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Effects of thermomechanical treatment on selected properties of *Acacia* hybrid wood

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ABSTRACT: Wood densification is a process combining heat, moisture, and mechanical action to improve the density of wood without changing the characteristics of wood, including density, water repellency effectiveness (WRE), modulus of rupture (MOR) and compressive strength (CS). This study aims to identify and evaluate the effect of the compression parameter on some physical and mechanical properties of *Acacia* hybrid wood. Design Expert 11.0.8 software was used to design experiments, and the experimental data was processed using SPSS Statistics 22.0. The obtained results indicate that the higher the compression ratio is, the higher the increased density of the compressed wood will be achieved. As the temperature and compression time increase, the density increases. However, the density of compressed wood will decrease slightly when the temperature and the time exceed 180°C and 180 minutes, respectively. *After treatment, Acacia hybrid wood has good WRE values of* 15.12 % to 31.21%. MOR and CS increased with the growing ratio, temperature and time of compression but tended to fall when the temperature and time surpassed 160°C and 120 minutes.
Keywords: thermomechanical compressed wood; *Acacia* hybrid wood; compression ratio; density; water repellency effectiveness.

Efeitos do tratamento termomecânico em propriedades da madeira de um híbrido de *Acacia*

RESUMO: A densificação da madeira é um processo que combina calor, umidade e ação mecânica para melhorar a densidade da madeira sem alterar suas características, incluindo densidade, eficácia de repelência à água (WRE), módulo de ruptura (MOR) e resistência à compressão (CS). Este estudo tem como objetivo identificar e avaliar o efeito do parâmetro de compressão em algumas propriedades físicas e mecânicas da madeira híbrida de acácia. O software Design Expert 11.0.8 foi usado para projetar experimentos, e os dados experimentais foram processados usando o SPSS Statistics 22.0. Os resultados obtidos indicam que quanto maior a taxa de compressão, maior será o aumento da densidade da madeira comprimida. À medida que a temperatura e o tempo de compressão aumentam, a densidade aumenta. No entanto, a densidade da madeira comprimida diminuirá ligeiramente quando a temperatura e o tempo excederem 180 °C e 180 minutos, respectivamente. A madeira híbrida de acácia, após o tratamento, apresenta boa WRE com valores de 15,12% a 31,21%. MOR e CS aumentaram com a taxa de crescimento, temperatura e tempo de compressão, mas tenderam a cair quando a temperatura e o tempo ultrapassaram 160°C e 120 minutos.
Palavras-chave: madeira comprimida termomecânica; madeira híbrida de acácia; taxa de compressão; densidade; eficácia de repelência à água.

1. INTRODUCTION

The mechanical properties of wood depend on its density (Telewski. 2016), so many studies have been conducted on the mechanical stability of fast-growing wood species with low density by pressing or compressing wood polymerization (BOONSTRA; BLOMBERG, 2007; KUTNAR; SERNEK, 2007). This solution is geared towards increasing the density of the wood. However, unlike mechanical compression, chemical impregnation affects the natural properties of the wood, affecting the lips and higher handling costs (NAVI; HEGER, 2004).

Thermal compression of wood is a common method used in industry, and pressed wood products may not need cooling in the press. The amount of compressed wood depends not only on the pressing parameters (humidity and temperature of the wood during pressing, pressing time, pressing pressure or compression level) but also on the wood species. Compression pressure relies on wood type, moisture, temperature, and compression ratio (STAMM, 1964; SANDBERG, 2007).

Compression temperature and ratio are the two important parameters that greatly affect the physical and mechanical properties of the wood. The determination of the temperature value must be based on two criteria: The

pressing temperature must be higher than the melting temperature of the lignin at the condition where the saturation humidity is 110 °C and 140 °C at the relative humidity of 80%; to limit the reduction of the mechanical strength of the wood (NAVI; SANDBERG, 2011).

The pressing temperature should not exceed 200 °C (SALMÉN, 1982; JIANG et al., 2009). Candan et al. (2013) studied the effect of the pressing temperature and pressure on wood properties. The author experimented with Populus (*Populus spp.*). With a thickness of 40 mm, wood samples are softened and pressed in a heat press with two temperature values of 150 °C and 170°C and two pressure levels of 1.0 MPa and 2.0 MPa in a pressing time of 45 minutes. The research results showed that the volumetric volume and static hardness of the wood increase with the growth of the pressing pressure. The pressing temperature and pressure unclearly influence the thickness expansion (TS) of compressed wood. Darwis et al. (2017) studied the effect of heat treatment time after compression on the returning elasticity of two wood species: Agathis (*Agathis loranthifolia Salisb*) and Gmelina (*Gmelina arborea Roxb*). Before pressing, the wood samples were soaked in water to achieve saturated humidity. Then, they were compressed on a hydraulic press with a pressing temperature of 100°C, with three compression ratios of 12.5%, 25% and 37.5%. After that, the pressed samples were dried at 103 ± 2 °C for 24 hours. Next, they were heat-treated in an oven at a temperature of 180°C, with time levels of 5, 10, 15 and 20 hours. The author concluded that the back elasticity of compressed wood is greatly reduced when post-pressed at 180°C. The longer the processing time, the less the wood's elasticity. The back elasticity of the wood grows with the increase of the compression ratio from 12.5% to 37.5%.

Acacia hybrid is a commonly planted forest tree abundantly available in Asia, with a reserve of about 500 thousand hectares (TRAN; TRAN, 2019). *Acacia* hybrid wood has many disadvantages, such as low density, low mechanical strength, and high water absorption. In addition, this type of wood is widely used in forestry production, contributing to supplementing or replacing the increasing demand for diminishing rare wood (VADIVEL, 2021). However, the literature review shows limited studies on the density, water-repellency effectiveness, static bending strength, and compressive strength of compressed Acacia hybrid wood. Hence, the main objective of the work is to find out the influence of heat-mechanical treatment parameters on some basic properties of *Acacia* hybrid wood, thereby serving as a basis for building a production process for *Acacia* hybrid wood flooring.

2. MATERIAL AND METHODS

2.1. Material

The wood species is a seven-year-old *Acacia* hybrid. The sampling site is at 20° 23' 8" N, 105° 36' 46" E, Hoa Binh province, Vietnam. The wood samples were prepared for experiments shown in Figure 1. This hybrid species from two purebred lines, *Acacia mangium* and *Acacia auriculiformis*, was identified in Vietnam as AH1. When grown, the AH1 acacia tree will have a long, balanced trunk of 25 - 30m high and a trunk diameter of 60 - 80cm with thick, long and dense foliage. The tree trunk is white-yellow and has wood grain and many small branches.

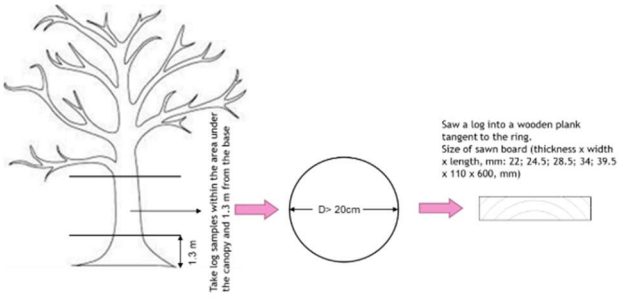


Figure 1. Preparation of wood samples of the *Acacia* hybrid.
Figura 1. Preparação das amostras de madeira de um híbrido de *Acácia*.

The equipment BYD113 heat pressing machine was used, with the largest pressing temperature of 300oC heated by electricity, maximum oil pressure of 24000 kg, and a press table size of 80 x 80 cm. The mechanical testing machine was designated Qtest/25. It used a TX4202L electronic scale (accuracy 0.01 g), a Mitutoyo 500-181-30 digital caliper (accuracy 0.02 mm), and a Mitutoyo ID-H0560 digimatic indicator (accuracy 0.0025 mm).

Tangent-sawn timber was chosen with no rotting, cracking, or heartwood. The samples were dried to reach the moisture 20 ± 2%, and they were cut and smoothly planed to the size (thickness × width × length, mm): 22; 24.5; 28.5; 34; 39.5 × 110 × 600, mm. The number of planks for an experiment is five panels. The wood samples were pressed to a thickness size (t) of 17 mm.

2.2. Method

2.2.1. Thermo-mechanical treatment process

Wood softening treatment was processed directly on a BYD113 press machine at 150 °C, 0.68 minutes/mm in thickness, and 0.5 MPa pressure. Preliminary compression and moisture discharge were conducted at 2.0 Mpa for 0.25 minutes/mm thick. The temperature at the heart of the wood reached 70-80 °C, and moisture discharge was done three times. Wood samples were compressed with different parameters, as shown in Table 1.

Table 1. Summary of the investigated parameters and their levels.
Tabela 1. Resumo dos parâmetros investigados e seus níveis.

Sample	Compression ratio (%)	Temperature (°C)	Time (minutes)
K1	40	160	120
K2	40	160	120
K3	30	140	180
K4	30	180	60
K5	40	160	120
K6	40	126	120
K7	50	140	180
K8	40	194	120
K9	50	180	180
K10	40	160	120
K11	40	160	19
K12	57	160	120
K13	23	160	120
K14	30	180	180
K15	40	160	120
K16	50	180	60
K17	50	140	60
K18	30	140	60
K19	40	160	120
K20	40	160	221

The basis for choosing the parameters in Table 1 is explained as follows: The built model is based on the experimental planning method with the dependence on density (γ), resistance to water absorption (WRE), static flexural strength (MOR), longitudinal compressive strength (σ_c). The levels of compression ratio (A), treatment temperature (B) and processing time (C) are given in Table 1. Design-Expert 11.0 software was used to calculate the reliability of the data, analyze ANOVA, and obtain the regression equations. The responses include Density (Y_1), Resistance to water absorption (Y_2), Static flexural strength (Y_3), and Longitudinal compressive strength (Y_4). The number of experiments performed was $N= 2^k +2k + 6$ (N= 20 with k= 3) (Table 1) (WITEK-KROWIAK et al., 2014).

Heat treatment after compression: The compressed wood was kept in the press, and the pressure was reduced to 1.2 Mpa in 120 minutes at 100 °C. The test samples, after compression, were kept in a laboratory room with a temperature of 20 ± 2 °C and humidity of 65 ± 2% for seven days. The samples were cut following the standards to check their physical and mechanical properties.

2.2.2. Density of compressed wood

The samples were tested according to National Standard TCVN 8048-2: 2009 (ISO 3131:1975). The sample size (radial x tangent x vertical grain, mm) is t × 20 × 25 mm. The sample capacity is 15 samples/mode. Testing tools include an electronic scale with an accuracy of ± 0.01 g, a caliper with an accuracy of 0.01mm, and a sample drying oven with a maximum temperature of 300 °C and an accuracy of ± 0.1 °C.

Test procedure: Samples were placed in the drying oven, and the temperature was gradually increased to 100 ± 5°C for complete dryness. To determine the completely dry state, the sample was weighted to check. If the mass between 2 consecutive weighings after 2 hours is not more than 0.01 g, the drying process is stopped, and the sample is dry. The dry sample is put into a desiccator to cool and then weighted m_0, g. Then, the caliper was used to measure the 3-dimensional dimension of the sample, from which the volume V_0, g cm^{-3} is calculated. The formula for the specific density of dry wood:

$$\gamma = \frac{m_0}{v_0} \ (\mathrm{g\ cm^{-3}}) \qquad (01)$$

where: γ is the specific density of dry wood (g/cm^3), m_o is the weight of dry wood (g), and V_0 is the volume of dry wood (cm^3).

2.2.3. Water repellency effectiveness (WRE)

The sample size (radial x tangent x vertical grain, mm) is t × 20 × 25 mm. The sample capacity is 15 samples/mode. Testing tools include an electronic scale with an accuracy of ± 0.01 g, a caliper with an accuracy of 0.01mm, and a sample drying oven with a maximum temperature of 300 °C and an accuracy of ± 0.1°C (ASTM D4466, 2008).

Samples were soaked in water for 24 hours, and their weight was measured. Next, they were dried completely and weighed. The process of soaking and drying takes place seven times. The water absorption value determined for the last immersion time was 30 days. The formula to determine the water repellency effectiveness (WRE) is given below:

$$\mathrm{WRE} = \frac{T_1 - T_2}{T_1} \times 100, \ (\%) \qquad (02)$$

where: WRE is the water repellency effectiveness (%), T_1 is the amount of water absorbed by the control sample, and T_2 is the amount of water absorbed by the treated sample. The formula calculates the percentage of absorbed water T:

$$T = \frac{m_s - m_0}{m_0} \times 100, (\%) \qquad (03)$$

where: T is the percentage of absorbed water (%), m_s is the sample weight after immersion (g), and m_o is the dry weight of the sample (g).

2.2.4. Modulus of rupture (MOR)

The samples were tested according to National Standard TCVN 8048-3: 2009 (ISO 3133:1975). Sample size (radial x tangent x vertical grain, mm) is t × 20 × 300 mm. Sample capacity is 15 samples/mode. Testing tools include the calipers with an accuracy of 0.01mm and the mechanical testing machine with the designation of Qtest/25. The formula to determine the modulus of rupture (MOR) is given as below:

$$\mathrm{MOR} = \frac{3 \times P_{max} \times l}{2 \times b \times h^2}, \ (\mathrm{MPa}) \qquad (04)$$

where: *MOR* is the modulus of rupture (MPa), P_{max} is the maximum load force (N), *l* is the distance between 2 supports (mm), *b* is the vertical dimension (mm), and *h* is the tangent dimension (mm).

2.2.5 Longitudinal compressive strength

The samples were tested according to National Standard TCVN 8048-5: 2009 (ISO 3132:1975). Sample size (radial x tangent x vertical grain, mm) is 20 × 20 × 30 mm. Sample capacity is 15 samples/mode. Testing tools include the calipers with an accuracy of 0.01mm and the mechanical testing machine with the designation of Qtest/25. The formula to determine longitudinal compressive strength is given below:

$$\sigma_C = \frac{P_{max}}{b \times t}, \ (\mathrm{MPa}) \qquad (05)$$

where: σ_C is longitudinal compressive strength (MPa), P_{max} is the maximum load force (N), b is the vertical dimension (mm), t is the tangent dimension (mm).

3. RESULTS

Design-Expert 11.0 software was applied to build the experiment design and analyze experimental results. The summary of experimental results is presented in Table 2.

3.1. Effect of treatment parameters on the density of compressed wood

The coefficient of determination R^2 shown in Table 3 evaluates the degree of agreement of the experimental model with the measured experimental data. This proves that the experimental model is very consistent with the experimental results. The correlation function is shown in Equation 6. Figure 2 shows surface plots of the effects of treatment parameters on the density of compressed wood.

Table 2 shows that the density of wood increases in direct proportion to the compression ratio; the highest density result of 1.09 g cm^{-3} was reported at the sample K12 with a compression ratio of 57%, a temperature of 160 °C, and a time of 120 minutes. In contrast, sample K13 has a

compression ratio of 23%, a temperature of 160 °C, and a time of 120 minutes, resulting in the lowest density of 0.73 g cm^{-3}. The remaining samples all increased from 0.8 to 1.0 g cm^{-3}. From Figure 2 and Equation 6, the compression ratio has the strongest influence on the density and has a proportional relationship with the density. From Table 4, temperature and time have small effects on density. The coefficient of variation reached 1.20%, and the coefficient of determination reached 0.9930, thus showing a very high degree of agreement. The correlation between the treatment parameters and the density is tight, as shown in Equation 6.

Table 2. Summary of the investigated parameters and their levels.
Tabela 2. Resumo dos parâmetros investigados e seus níveis.

Sample	γ (g/cm³)	WRE (%)	MOR (Mpa)	CS (Mpa)
K1	0.91	45.51	117.27	61.17
K2	0.91	45.86	117.28	61.24
K3	0.81	38.05	85.72	48.03
K4	0.81	38.90	85.61	48.15
K5	0.90	45.20	116.75	61.03
K6	0.87	49.76	90.41	52.86
K7	1.01	41.38	116.83	61.36
K8	0.95	35.19	87.32	51.04
K9	1.05	37.89	102.3	58.69
K10	0.91	45.24	117.19	61.65
K11	0.86	49.99	90.10	52.64
K12	1.09	47.41	121.87	65.90
K13	0.73	40.03	90.81	53.22
K14	0.83	31.80	80.02	43.19
K15	0.91	44.95	117.23	61.12
K16	1.01	42.22	98.55	56.99
K17	1.00	44.47	102.89	58.40
K18	0.76	43.04	87.08	51.26
K19	0.90	46.10	117.21	60.87
K20	0.93	31.84	91.05	52.19

Table 3. Fit Statistics.

Parameter	Value	Parameter	Value
Std. Dev.	0.0109	R^2	0.9930
Mean	0.9075	Adjusted R^2	0.9866
C.V. %	1.20	Predicted R^2	0.9469
		Adeq Precision	470.196

$$Y_\gamma = 0.365 + 0.013A - 0.000434B + 0.00058C - 0.0002AB - 5.139AC + 6.250BC + 0.000024A^2 + 5.790B^2 - 7.791C^2 \quad (06)$$

3.2. Effects of treatment parameters on WRE

Table 4 analyzes the influence of the treatment parameters on the WRE capacity through fit statistics. Equation 7 shows the correlation function. Figure 4 shows surface plots of the effects of treatment parameters on WRE.

Table 4. Fit Statistics.
Tabela 4. Estatísticas de ajuste.

Parameter	**Value**	**Parameter**	**Value**
Std. Dev.	1.37	R^2	0.9449
Mean	21.43	Adjusted R^2	0.8953
C.V. %	6.41	Predicted R^2	0.5838
		Adeq Precision	14.1873

$$Y_{WRE} = 87.23 - 0.37A - 0.75B - 0.25C + 0.001AB - 0.00027AC + 0.002BC + 0.0024A^2 + 0.0022B^2 + 0.00017C^2 \quad (07)$$

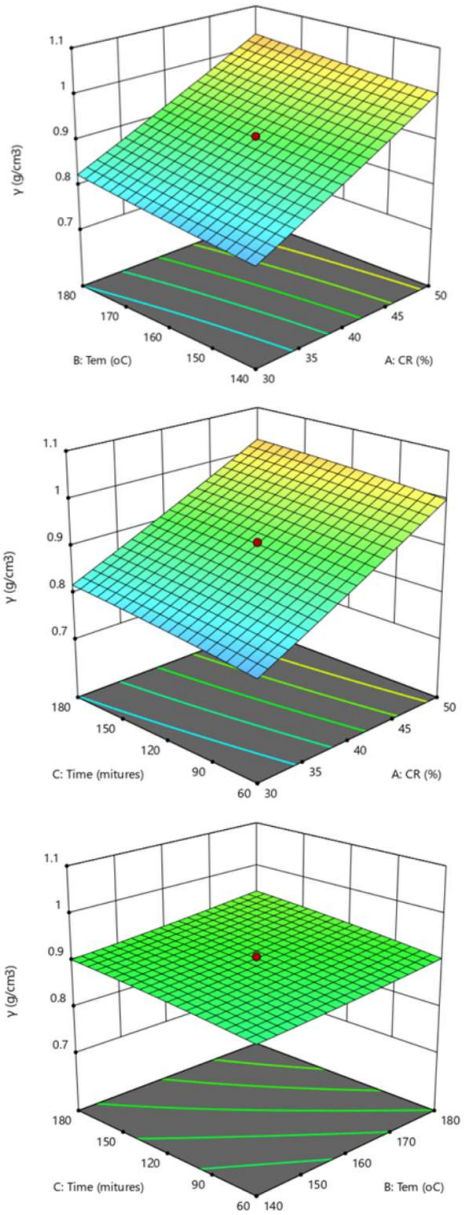
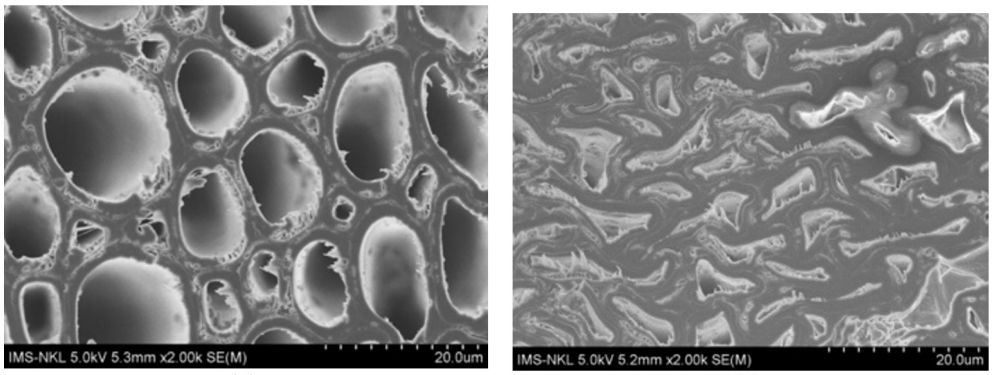


Figure 2. Surface plots of effects of treatment parameters on the density of compressed wood.
Figura 2. Gráficos de superfície dos efeitos dos parâmetros de tratamento na densidade da madeira comprimida.

Table 2 shows that sample number K14 has a temperature of 180 °C, a time of 180 minutes, and a compression ratio of 30% for the best WRE of 31.21%. The sample K6 has a temperature of 126 °C, a time of 120 minutes, and a compression ratio of 40%, resulting in the worst resistance to WRE of 15.12%. All remaining samples had lower levels than the control samples by 20%. Figure 4 and Equation 7 show that the water absorption capacity of compressed wood will increase with the rise in temperature and time but decrease slightly with the growth of the compression ratio. Temperature and time have greater influences than compression ratio. In Table 4, the R^2 value of over 0.94 shows that the experimental model is consistent with the experimental results. In short, the resistance to water absorption of wood samples treated by thermomechanical methods strongly depends on the time and temperature of compression. In addition, the compression ratio causes an insignificant effect on the resistance to water absorption.



(a) (b)

Figure 3. Comparison of *Acacia* hybrid wood structure with a magnification of 2000 times before and after compression: (a) Uncompressed wood; (b) Compressed wood.
Figura 3. Comparação da estrutura de madeira de um híbrido de *Acacia* com ampliação de 2.000 vezes antes e depois da compressão: (a) Madeira não comprimida; (b) Madeira comprimida.

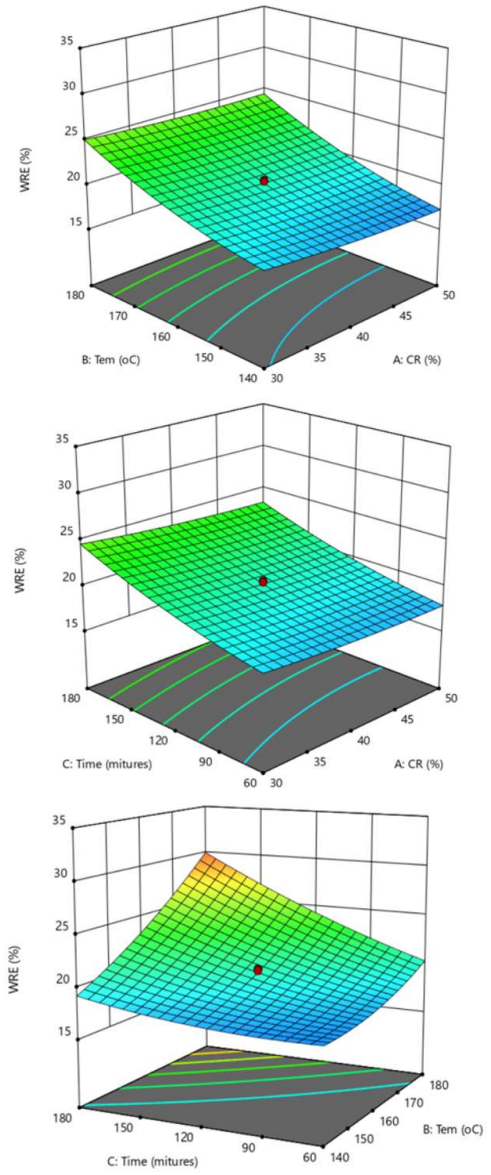


Figure 4. Surface plots of the influences of treatment parameters on WRE.
Figura 4. Gráficos de superfície das influências dos parâmetros de tratamento na WRE.

3.3. Effects of treatment parameters on the static bending strength

The influence of the treatment parameters on the static flexural strength is analyzed through fit statistics in Table 5. The correlation function is shown in Equation 8. Surface plots of the effects of treatment parameters on the static flexural strength are shown in Figure 5.

Table 5. Fit Statistics.
Tabela 5. Estatísticas de ajuste.

Parameter	Value	Parameter	Value
Std. Dev.	1.81	R^2	0.9918
Mean	101.67	Adjusted R^2	0.9843
C.V. %	1.78	Predicted R^2	0.9359
		Adeq Precision	340.088

$$Y_{MOR} = -678.961 + 4.438A + 8.201B + 0.663C - 0.007AB + 0.005AC - 0.002BC - 0.036A^2 - 0.002B^2 - 0.003C^2 \quad (08)$$

Table 2 shows that the best flexural strength of 121.87 Mpa was reported in sample K12. The K1, K2, K5, K10, K15 and 19 yielded flexural strength from about 116 to 117 MPa. The flexural strength of the sample K14 was lowest at 80.02 MPa. From Figure 5, when the compression ratio increases, the bending strength goes up. When the temperature surpasses 160 °C, the bending resistance of wood samples tends to decrease. When the compression time is greater than 120 minutes, the flexural strength of the wood sample reduces. The compression ratio has the strongest influence among the investigated variables, followed by the temperature.

The reasons behind this are the thermal decomposition of cell wall polymers, especially hemicellulose, from long chains to shorter chains when the wood is heat-treated, reducing flexural strength. On the other hand, the static bending strength decreases with the high temperature and long processing time. During the compression, the extracts in the wood are removed, the hemicellulose is decomposed, and the wood becomes hollow and porous. The decrease in density causes the bonds between the cellulose micelles to lose, reducing the static flexural strength. Especially in mode 14, with the temperature of 180 °C and the processing time of 180 minutes, the static bending strength of wood is

decreased drastically (KUTNAR; KAMKE, 2006; NAVI; SANDBERG, 2012).

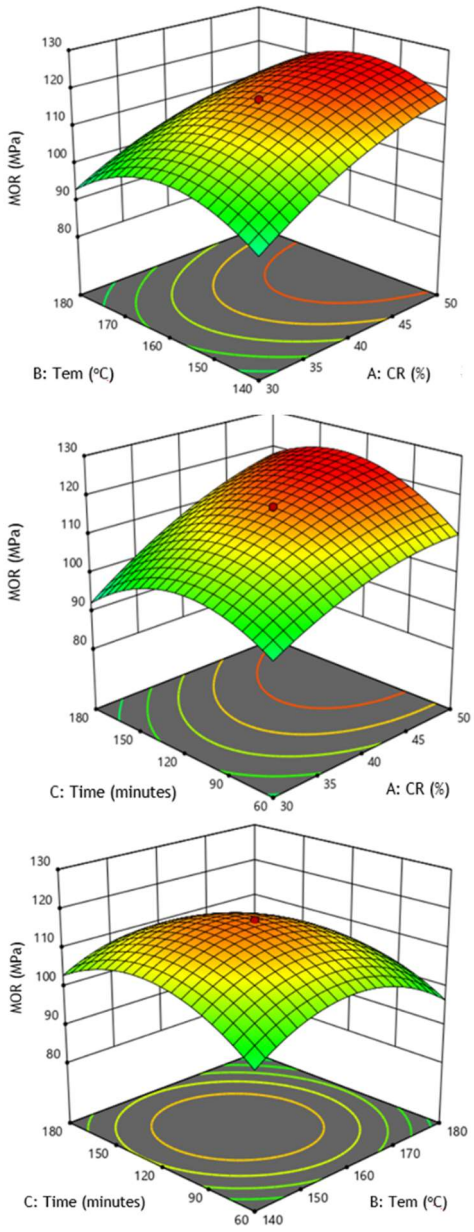


Figure 5. Surface plots of the influences of compression parameters on the static bending strength.
Figura 5. Gráficos de superfície das influências dos parâmetros de compressão na resistência à flexão estática.

3.4. Effects of treatment parameters on the compressive strength.

Table 6 analyzes the influences of the treatment parameters on the compressive strength through fit statistics. Equation 9 shows the correlation function. Figure 6 shows surface plots of the effects of treatment parameters on the compressive strength.

Table 6. Fit Statistics.
Tabela 6. Estatísticas de ajuste.

Parameter	Value	Parameter	Value
Std. Dev.	1.34	R^2	0.9736
Mean	56.05	Adjusted R^2	0.9499
C.V. %	2.39	Predicted R^2	0.8029
		Adeq	234.354

$$Y\sigma_C = -174.246 + 0.400A + 2.663B + 0.158C + 0.002AB + 0.003AC - 0.0003BC - 0.008A^2 - 0.009B^2 - 0.001C^2 \quad (09)$$

Table 2 shows that the best longitudinal compressive strength of 65.90 Mpa was recorded in sample K12. The samples K1, K2, K5, K10, K15, and K19 have compressive strength ranging from 60 to 61 MPa. The sample K14 has the lowest longitudinal compressive strength of 43.19 MPa. From Figure 6, when the temperature rises too high (over 160°C), the compressive capacity of wood samples experiences a downward trend. For the too-long compression time (over 120 minutes), the compressive strength of the wood sample falls. The compression ratio causes the strongest effect among the investigated variables, followed by the compression temperature and time.

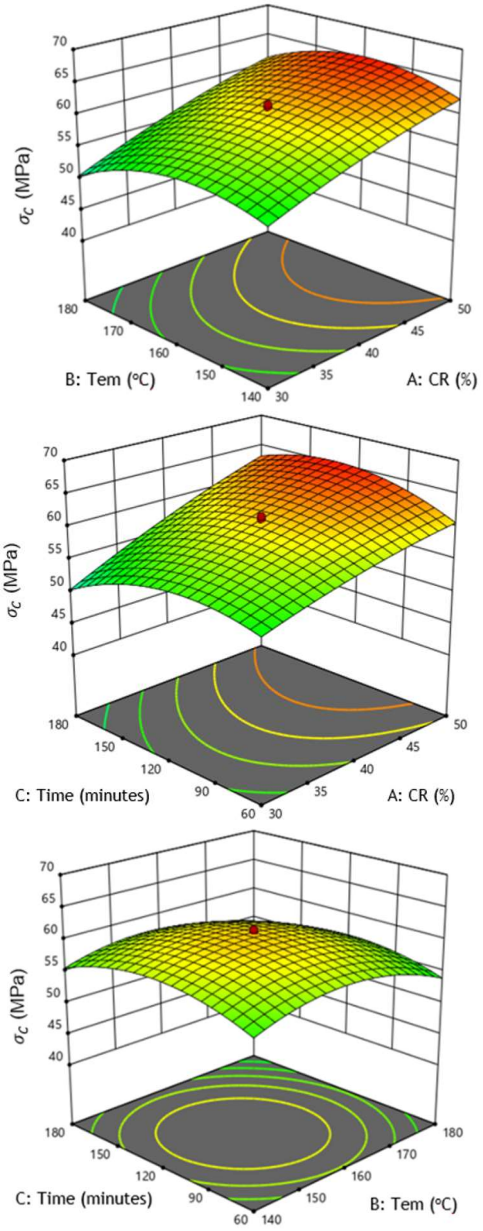


Figure 6. Surface plots of the influences of the compression parameters on the compressive strength.
Figura 6. Gráficos superficiais das influências dos parâmetros de compressão na resistência à compressão.

4. DISCUSSION

During the compression process, the lignocellulose structure changes due to the simultaneous action of temperature and humidity. The carboxyl groups in hemicellulose are destroyed, or part of the hemicellulose has been hydrolyzed or removed. Ester bonds of carboxylic groups from lignin and hemicellulose are formed. Temperature and humidity have markedly influenced the transition from an elastic-to-elastic state of wood, and under the effect of compressive pressure, it will reduce the porosity in wood. New physical and chemical bonds are formed during compression and when the compressed wood is cooled. The strength and hardness of the wood increase in proportion to the rise in the wood density (RAUTKARI et al., 2011; ZHOU et al., 2019). Observations on SEM images of uncompressed and compressed wood samples in Figure 3 support this result.

The ability of wood to absorb water depends on its structure and components. Wood may have some extracts removed, or the hemicellulose in the wood is decomposed under the effect of high-temperature long processing time, leading to a decrease in the number of hydroxyl groups (-OH) in the wood, which reduces water absorption into wood (ARRUDA et al., 2013).

Similar to the flexural strength mentioned above, the main cause is the thermal degradation of cell wall polymers, especially hemicellulose, from long chains into shorter chains, and the binding force in the wood bundle is separated when the wood samples are thermo-treated, resulting in the reduction of compressive strength. On the other hand, with the high temperature and long processing time, the vertical compressive strength is lower. During the compression process, the extracts in the wood are removed, and the lignin and hemicellulose are decomposed. The reduced density makes the wood hollow and porous, causing the bonds between the micelles to lose and reducing the static flexural strength. Especially in mode 14, with the temperature of 180 °C and the treatment time of 180 minutes, the compressive strength of wood is decreased significantly (KUTNAR; KAMKE, 2006; NAVI; SANDBERG, 2012).

5. CONCLUSIONS

This paper investigated and analyzed the influences of wood compression parameters by thermos-mechanical method on some properties of Acacia hybrid wood. The results are summarized as follows:

The higher the compression ratio, the higher the increased density of the compressed wood. The density of timber ranges from 0.76 g cm^{-3} to 1.09 g cm^{-3}. Also, the wood density rises with the increase of compression temperature and compression time. However, it will decrease slightly when the compression temperature exceeds 180^{o}C and the compression time exceeds 180 minutes. After treatment, *Acacia* wood has good water repellency effectiveness (WRE), ranging from 15.12% to 31.21%. Moreover, WRE depends mainly on the temperature and time of compression.

The flexural strength and the longitudinal compressive strength increase with the growth of the compression ratio. For the compression temperature and compression time over 160 °C and 120 minutes, downward trends were observed in the flexural strength and longitudinal compressive strength. The flexural strength values reached 80.02 ÷ 121.87 MPa, and the compressive strength ranged from 43.19 to 65.90 MPa.

In further studies, more investigations should focus on optimizing the ratio, temperature, and compression time to find the optimal set of parameters.

6. REFERENCES

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