many areas of life due to their advantages, such as aesthetics, high impact resistance, and low cost (Birinci *et al*. 2021; Yumrutaş *et al*. 2021). Because of wood's abundance, its use and production are increasing (Imren 2022). Wood deteriorates when exposed to natural conditions without any protective treatment (De la Caba *et al*. 2007). The biological and hygroscopic structure of wooden materials makes such materials sensitive to various destruction factors and biotic factors (fungi, insects, termites, *etc.*). This essential factor limits wood's use as a long-lasting building material. In particular, the effect of biotic factors on the mechanical properties of wood can negatively affect axial compression and bending resistance (Dimou *et al*. 2017). Additionally, wooden materials have an anisotropic structure. The anisotropic structure causes wood to behave differently under different types of loads, such as bending, tension, and compression. This can lead to various problems in engineering applications and structural designs (Zhao *et al*. 2016). Such challenges require the development of various methods for processing and preserving wooden materials. Physical methods, such as chemical impregnation treatments and heat treatment, can improve the mechanical properties of wood and make it more resistant to biotic factors (Li *et al*. 2022).

To optimize the experiments applied to the physical and mechanical properties of wooden materials, optimization of the effect of accelerated weathering conditions on wooden surfaces has been applied, using the Taguchi method (Kurt and Can 2021). The effect of artificial weather conditions on wood surface roughness (Imren 2022), optimization of wood laser cutting parameters (Nguyen and Dang 2023), determination of wood surface roughness in CNC milling (Budakci *et al.* 2013), improvement of heat-treated wood coating performance (Hazir 2021), and development of heat treatment parameters in wood materials (Workie and Tsegaw 2021).

When studies in the literature were examined, it was seen that the mechanical properties, modulus of elasticity, and bending resistance of wooden materials of different structures were calculated. The Taguchi method has been a preferred way to determine the factors affecting the change in bending strength and elastic modulus of the wood material, which was heat treated after tannin impregnation under artificial climate conditions, and to reduce the number of experiments (Taguchi 1993). In this study, the Taguchi method was used to examine heat treatment, tannin impregnation, and artificial climate conditions to determine which of the identified factors significantly impact the elastic modulus resistance of wood in bending. Test samples were obtained from 1/5 scale Scots pine, oak, and chestnut wooden beams. The process parameter was divided into three groups: 1. Untreated wooden control samples, 2. Samples were heat-treated in the oven at 160 ºC for 2 hours, and 3. Wooden beam samples were heat-treated in a 10% acorn tannin solution for 24 hours.

EXPERIMENTAL

Materials

The wood materials used in the study were selected from Scots pine, oak, and chestnut wood used in the furniture and woodworking industry. The samples were supplied from the same enterprise in Ankara Siteler industrial zone using a random selection method. Care was taken to ensure there were no knots, fungi, or mold on the trees used in the experiments. Air-dry and fully dry density values of the tree species used are given in Table 1. Among the tree species used in the experiments, the air dry density of Scots pine (*Pinus sylvestris* L.) was 0.46 (g/cm^3), of oak (*Quercus petraea* L.) was 0.84 (g/cm^3), and of chestnut (*Castanea sativa* M.) was 0.45 (g/cm^3). The trees supplied in lumber form were kept in the workshop environment until they became equilibrated with the air. Wood samples were positioned in the conditioning cabinet at 65±5% relative humidity (RH) and 20±2 °C to reach a constant weight, following the DIN EN 554 (2016) method. 3.2 cm x 6.4 cm x 88 cm method.

Methods

Tannin impregnation

Acorn tannin is an environmentally friendly and natural material obtained by extraction from acorns, an oak tree fruit abundant in forest regions. Tannin is most used in the leather industry (Merdan and Eyupoglu 2022). Tannin impregnation was used in the independent variable, the treatment factor. Some samples were determined as control samples, and bending strength tests were performed on wooden beams without any treatment. Some of the other samples were heat treated at 160 °C, and the rest were tannin impregnated before heat treatment. The samples with tannin impregnation were then subjected to heat treatment at 160 °C for 2 h. Acorn tannin was used to impregnate the samples. The test samples were kept in a plastic container for 24 h by dipping in 100 L of 10% acorn tannin solution (Fig. 1).

Fig. 1. Samples with impregnation application

For the impregnation process to be efficient, all samples were positioned so they were submerged in the solution and the container did not touch the ground. The samples, whose impregnation was completed, were ready for heat treatment.

Heat treatment application

After impregnation, each wood species was placed separately in the oven on the shelves shown in Fig. 2. The oven temperature was increased to 100 °C in 6 h. Then, the drying process was carried out by increasing it to 130 °C in 12 h. After the drying phase, the temperature was increased to 160 °C in 6 h, kept at this temperature for two h, and then the cooling phase was started. In the cooling process of the last heat treatment stage, the temperature was reduced to ambient temperature in 12 h. Hot steam was sprayed into the furnace at 3 atm pressure for 5 s every 60 s during heat treatment.

Fig. 2. Heat treatment oven

Conditioning

An artificial conditioning cabin was used to control the temperature and moisture content of the wooden material, which varies according to climatic conditions. The relative humidity and temperature in the air conditioning cabin were adjusted to mimic the summer, winter, and spring seasons. After the heat treatment, each tree species was placed in a separate air-conditioning cabinet, as shown in Fig. 3. The test samples were weighed every 12 h and kept in the air-conditioning cabinet at 20 °C/65% (spring) to 40 °C/35% (summer) to 10 °C/50% (winter) relative humidity, respectively, until they reached a constant weight for each climatic condition according to the DIN EN 325 (1993) standard. The samples that reached a constant weight were individually removed from the air-conditioning cabinet, and experiments were conducted.

Fig. 3. Universal climate test device

Flexural strength tests

Flexural strength tests were carried out on prepared Scots pine, oak, and chestnut beam samples with 32 x 64 x 880 mm dimensions by ISO 13061-3 (2014). A universal test device conforming to DIN EN 325 (1993) was used for bending strength measurement. In the experiments, the spacing of the fulcrum points was set as 832 mm (Fig. 4), the force at breakage (P_{max}) was read from the midpoint of the part with a forward speed of 2 mm/min, and the bending resistance was calculated according to Eqs. 1 and 2.

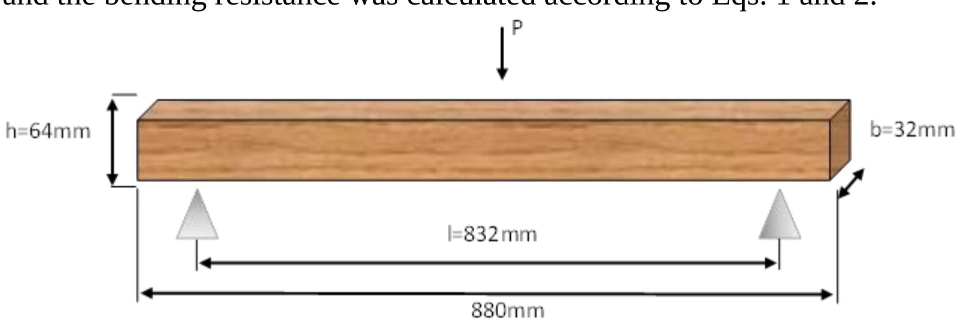

Fig. 4. Universal climate test device

$$\sigma_e = (3\ x\ P_{\max}\ x\ l)\ /\ (2\ x\ b\ x\ h^2) \quad (1)$$

$$E_m = (\Delta F\ x\ l^3)\ /\ (4\ x\ b\ x\ h^3\ x\ \Delta f) \quad (2)$$

where P_{max} is the maximum force applied at the moment of fracture (N), P is the load equal to the difference between the arithmetic averages of the lower and upper limits of the loading (N), ΔF is the force difference in the elastic region (N), l is the spacing between the support points (mm), b is the width of the test sample (mm), h is the height of the test sample (mm), and f is the deflection in the net bending area (mm).

Taguchi experimental design

In addition to their statistical significance, experimental design methods are complementary supportive methods that can be used in all research and development applications, increasing quality, minimizing costs, and thus strengthening the reliability of the outputs (Balki *et al*. 2016). The Taguchi method is widely used in engineering and industrial problems (Chamoli 2015; Kaya *et al.* 2020). Dr. Taguchi introduced a solution to increase efficiency in performing experiments and evaluating applications (Ross 1988). In addition to being an experimental design method, the Taguchi method is a valuable technique for high-quality system design by reducing the number of experiments (Taguchi 1993). To analyze the test outputs obtained in the Taguchi experimental design method, the loss function is converted into a statistical measure of performance known as the signal-to-noise ratio (S/N ratio). In this way, the deviation between the data is calculated.

According to its characteristic feature, this ratio is calculated with the objective functions (Masmiati and Sarhan 2015) given in Eq. 3:

$$\text{Nominal best } \frac{S}{N} = -10\ x \log\left(\frac{\bar{y}}{S^2{}_y}\right)$$

$$\text{Highest best } \frac{S}{N} = -10\ x \log\left(\frac{1}{n}\sum_{i:1}^{n}\frac{1}{y_i^2}\right)$$

$$\text{Lowest best } \frac{S}{N} = -10\ x \log\left(\frac{1}{n}\sum_{i:1}^{n} y_i^2\right) \quad (3)$$

The orthogonal array is used to create a custom design to determine the entire parameter space with a small number of experiments. The S/N ratio is used to analyze experimental results obtained from orthogonal array design. In the calculation of S/N ratios, “smaller is better”, “larger is better”, or “nominal is better” methods are used, depending on the characteristic type (Abdulaziz *et al.* 2020). Because bending resistance and elastic modulus resistance values were desired to be the highest among the dependent variables, S/N ratios were calculated using the more significant, better formula in Eq. 1.

Table 1. Factors and Values at Different Levels.

Factors		Levels		
		1	2	3
1	**Wooden**	Scots pine	Oak	Chestnut
2	**Treatment**	Control (Non- Heat-Treatment)	Heat-Treatment	Tannin Impregnation and Heat-Treatment
3	**Climate**	20 °C/65%	40 °C/35%	10 °C/50%

Wood type, processing type, climate type factors, bending strength, and elastic modulus dependent variables were designed according to 9 experiments in the Taguchi L9 (3^3) orthogonal array in Table 2.

Statistical analysis

Statistical analysis was performed using Minitab 21 software (Minitab LLC, State College, PA, USA).

Table 2. Taguchi L9 (3^3) Orthogonal Experimental Design Matrix

Experiment No	Wooden	Treatment	Climate	Elastic Modulus (N/mm^2)
1	Scotch pine	Control (Non- Heat-Treatment)	20 °C/65%	8213
2	Scotch pine	Heat-Treatment	40 °C/35%	8800
3	Scotch pine	Tannin Impregnation and Heat-Treatment	10 °C/50%	8658
4	Oak	Control (Non- Heat-Treatment)	40 °C/35%	10459
5	Oak	Heat-Treatment	10 °C/50%	11984
6	Oak	Tannin Impregnation and Heat-Treatment	20 °C/65%	12620
7	Chestnut	Control (Non- Heat-Treatment)	10 °C/50%	7063
8	Chestnut	Heat-Treatment	20 °C/65%	8304
9	Chestnut	Tannin Impregnation and Heat-Treatment	40 °C/35%	8874

RESULTS

According to the S/N response ratios obtained in Table 3, the factor that effects the elastic modulus the most is the wooden, followed by the treatment, and the factor that affects the least is the climate factor. According to S/N ratios, it was understood that the wood factor had the most impact on the elastic modulus. It was found that the effect of climatic conditions on the elastic modulus was minimal.

Table 3. S/N Response Table for Factors (Larger is Better)

Level	Wooden	Treatment	Climate
1	8080	9696	9235
2	11688	8578	9712
3	8557	10051	9378
Delta	3607	1472	477
Rank	1	2	3

An analysis of variance (ANOVA) was applied to these values in Table 4. Wood species provided the highest contribution to elastic modulus values, with 84.1%. When the factors affecting the elastic modulus were analyzed at the $P < 0.05$ confidence interval level, wood type was found to be the independent variable with the highest effect on the elastic modulus resistance with 84.1%. In contrast, it was determined that other factors, except wood, were insignificant. The contribution of process type was 12.9%, and the lowest contribution was made by climate type with 1.3%. From this, it is understood that the climate type factor has the most negligible impact on the elastic modulus.

Table 4. Elastic Modulus Variance Analysis

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Wooden	2	23 041 825	84.06%	23 041 825	11 520 912	49.44	0.020
Treatment	2	3 543 402	12.93%	3 543 402	1 771 701	7.60	0.116
Climate	2	359 993	1.31%	359 993	179 996	0.77	0.564
Error	2	466 039	1.70%	466 039	233 020		
Total	8	27 411 259	100.00%				

In Fig. 5, the effect of S/N ratios on the factors was calculated. The highest elastic modulus values were detected in oak wood. The highest values in the processing factor were obtained in control samples without heat treatment. In terms of climate, the highest values were found in the test samples conditioned at 10 °C/50%.

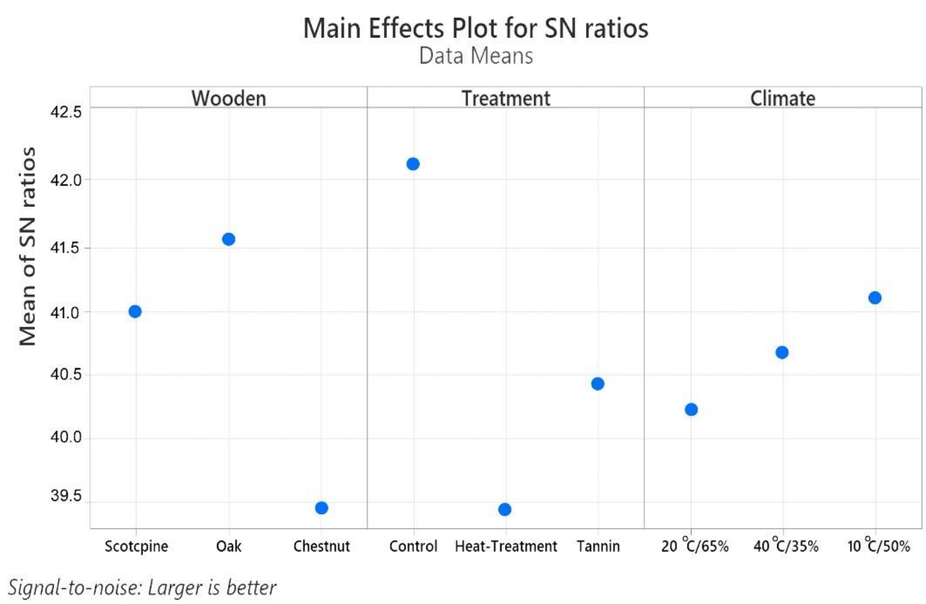

Fig. 5. Taguchi analysis modulus of elasticity *versus* wooden, treatment, and climate

Both bending strength and modulus of elasticity (MOE) values decreased in heat-treated samples compared to pine (Herrera *et al*. 2021), oak (Kubovský *et al*. 2020), and chestnut (Gunes and Altunok 2022) wood control samples. A more significant decrease in the elastic modulus was observed as the temperature and processing time increased (Hasanagic *et al*. 2023). It was determined that the elastic modulus values of sessile oak wood were higher than Scots pine and chestnut wood (Todorović *et al*. 2022). Elastic modulus values of wood exposed to artificial air conditioning conditions varied depending on the amount of moisture it contained. (Stadlmann *et al*. 2020). In line with previous studies, the elastic modulus values of oak wood were higher than those of Scots pine and chestnut wood among wood types and were parallel to the literature. The MOE values of treated wood decreased compared to control samples. There was a slight increase in tannin-impregnated samples compared to treated samples.

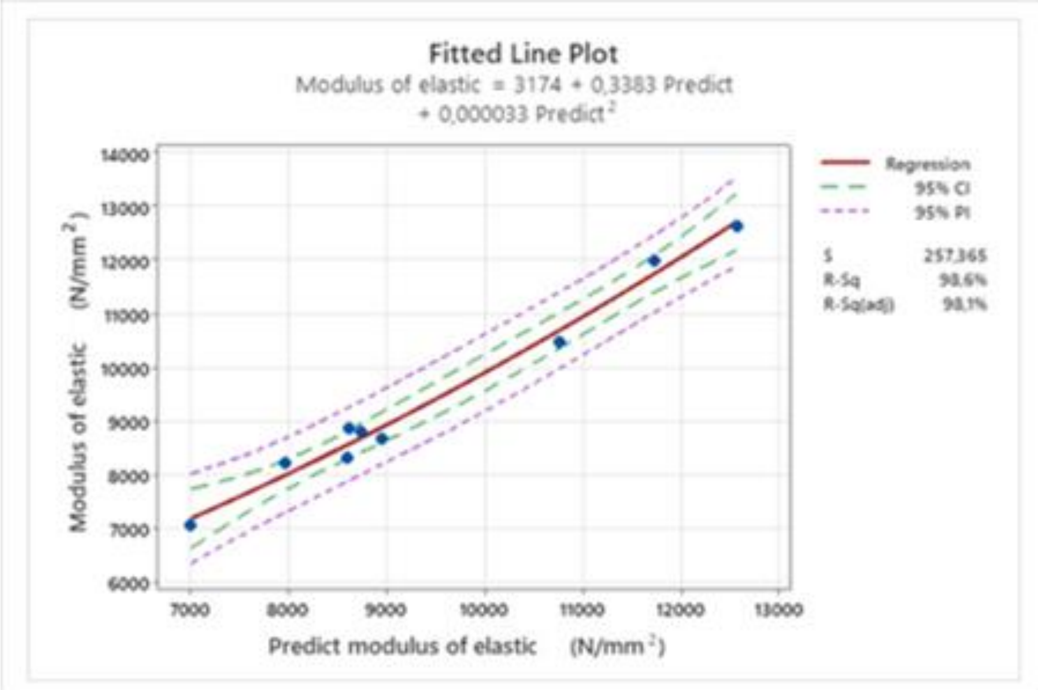

Fig. 6. Polynomial regression analysis: modulus of elastic *versus* predicted value

The mathematical model of the elastic modulus is shown in Fig. 6. When the estimated values limit, confidence interval and regression curve were examined, the estimated values (Modulus of elasticity = 3174 + 0.3383 Predict + 0.000033 Predict^2) were predicted with a high accuracy of 98.6% by the specified mathematical model.

CONCLUSIONS

This study investigated the effects of heat treated with tannin impregnation and artificially conditioned trees on the elastic modulus values in bending. An experimental design was made on the elastic modulus values with the Taguchi L9(3^3) octagonal matrix, and a mathematical prediction model was created by optimizing the values.

1. According to the S/N ratio and ANOVA analysis, it was determined that the independent variable that most affects the elastic modulus in bending was the tree type. The climate parameter had the lowest impact. Elastic modulus values of unheat-treated wooden beams were higher than heat-treated and tannin-impregnated samples.
2. It has been understood that the Taguchi design method is the appropriate analysis method to determine the elastic modulus of wooden materials by performing several experiments. It can be said that this methodology provides an accurate and effective method when determining the effective parameters in the mechanical properties of wood.
3. Using the created mathematical model, and R^2 value of 98.6% was reached, indicating high accuracy in estimating the factors affecting the elastic modulus. In

this way, both test costs and time can be saved by reducing the number of experiments and the number of experiment repetitions.

4. This study will contribute to the woodworking industry in selecting the parameters that most affect the elastic modulus and improving the mechanical properties of wood. The effects of tannin and similar impregnation substances applied to wood material on the modulus of elasticity can be determined by reducing the number of tests.

The response surface method can be applied in future studies by changing the number of dependent variables and factors. A mathematical model can obtain the desired dependent variable values by optimizing the factors.

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