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# EFFECT OF THE TEMPERATURE AND PRESSURE ON PROPERTIES OF DENSIFIED MEDIUM DENSITY FIBERBOARDS

Mariana Neves Ferreira Ribeiro, Cláudio Henrique Soares Del Menezzi
University of Brasília
Faculty of Technology
Department of Forest Engineering
70910-900, Brasília Df
Brazil

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## ABSTRACT

The objective of this work was to evaluate the physical and mechanical properties of thermally compressed MDF (medium density fiberboard). For this purpose, MDF boards were subjected a combination of two temperatures (150˚C and 170˚C) and two pressures (25% and 50% of the perpendicular compression strength). After the treatment the following properties were assessed: bending strength and stiffness, compressive parallel strength, surface hardness, thickness swelling and water absorption after 2, 24 and 72 hours of immersion in water. It was found that in general, the results did not show any significant improvements regarding physical properties. However, mechanical properties were positively affected by treatments and densified boards had higher values than untreated boards, reaching a fourfold value in the case of the surface hardness. Regarding physical properties, there were no improvements compared to the untreated board for the thickness swelling, despite all treatments have showed lower water absorption. In general, temperature was the most important factor for physical properties and the pressure was the most important factor for mechanical properties.

KEYWORDS: Thermo-mechanical process, densification, non-destructive evaluation, properties improvement, dimensional instability, commercial product.

## INTRODUCTION

Medium density fiberboard (MDF) is one of the fastest growing reconstituted wood board product on the market. This material has excellent workability and good surface finish and is more homogeneous material when compared to solid wood. This board is produced in a dry-

process with synthetic resin adhesives, which are cured under heat and pressure. Its density ranges from 500 kg·m$^{-3}$ to 1000 kg·m$^{-3}$, according to ANSI A208.2 (2002).

In general, MDF boards show good dimensional stability. However, when in relatively high humidity environments, this material tends to vary its dimensions. Resulting from this fact, MDF boards are not indicated for several applications, such as kitchen and bathroom furniture (Garcia et al. 2006).

Several researches have been done to change the hygroscopic characteristics and to improve the dimensional stability of MDF by means of thermal treatments (Oliveira et al. 2017, Ates et al. 2017, Wandscheer et al. 2016, Lunguleasa and Spîrchez 2015). However, the main drawback is the side effect of decreasing of the mechanical properties. It can be overcome by using thermo-mechanical treatment which combines high temperatures along with pressure, providing the thermal degradation of hydrophilic components and increasing the density of the material. The gain in density can provide mechanical properties improvement, while the thermal degradation is responsible for the reduction of the hydrophilic characteristics of wood and its derivatives (Del Menezzi et al. 2009). This approach has been extensively tested on wood, but not often on wood-based boards. Costa and Del Menezzi (2017) evaluated the effect of the densification process on properties of commercial plywoods from paricá (*Schizolobium amazonicum*). They found that the densification process improved significantly the bending strength (+51%) of the densified plywood, while the bending stiffness and the glue-line shear strength remained unaffected. Santos and Del Menezzi (2018) evaluated properties of oriented strand boards subjected to densification and they found that all mechanical properties were significantly improved, although dimensional stability remained as an issue. In this context, this work aimed to evaluate the physical and mechanical properties of MDF subjected to thermo-mechanical treatment (densification).

## MATERIALS AND METHODS

### General description

The MDF boards were obtained from a supplier located in Brasília, Distrito Federal, Brazil, with dimensions of 2750 x 1830 x 15 mm (l x w x t). This material was cut into 20 boards with dimensions of 400 x 400 x 15 mm (l x w x t). They were put at air conditioning room (20±3°C; 65±1%) until the constant mass of the samples was obtained. After that, each board was weighted and had its thicknesses measured at four points distanced 20 mm from the edge to calculate the initial density of the board ($\rho_i$). Five samples were to cut to assess the perpendicular compression strength ($f_{c,90}$) to determine the pressure applied in each treatment, those being 25% and 50% of this value.

Subsequently, the stress wave velocity was assessed using the Stress Wave Timer Metriguard 239A and the result obtained were used to calculate the dynamic modulus of elasticity of the material according to Souza et al. (2011). Finally, mechanical and physical tests were performed on the densified boards as well as on the controls, based on ASTM D1037 (1999). Data analysis was obtained using the Dunnett and Tukey averages, paired t-test and factorial variance analysis, all tests considering a level of significance less than or equal to 5%.

### Thermomechanical treatment

The conditioned boards were treated with combination of two temperature levels (150°C and 170°C) and two pressures (25% or 50%) of the value found in the perpendicular compression strength test ($f_{c,90}$). Each combination of temperature-pressure was considered as a group:

T1 (150°C; 25%), T2 (150°C; 50%), T3 (170°C; 25%), T4 (170°C; 50%). Another group was kept untreated as a control (Tab. 1).

*Tab. 1: Temperature and pressure used in each treatment and control.*

| Treatment | Temperature (°C) | Pressure (%) | # Boards |
|---|---|---|---|
| Control | 0 | 0 | 4 |
| T1 | 150 | 25 | 4 |
| T2 | 150 | 50 | 4 |
| T3 | 170 | 25 | 4 |
| T4 | 170 | 50 | 4 |

A hydraulic press (INDUMEC, 1000 kN) with controlled pressure and temperature was used to perform the treatment. During the treatment the internal temperature of the board was measured every 20 seconds by a thermocouple positioned in a hole drilled at half thickness of the board and connected to digital thermometer model TD-890 which collect data. The thermo-mechanical treatments consisted of placing the board in the press until the treatment temperature was reached inside the board. Thereafter, the pressure was held constant for 10 minutes; at each press adjustment the temperature and time were recorded. The pressure was then relieved by 50% for 5 minutes. Finally, the pressure was completely relieved and the treatment continued for further 5 minutes. Further details about the applied thermo-mechanical treatment can be found in Santos and Del Menezzi (2018). After the treatment the boards were again weighted and measured, as mentioned previously, to calculate the final density ($\rho_f$).

The densification rate (TxD, %), compression rate (TxC, %) and mass loss (ML, %) were calculated according to Eqs. 1, 2 and 3.

$$TxD = [(\rho_f / \rho_i) - 1] * 100 \quad (1)$$

$$TxC = [1 - (T_f / T_i)] * 100 \quad (2)$$

$$ML = [(M_i - M_f) / M_i] * 100 \quad (3)$$

where: $\rho_i$ - initial density, $kg \cdot m^{-3}$,
$\rho_f$ - final density, $kg \cdot m^{-3}$,
$T_i$ - initial thickness, mm,
$T_f$ - final thickness, mm,
$M_i$ - initial mass, g,
$M_f$ - final mass, g.

## Material properties

At the end of the treatments the boards were once nondestructively evaluated as previously mentioned and the following properties were assessed: static bending modulus of elasticity ($E_M$) and static bending modulus of rupture ($f_m$), parallel compression strength ($f_{c,0}$), surface Janka hardness ($f_H$), thickness swelling (TS) and water absorption (WA) after 2, 24 and 72 hours of immersion in water. Permanent thickness swelling (PTS) and equilibrium moisture content (EMC) were determined according to Del Menezzi et al. (2009). The control and treated boards were evaluated according to the ASTM D1037 (1999). For each test, 16 samples were obtained for every treatment.

## RESULTS AND DISCUSSION

### Thermo mechanical treatment

The average density of the material before the treatments was approximately 698 $kg \cdot m^{-3}$ and the coefficient of variation was approximately 0.6%. The equilibrium moisture content was approximately 9%, with coefficient of variation of 0.07%. The maximum stress found in the preliminary test of perpendicular compression strength of the board ($f_{c,90°}$) was 8 MPa, thus, the values of 25% and 50% were 2 and 4 MPa, respectively.

The treatments were 36 minutes long (Fig. 1). The highest heating rate was reached for all treatments in the first three minutes, caused by the presence of water in the material. When 100°C (boiling temperature of the water) was reached, the rate of heating reduced considerably.

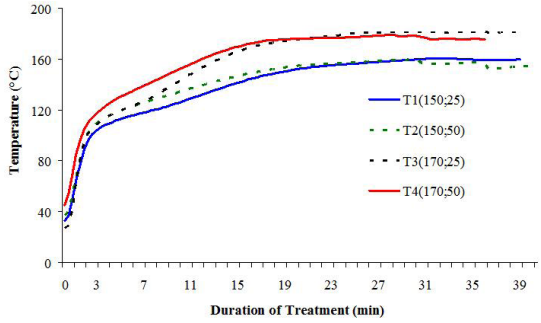


*Fig. 1: Temperature variation inside the boards during the treatments.*

Fig. 1 shows the temperature variation during the treatments. It was observed that the higher temperature treatments (170°C) had a faster increasing of the temperature when compared to the treatments of lower temperature (150°C). It was possible to observe three phases of heating, in accordance to Del Menezzi et al. (2009) findings: the first characterized by the high rate of heating, the second by a lower rate of heating, starting when the material reached a temperature close to 100°C and finally the third stage characterized by the stabilization of the heating rate when the treatment temperature (150°C or 170°C) was reached.

The Tukey's test (Fig. 2) showed that for the densification rate, treatments T1 (150°C; 25%) and T3 (170°C; 25%) did not differ statistically from each other and had the lowest values, 29.95% and 34.03% respectively.

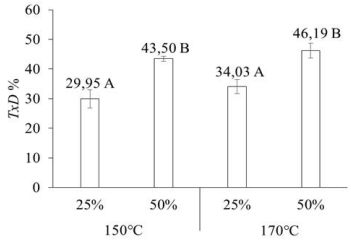


*Fig. 2a: Mean values for densification rate (TxD). Tukey's mean test with significance level of 5%, where different letters represent statistically different values.*

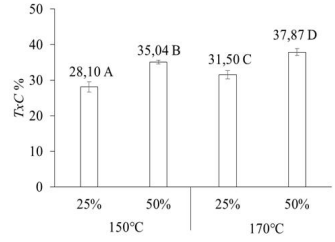


*Fig. 2b: Mean values for compression rate (TxC). Tukey's mean test with significance level of 5%, where different letters represent statistically different values.*

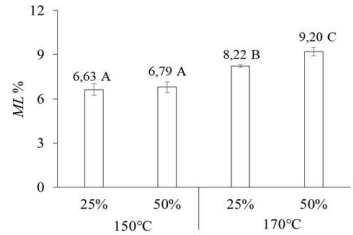


*Fig. 2c: Mean values for mass loss (ML). Tukey's mean test with significance level of 5%, where different letters represent statistically different values.*

The treatments T2 (150°C; 50%) and T4 (170°C; 50%) did not differ statistically from each other, representing the highest values. Tab. 2 shows the influence of temperature and pressure on this property, an increment of both contributed to an increase in densification rate; however, the increase in pressure had the highest value. There was no interaction between the factors.

For the compression rate (Fig. 2b), all treatments differed statistically from one another. T4 (170ºC; 50%) presented the highest TxC (37.87%) and the lowest TxC (28.10%) was obtained by the T1 treatment (150ºC; 25%). There was no interaction between the pressure and temperature factors for this property.

According to Callister (2007), the increase in temperature plays an important role in the softening of amorphous polymers, characterizing the glass transition temperature ($T_g$). In this phase, according to Mano and Mendes (1990), the polymers go from a rigid to a rubbery stage. With the stiffness loss during $T_g$, the pressure acts reducing thickness of the material, being fundamental for the densification.

For the mass loss (Fig. 2c), treatments T1 (150ºC; 25%) and T2 (150ºC; 50%) did not differ statistically from each other. T4 (170ºC; 50%), the treatment with higher pressure and temperature, presented the highest mass loss (9.20%).

*Tab. 2: Densification and compression rate mean values, considering the influence of pressure and temperature.*

| Property (%) | Factor | | | |
|---|---|---|---|---|
| | Temperature (°C) | | Pressure (%) | |
| | 150 | 170 | 25 | 50 |
| TxD | 36.73* | 40.11* | 31.99** | 44.85** |
| | (18.43) | (15.16) | (10.03) | (4.50) |
| TxC | 31.57** | 34.69** | 29.8** | 36.46** |
| | (10.99) | (9.19) | (6.54) | (3.87) |
| ML | 6.71** | 8.71** | 7.42* | 8.00* |
| | (5.51) | (5.85) | (10.65) | (15.00) |

* Significant values at 5% level **, significant values at 1% level *; values in parentheses correspond to the coefficients of variation in %.

The factorial analysis (Tab. 2) showed that increases in pressure and temperature caused an incrementation in mass loss; however, the higher loss was obtained by increasing the temperature. The temperature influence on mass loss can be explained by the thermal degradation of the constituent polymers. According to Schaffer (1973), lignin begins to lose weight at 110°C,

at 120°C the hemicellulose content begins to decrease, alpha cellulose begins to increase and lignin begins to soften. There was no statistically significant interaction for mass loss between the pressure and temperature factors.

Tab. 3 shows the averages and coefficients of variation for the swelling properties in thickness (TS), water absorption (WA), equilibrium moisture content (EMC) and permanent thickness swelling (PTS). The PTS derives from the release of internal compression stresses and expresses the increase in definitive thickness of the material (Del Menezzi et al. 2009).

*Tab. 3: Physical properties of the control and densified MDF boards.*

| Property (%) | Treatment (T°C - P%) | | | | |
|---|---|---|---|---|---|
| | Control | T1 | T2 | T3 | T4 |
| | | 150°C;25% | 150°C;50% | 170°C;25% | 170°C;50% |
| TS 2h | 4.92 | 12.03** | 13.73** | 11.54** | 10.8** |
| | (11.99) | (6.15) | (10.34) | (14.64) | (15.74) |
| TS 24h | 23.43 | 46.42** | 57.09** | 43.54** | 36.36** |
| | (2.39) | (5.36) | (8.77) | (16.03) | (27.42) |
| TS 72h | 37.32 | 72.07** | 88.96** | 63.81** | 49.51** |
| | (2.84) | (4.95) | (7.26) | (19.43) | (28.76) |
| WA 2h | 13.22 | 6.89** | 6.42** | 6.30** | 4.77** |
| | (23.15) | (9.72) | (17.91) | (18.89) | (20.96) |
| WA 24h | 58.96 | 51.73** | 52.64* | 44.81** | 25.67** |
| | (2.85) | (2.30) | (9.90) | (19.44) | (35.53) |
| WA 72h | 81.9 | 90.51$^{NS}$ | 94.05** | 63.37** | 40.89** |
| | (2.69) | (4.71) | (9.47) | (22.31) | (38.86) |
| EMC | 8.88 | 9.07$^{NS}$ | 9.23* | 8.62$^{NS}$ | 7.99** |
| | (1.35) | (1.76) | (2.49) | (4.99) | (5.13) |
| PTS | 11.52 | 57.3** | 79.36** | 36.14** | 17.83$^{NS}$ |
| | (16.93) | (13.73) | (29.14) | (45.02) | (58.83) |

*, ** significant values at α = 0.05 and α = 0.01 respectively and NS represents a non-significant difference in relation to the control, according to the Dunnett test; values in parentheses correspond to the coefficients of variation in %.

Regarding the control, there was no statistically significant difference for WA after 72 h for T1 (150°C; 25%), EMC for T1 (150°C; 25%) and T3 (170°C; 25%) and for PTS for T4 (170°C; 50%). It was observed an increase in TS for all treatments in comparison to the control.

The T2 treatment (150°C; 50%) presented the highest values throughout the test, the highest absolute value of the treatments was observed in 72 h, about 88.96%. The lowest values of the treatments were obtained by T4 (170°C; 50%), the lowest value of the treatments being equal to 10.8% in 2h. For the control, the lowest value was obtained in 2 h (4.92%) and the highest in 72 h (37.32%). According to the ANSI A208.2 (2002) standard the maximum TS after 24 hours should be 10%, a requirement not reached neither control nor densified boards. Garcia et al. (2006) manufactured MDF boards with thermally treated fibers which did not meet ANSI standard as well. The treatments were the combination of two temperatures (150°C and 180°C), three times (15, 30 and 60 min) and the adhesive used was urea-formaldehyde (UF). According to the authors, the reduced size of the samples increased the edge effect, what explain the results.

For WA after 2 and 24 h, a reduction was observed for all treatments in comparison to the control. For WA at 72 h, there was an increase for T2 (150°C; 50%) and reduction for T3 (170°C; 25%) and T4 (170°C; 50%).

Tab. 4 shows the factorial analysis for pressure and temperature factors. There was interaction for TS in all three times, for WA at 24 and 72 h, for EMC and PTS. The increase in temperature of thickness swelling caused a reduction of this property, the same occurred for WA. For EMC, both the increase in pressure and the temperature led to a reduction of this property. For PTS, the increase in temperature caused a reduction of this property and the increase in pressure showed no significant difference. The interaction between temperature and pressure indicates that increasing the temperature and pressure simultaneously is more efficient for improving physical properties, since these both factors affected significantly the physical properties, as can be seen in Tab. 4.

*Tab. 4: Average values of physical properties considering the effect of pressure and temperature of the densification.*

| Property (%) | Factor | | | |
|---|---|---|---|---|
| | Temperature (°C) | | Pressure (%) | |
| | 150 | 170 | 25 | 50 |
| TS 2h | 12.63** | 11.10** | 11.66$^{NS}$ | 11.90$^{NS}$ |
| | (9.50) | (15.31) | (11.75) | (16.39) |
| TS 24h | 50.47** | 39.54** | 44.30$^{NS}$ | 44.45$^{NS}$ |
| | (10.54) | (24.13) | (12.69) | (28.14) |
| TS 72h | 80.34** | 55.85** | 67.48$^{NS}$ | 65.89$^{NS}$ |
| | (10.47) | (27.63) | (16.14) | (34.53) |
| WA 2h | 6.70** | 5.51** | 6.51** | 5.56** |
| | (11.94) | (21.96) | (15.36) | (21.76) |
| WA 24h | 51.89** | 34.76** | 47.45** | 37.22** |
| | (8.00) | (37.83) | (15.95) | (42.29) |
| WA 72h | 92.33** | 52.40** | 76.14** | 63.98** |
| | (7.35) | (36.98) | (23.19) | (46.64) |
| EMC | 9.11** | 8.31** | 8.80* | 8.53* |
| | (2.19) | (6.38) | (4.54) | (8.09) |
| PTS | 67.57** | 26.38** | 45.00$^{NS}$ | 44.19$^{NS}$ |
| | (30.66) | (63.30) | (38.42) | (80.36) |

*, ** significant values at α = 0.05 and α = 0.01 respectively and NS represents a non-significant difference; values in parentheses correspond to the coefficient of variation in%.

All treatments led to higher values of density, stress wave velocity and dynamic modulus of elasticity in comparison to the controls (Tab. 5). T4 (170°C; 50 %) obtained the highest improvement, representing an increase of 44% for density (ρ), 22% for velocity (v) and 115% for dynamic modulus of elasticity (Ed). T1 (150°C; 25 %) obtained the lowest gains, representing an increase of 27% for density, 13% for velocity and 64% for dynamic modulus of elasticity.

*Tab. 5: Density, stress wave velocity and dynamic modulus of elasticity values before and after the densification process.*

| Property | Treatment (°C - %) | | | |
|---|---|---|---|---|
| | T1 150°C;25% | T2 150°C;50% | T3 170°C;25% | T4 170°C;50% |
| ρ before ($kg \cdot m^{-3}$) | 695.36 | 697.97 | 701.50 | 697.62 |
| ρ after ($kg \cdot m^{-3}$) | 887.21** | 970.33** | 913.39** | 1006.69** |
| v before ($m \cdot s^{-1}$) | 2133.11 | 2179.25 | 2139.20 | 2177.92 |
| v after ($m \cdot s^{-1}$) | 2421.05** | 2540.60** | 2457.50** | 2657.11** |
| Ed before (MPa) | 3163.59 | 3315.00 | 3201.88 | 3309.09 |
| Ed after (MPa) | 5200.54** | 6263.33** | 5516.72** | 7109.92** |

** significant values at α = 0.01, according to the t-paired test.

Del Menezzi et al. (2007) performed thermal treatments in OSB, combining two temperatures (190 and 220°C) and three times (12, 16 and 20 minutes). According to the authors, higher temperature and longer treatment led to larger changes in the stress wave properties. According to Han et al. (2006), the existence of voids and discontinuities in composite materials can influence the wave propagation in order to dissipate it and thus increase its propagation time. Therefore, all the treatments were effective in reducing voids and discontinuities in the MDF.

For the mechanical properties, the parallel compression strength ($f_{c,0°}$) of T3 (170°C; 25%) was the only result that did not statistically differ from the control. For all other properties of the densified boards there was an increase in comparison to the controls (Tab. 6).

*Tab. 6: Mechanical properties of the control and densified MDF boards.*

| Property | Treatment (°C - %) | | | | |
|---|---|---|---|---|---|
| | | T1 | T2 | T3 | T4 |
| | Control | 150°C;25% | 150°C;50% | 170°C;25% | 170°C;50% |
| $f_m$ (MPa) | 26.92 | 33.36** | 44.35** | 36.51** | 50.85** |
| | (4.79) | (6.05) | (10.53) | (10.46) | (11.54) |
| EM (MPa) | 3798.98 | 4852.39** | 5840.10** | 5176.35** | 5700.51** |
| | (2.01) | (6.17) | (13.08) | (10.7) | (5.94) |
| $f_H$ (N) | 4518.94 | 11523.29** | 15798.06** | 12265.82** | 17159.77** |
| | (5.22) | (6.48) | (10.16) | (6.37) | (3.33) |
| $f_{c,0°}$ (MPa) | 15.18 | 20.9** | 22.42** | 17.62NS | 18.69** |
| | (9.88) | (18.90) | (13.38) | (15.83) | (12.52) |

*, ** significant values at α = 0.05 and α = 0.01 respectively and NS represents a non-significant difference in comparison to the control, according to the Dunnett test; values in parentheses correspond to the coefficient of variation in %.

The modulus of rupture in static bending ($f_m$) is the most affected property of treated wood with high temperatures (Bekhta and Niemz 2003), which did not occur with the thermo-mechanical treatment performed in the present work, representing a gain of up to 89% T4 (170°C; 50%) in comparison to the control (Tab. 7). Therefore, the treatment performed here is an interesting approach to reduce that undesirable effect of the thermal treatments on the bending strength reduction. For this property, T1 (150°C; 25%) (23.9%) obtained the lowest increase, followed by T3 (170°C; 25%) (35.6%) and by T2 (150°C; 50%) (64.7%).

*Tab. 7: Mean values of mechanical properties considering the effect of pressure and temperature of the densification.*

| Property | Source of variation | | | |
|---|---|---|---|---|
| | Temperature (°C) | | Pressure (%) | |
| | 150 | 170 | 25 | 50 |
| $f_m$ (MPa) | 38.86** | 42.33** | 34.94** | 46.65** |
| | (17.01) | (18.99) | (9.76) | (12.15) |
| $E_M$ (MPa) | 5346.69 NS | 5385.66 NS | 5014.37** | 5752.36** |
| | (14.22) | (9.68) | (9.34) | (10.63) |
| $f_H$ (N) | 13660.67** | 14428.26** | 11894.6** | 16377.1** |
| | (18.27) | (17.60) | (7.07) | (8.56) |
| $f_{c,0}$ (MPa) | 21.66** | 18.1** | 19.25 NS | 20.75 NS |
| | (16.34) | (14.42) | (19.53) | (15.81) |

*, ** significant values at α = 0.05 and α = 0.01 respectively and NS represents a non-significant difference; values in parentheses correspond to the coefficients of variation in %.

For the modulus of elasticity (EM), T2 (150°C; 50%) had the highest increase: 54% compared to the control. T1 (150°C; 25%) (27.7%) obtained the lowest increase, followed by T3 (170°C; 25%) (36.2%) and T4 (170°C; 50%) (50%).

T4 (170°C; 50%) presented the highest increase in Janka hardness ($f_H$), about 280% in comparison to the control. T1 (150°C; 25%) obtained the lowest increase (155%), followed by T3 (170°C; 25%) (171.4%) and T2 (150°C; 50%) (249.6%). It can be inferred from Tab. 6 that the temperature increase did not impart significant differences for the modulus of elasticity ($E_M$), since the increase in pressure increased this property by about 7.6%. There was no correlation to any mechanical properties.

Regarding the modulus of rupture ($f_m$), both increase in pressure and temperature were effective for enhancing this property. The raise in temperature showed an increase of 8.9%, while the pressure an increase of 20%. The increase in temperature was more effective for $f_m$ than for $E_M$, as a result also obtained by Moura et al. (2012). According to the authors, heat treated wood tend to present more brittle ruptures.

For parallel compression ($f_{c,0°}$), the pressure increase was not significant and the increase in pressure reduced this property by about 16.4%. For Janka hardness ($f_H$), the temperature increase showed an improvement of 5.6%, already the pressure an increase of 20%.

## CONCLUSIONS

All thermo-mechanical treatments were efficient in enhancing MDF density, being the highest increase due to the more severe treatment and the lower increase resulting from the least severe, respectively 46% and 30% in comparison to the control. No treatment was effective to reduce thickness swelling in comparison with control boards. However, within the treated boards, it has been observed that T4 (170°C; 50%) was the treatment with lowest values for thickness swelling, water absorption, permanent thickness swelling and moisture content, suggesting that this was the best treatment for controlling the dimensional instability.

For the mechanical properties, T4 (170°C; 50%) presented the highest values for modulus of rupture and Janka hardness, while T2 (150°C; 50%) presented the highest values for modulus of elasticity and parallel compression strength. In general, the increase of the pressure showed to be more effective than the increase of the temperature for mechanical properties improvement.

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Mariana Neves Ferreira Ribeiro, Cláudio Henrique Soares Del Menezzi*
University of Brasília
Faculty of Technology
Department of Forest Engineering
70910-900, Brasília Df
Brazil
*Corresponding author: cmenezzi@unb.br or cmenezzi@gmail.com