FLOORING CHARACTERISTICS OF THERMO-MECHANICAL DENSIFIED WOOD FROM THREE HARDWOOD TROPICAL SPECIES IN COSTA RICA

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ABSTRACT

Densification is one method used to modify low-density woods to make them achieve the hardness required for flooring application. The purpose of this study was to investigate the effect of thermo-mechanical densification with pre-heating in wood of *Alnus acuminata*, *Vochysia ferruginea* and *Vochysia guatemalensis* from, seeking to stabilize and reduce spring-back of the densified wood and evaluate its performance in flooring applications. The results showed that the wood of the three species turned dark. This is because brightness diminished and yellowness and redness increased. Weight loss due to pre-heating was statistically higher in *V. ferruginea* and *V. guatemalensis*. The final density and spring-back were statistically similar in the three species. The percentage of densification of *A. acuminata* and *V. guatemalensis* were statistically higher than for *V. ferruginea* and the degree of compression was statistically higher in *V. guatemalensis*. As for flooring evaluation, the percentage of densification, temperature and time of pre-heating affected the behavior of densified wood flooring. The low percentage of densification and high weight loss in the pre-heating stage caused greater values of wear, wear index, residual deformation, residual indentation for the falling ball indentation test, and more damages in the surface indentation test in wood of *V. ferruginea*.

Keywords: Densification, Flooring properties, low density, spring-back, tropical species, wear index.

INTRODUCTION

Wood as a constructive element is aesthetically pleasing, provides thermal isolation and mechanical resistance (Blanco-Flórez *et al.* 2015). However, compared to other materials used for flooring, wood suffers damage caused by objects, wear from abrasive elements and people traffic, among others (Blanchet *et al.* 2003). The main factor when choosing wood for flooring is its specific gravity (SG) (Zhou *et al.* 2019). There is a high correlation between SG and its mechanical properties; high SG provides enhanced mechanical resistance, therefore improved hardness (Sadatnezhad *et al.* 2017). For this reason, solid wood from high SG species has been widely used for flooring, but the species must be presented adequate ratio of shrinkage (Feifel

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et al. 2015).

In Costa Rica, wood with SG above 0,7 has been used for flooring (United States. Office of Inter-American Affairs 1943). Currently, however, the woods commonly used for flooring are banned, listed as endangered, or threatened (Moya *et al.* 2013). As a result, prices of these woods are high, which promotes the importation of woods or wood-based products to satisfy the demand of this sector (Serrano and Moya 2011). This has led to the search for new options to replace high SG woods with lower SG woods produced in fast-growing forest plantations (Nölte *et al.* 2018). *A. acuminate* (SG=0,34), *V. ferruginea* (SG=0,37) and *V. guatemalensis* (SG=0,32) are among the forest plantations species used in Costa Rica, the three of them are fast-growing hardwood species (Moya 2018) with low SG woods, considered in the market as easy-to-work softwoods (Tenorio *et al.* 2016). Because of their low SG, the mechanical properties of these woods are also low, therefore not convenient for structural uses, but for products with low structural demand in low commercial value markets (Serrano and Moya 2011).

On the other hand, the densification process makes it possible for low or moderate SG woods to replace high density species by modifying them to meet the hardness requirements necessary for some uses, such as flooring (Fang *et al.* 2012). There are several densification processes, generally consisting of the following stages: (i) soften the structure of the wood by using temperatures between 150 °C- 200 °C and convenient moisture contents; (ii) compress the wood by means of two metal plates and (iii) stabilize and keep the deformation obtained in the wood (Sandberg *et al.* 2013).

Thermo-mechanical densification is the simplest densification method. It reduces the empty spaces of the wood cells, called the lumen, through the joint action of heat and radial compression (Navi and Heger 2004). Thermomechanical densification gives some enhanced mechanical properties to the compressed wood, but the compression set is unstable, and wood tends to recover its original shape even after large deformation, especially under conditions of high humidity and high temperature (Navi and Heger 2004, Sadatnezhad *et al.* 2017). This phenomenon is known as spring-back.

The permanent fixation of large deformation as a result of compression is very important for densified wood to be utilized as an engineering material (Inoue *et al.* 2008), especially for flooring applications. Many studies have been conducted regarding stabilization of compressed wood, with techniques such as impregnation with resins and physical or chemical treatments (Inoue *et al.* 1993, Kutnar and Kamke 2012, Pelit *et al.* 2016). Among these techniques, physical treatments are preferred, such as steaming or heating, since they do not require any chemicals (Darwis *et al.* 2017). Heating and/or steaming before compression have been found to reduce densified wood spring-back significantly (Inoue *et al.* 2008, Darwis *et al.* 2017). However, heat treatments have the disadvantage of reducing the strength properties of the wood due to weight loss and chemical degradation of wood, when it exposed to high temperatures (Perçin *et al.* 2015).

Densification of wood from forest plantations in Costa Rica has been successfully tested in *A. cuminata*, *V. ferruginea* and *V. guatemalensis* wood (Tenorio and Moya 2020, Tenorio and Moya 2021, Tenorio *et al.* 2020). In addition to adapting to the densification process (Tenorio and Moya 2020), the characteristics of the densified wood of these species are appropriate and comparable to those of other high SG tropical woods (Tenorio and Moya 2020, Tenorio and Moya 2021). However, the inconvenient found is that the treatment used in the initial stage of the process - heating and steaming for 10 minutes between two metal plates - is that it produces low dimensional stability and high spring-back in the densified wood obtained (Tenorio and Moya 2020), making it unsuitable for flooring application.

Thus, the objective of the present study was to investigate the effect of densification using pre-heating on stabilization and spring-back reduction of densified wood; then, evaluate the behaviour of this wood in a flooring application. *A. acuminata*, *V. ferruginea* and *V. guatemalensis* woods were used and variables specific to the densification process (final density, degree of compression, percentage of densification, spring-back and color change), as well as the wood characteristics for flooring application (compression shear strength of the glue line, resistance to abrasion, resistance to indentation by the falling ball, concentrated loading and surface indentation), were analysed. The results obtained will provide key information to make these species with low values in mechanical properties suitable to produce new high-performance wood products such as flooring.

MATERIALS AND METHODS

Origin and characteristics of the wood before densification

A. acuminata, *V. ferruginea* and *V. guatemalensis* woods coming from fast growing forest plantations in Cartago and Alajuela in Costa Rica were tested. The trees used were around 8 years old. The wood used was mostly sapwood, as trees this age generally present low heartwood content (Tenorio *et al.* 2016). Fifty wood samples 300 mm long x 70 mm wide and 20 mm thick were prepared from each species. The dimensions (length, width and thickness), density and moisture content of each sample were determined previous to densification (Table 1). The density was calculated by the ratio of weight and volume, measuring the initial thickness, initial width and length. The moisture content was calculated as the ratio of the initial weight and dry oven weight, expressed as a percentage according to ASTM D-4442-16 (2016).

Table 1: Thickness, density and moisture content of the wood samples before densification.

Species	*A. acuminata*	*V. ferruginea*	*V. guatemalensis*
Specific gravity*	0,34	0,37	0,32
Initial thickness (mm)	19,88 (0,41)	19,88 (0,38)	20,05 (0,32)
Initial wood density (g/cm^3)	0,42 (0,03)	0,45 (0,05)	0,42 (0,06)
Initial moisture content (%)	10,75 (0,33)	10,99 (0,26)	10,87 (0,67)

Values in parenthesis mean standard deviation.
* Data from Tenorio *et al.* (2016)

The initial colour of the wood before densification was also determined by means of a HunterLab Mini Scan XE Plus spectrophotometer, CIEL*a*b* system (Table 1). The range of this measurement is from 400 to 700 nm with an opening at the point of measurement of 11 mm. For the observation of reflection, the specular component (SCI model) was included at a 10º angle, which is normal for the specimen surface (D65/10); a field of vision of 2º (Standard observer, CIE 1931) and an illumination standard of D65 (corresponding to daylight in 6500 K). The mini Skan XE Plus generated three parameters for each measurement, namely: L* (luminosity), a* (the tendency of color from red to green), and finally b* (the tendency of color from yellow to blue).

Densification process

The densification process for the three species consisted of three stages: stage 1, heating, where heat was applied to the wooden samples in a closed system for 60 minutes, for *A. acuminata* and *V. guatemalensis* a temperature of 180 °C was used and for *V. ferruginea* of 160 °C. Stage 2, compression, where the samples were compressed perpendicularly to the grain until reaching the target thickness of 9 mm (55 % degree of compression) for 15 minutes keeping the temperature used in stage 1 (heating) of the process. Stage 3, stabilization, where the samples were kept pressed and heated but without load for 10 more minutes. After densification, the samples were placed into an oven at 103 °C for 24 hours. In total, 50 samples were densified per species.

The differences in temperature for *V. ferruginea* in comparison with the other two species are because that when carrying out the first tests with 180°C the surface of the wood samples burned and, in some cases, parts adhered to the metal plates, making it impossible the evaluation of the process. Because of that it was decided to work with a different temperature for this species.

Evaluation of the densification process

At the end of stage 1 (heating) wood weight loss was calculated as the ratio between the initial weight of the wood and the weight after stage 1, expressed as a percentage of the initial weight. This ratio includes the lost water vapor that can be evaporated. Besides, the wood colour was determined as described above.

During the densification process, the thickness of each wood sample was determined at finalizing stages 2 and 3 (compression and stabilization thickness). After the densification process the dimensions, weight,

colour, density and percentage of densification of each sample were determined. For colour measurement the same procedure used before densification was utilized. Two colour changes (ΔE*) were observed, the first after stage 1 (heating), which was called heating ΔE*, and the second after finishing the densification process (after placing the samples into the oven for 24 hours), called densification ΔE*. The density was calculated as the ratio between weight and volume of the wood sample after stage 3 (stabilization). For volume, the sample's dimensions (stabilization thickness, length and width) were determined. The percentage of densification was calculated as the relation between the initial density and the density of the densified sample.

The thicknesses determined in stages 2 and 3 (compression and stabilization thickness), were used to determine the degree of compression and the spring-back of the sample thickness. The degree of compression was calculated as the ratio between the initial thickness and the compression thickness, expressed as a percentage. The spring-back of the thickness of the densified wood was calculated as the absolute value of the ratio between the compression thickness and the stabilization thickness, also expressed as a percentage.

Flooring evaluation

In the evaluation of the densified wood flooring, the shear strength of the glue line was determined for two densified pieces glued with an adhesive used to glue flooring, following the norm ASTM D905-08 (2013). Twenty samples per species bonded with Advantage EP-950A from Franklin Adhesives Polymers (Franklin Division, Columbus, Ohio, USA) were prepared.

Abrasion resistance was determined according to ASTM D4060-14 (2014). Three square samples of 100 mm at the densified thickness were used and the wear index was determined by Equation 1:

$$I = (A - B) * \frac{1000}{C} \quad (1)$$

Where: I = wear index, A = weight of test specimen before abrasion (mg), B = weight of test specimen after abrasion (mg) and C = number of cycles of abrasion recorded.

Three indentation tests using the densified wood and following ASTM D2394-17 (2017), were performed: i) falling ball indentation, ii) concentrated loading and iii) surface indentation. i) Falling ball indentation was performed using 9 samples per species with seven different heights ranging from 122 cm to 213 cm at 15 cm intervals. ii) Concentrated loading test were performed on 3 boards 457 mm^2 of the densified wood from each species glued on a 19 mm thick structural plywood. As support for the boards 3 pieces of *Gmelina arborea* were used, with dimensions of 5 cm x 7,5 cm x length of the lower side of the board, one at each side and one on the centre of the board. Two loading points were used for each board according to the ASTM D2394-17 (2017). The residual deformation and the maximum deformation in a load vs. deformation plot for each species were determined. iii) Surface indentation test was performed using a sample comprised of two densified pieces; one beside the other placed on 19 mm thick structural plywood, totaling 6 samples per species. For each test the percentage of samples completely, severe, or moderately damaged was determined, according to ASTM D2394-17 (2017).

Statistical analysis

Measured variables complied with the assumptions of normal distribution and homogeneity of variance. The presence of outliers was also verified. An analysis of variance was performed to verify the effect of wood species on parameters of the densification process i.e. wood color before and after heating, heating ΔE*, densification ΔE*, weight loss after heating, final density, percentage of densification, degree of compression and spring-back and flooring parameters (shear strength of the glue line and residual deformation for concentrated loading test). The analysis of variance and Tukey tests were performed with the SAS software (SAS Institute Inc., Cary, NC). The category variables measured in flooring (wear index and surface indentation) were not applied to any statistical test.

RESULTS

Densification process

In this study, high temperatures (180 °C for *A. acuminata* and *V. guatemalensis* and 160 °C for *V. ferruginea*) produced changes in the color parameters during densification (Table 2). After stage 1 (heating) brightness (L*) and yellowness (b*) decreased in the three species and redness (a*) decreased in *A. acuminata* and *V. ferruginea* wood (Table 2). After densification, at the end of stage 3, the parameter brightness (L*) decreased in the three species, while yellowness (b*) and redness (a*) increased in the three species (Table 2). Heating ΔE* (color change after heating and before compression) was greater than densification ΔE* (color change after stage 3) for the three species (Table 2). *A. acuminata* and *V. ferruginea* woods presented heating ΔE* statistically higher compared to *V. guatemalensis* wood (Table 2), in contrast with densification ΔE*, where *V. guatemalensis* wood showed the statistically higher value (Table 2).

Weight loss after stage 1 (heating) was statistically higher in *V. ferruginea* and *V. guatemalensis* woods compared to *A. acuminata* wood (Table 2). Concerning to the final density, no differences were observed among the woods of the three species (Table 2). The percentage of densification in *A. acuminata* and *V. guatemalensis* woods was statistically higher than in *V. ferruginea* wood (Table 2), while the degree of compression was statistically higher for *V. guatemalensis* wood (Table 2). Regarding wood spring-back after densification, no statistical differences among species were observed (Table 2).

Table 2: Characteristics of wood samples after the densification.

Parameters		*A.acuminata*	*V. ferruginea*	*V. guatemalensis*
Wood color parameter before heating	L*	67,66^C (2,47)	73,63^A (4,22)	70,82^B (2,48)
	a*	10,73^A (1,37)	8,78^C (1,90)	9,93^B (1,55)
	b*	22,38^A (2,40)	16,96^C (1,56)	21,40^B (1,51)
Wood color parameter after heating	L*	60,93^B (2,49)	65,06^A (4,63)	64,45^A (3,27)
	a*	6,49^B (0,75)	6,13^B (1,44)	10,03^A (1,52)
	b*	15,95^B (1,84)	16,03^B (1,18)	21,24^A (0,85)
Wood color parameter after densification	L*	60,01^C (2,08)	64,89^A (4,34)	62,14^B (3,38)
	a*	6,72^A (0,52)	6,84^A (1,66)	11,39^B (1,61)
	b*	16,00^C (1,52)	16,93^B (1,22)	21,68^A (0,71)
Heating ΔE*		10,36^A (3,01)	9,27^A (3,21)	6,33^B (2,18)
Densification ΔE*		1,69^B (1,45)	1,87^B (0,82)	2,99^A (1,63)
Weight loss after heating (%)		11,80^B (0,37)	12,16^A (0,43)	12,03^A (0,54)
Final density (g/cm^3)		0,71^A (0,06)	0,72^A (0,08)	0,69^A (0,08)
Percentage of densification (%)		41,61^A (2,57)	37,71^B (3,96)	40,10^A (3,33)
Degree of compression (%)		53,04^B (1,40)	52,33^B (1,68)	53,86^A (1,90)
Spring-back (%)		5,61^A (4,24)	3,62^A (4,06)	3,76^A (4,33)

Different letters for each parameter denote statistical differences between treatments (level of significance 0,05). Values in parentheses are standard deviation.

Flooring evaluation

In the flooring evaluation of the densified wood of the three species, the shear stress by compression loading was statistically higher in *A. acuminata* wood relative to *V. ferruginea* and *V. guatemalensis* woods (Table 3). In relation to resistance to abrasion, although no statistical analysis was performed, the wear index of densified wood of *V. ferruginea* presented the highest value, while *A. acuminata* and *V. guatemalensis* densified wood showed the lowest values, between 0,04 and 0,05 (Table 3).

For the indentation tests, in the concentrated loading test, no differences were observed between densified wood of the three species in the residual deformation (Table 3). Figure 1a, Figure1b, Figure1c present the load vs. deformation curves obtained for the wood of the three species in the concentrated loading test. In the case

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of *A. acuminata* densified wood, the deformation observed when applying a load of 500 kg was 8,34 mm on average (Figure 1a). For *V. ferruginea* the deformation was 8,50 mm on average (Figure 1b), while for *V. guatemalensis* deformation of the densified wood was 7,54 mm on average (Figure 1c).

Table 3: Results of flooring tests for the densified wood of the three species.

Parameter		*A. acuminata*	*V. ferruginea*	*V. guatemalensis*
Glue line shear strength (MPa)		6,20[A] (1,98)	3,61[B] (0,80)	2,93[B] (0,83)
Wear index (g)		0,04	0,12	0,05
Residual deformation for concentrated loading test (mm)		1,14[A] (0,39)	1,18[A] (0,36)	1,26[A] (0,70)
Surface indentation (% of samples)	Moderate	50,00	50,00	50,00
	Severe	33,33	16,66	33,33
	Complete	16,66	33,33	16,66

Different letters for each parameter denote statistical differences between treatments (level of significance 0,05). Values in parentheses are standard deviation.
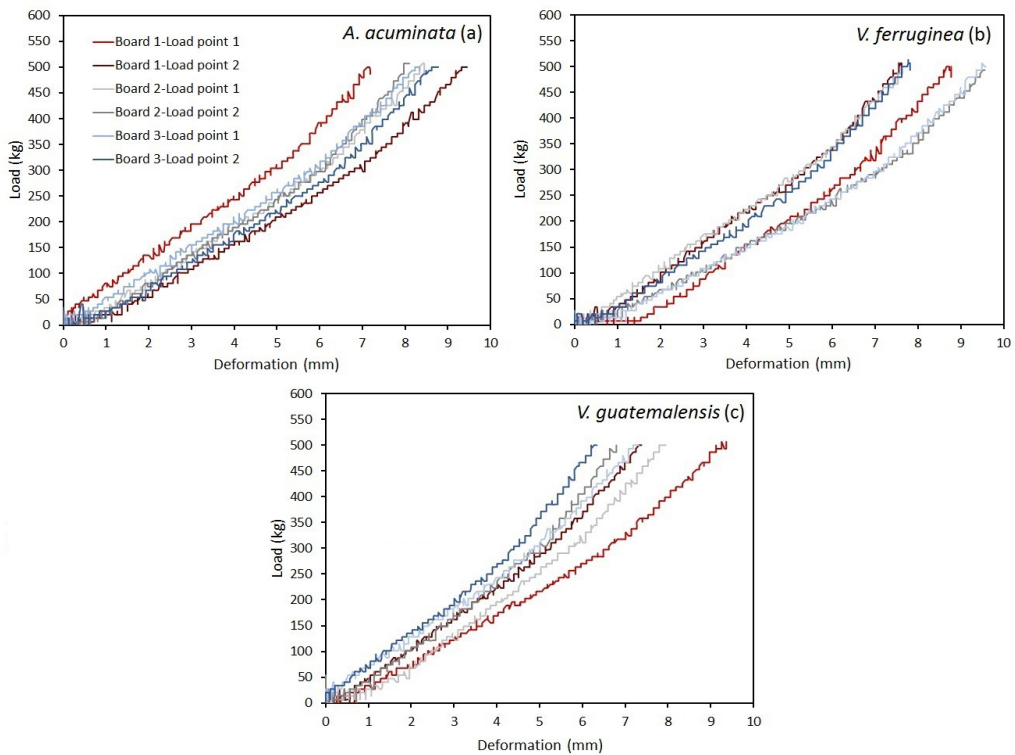

Figure 1: Load vs. deformation for (a) *A. acuminata* , (b) *V. ferruginea* and (c) *V. guatemalensis*.

As for the falling ball indentation test, the values of residual indentation vs. drop height for the three species were plotted in Figure 2. The densified wood of the three species showed an increase in the residual indentation with increasing drop height. Such behaviour was more evident in densified wood of *V. guatemalensis*. As for densified wood of *A. acuminata*, with 122 cm drop height the residual indentation was 0,043 mm, while with 213 cm drop height it was 0,077 mm. For *V. ferruginea* the residual indentation increased from 0,067 mm with 122 cm drop height to 0,085 mm with 213 cm drop height. On the other hand, in *V. guatemalensis* the residual indentation increased from 0,047 mm with 122 cm drop height to 0,089 mm with 213 cm drop height (Figure 2). Moreover, *V. ferruginea* presented values of residual indentation higher than those of the other two species in most drop heights, except for drop heights 198 and 213 cm, where *V. guatemalensis* presented the
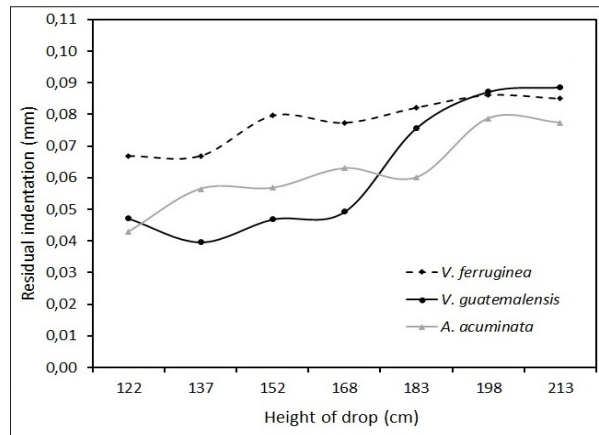
greatest values.

Figure 2: Residual indentation vs. drop height plotting for falling ball indentation test for the densified wood of the three species.
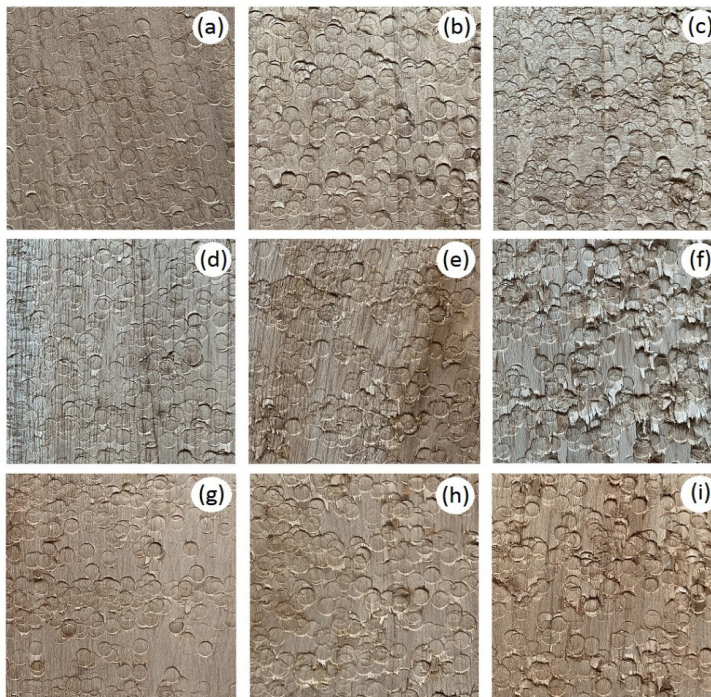

Figure 3: Moderate, severe and complete surface indentation of the densified wood; *A. acuminata* ((a), (b) and (c), respectively), *V. ferruginea* ((d), (e) and (f), respectively) and *V. guatemalensis* ((g), (h) and (i), respectively).

In the surface indentation test, the three species presented moderate, severe and complete damages. As for *A. acuminata* and *V. guatemalensis*, 50% of the densified wood samples sowed moderate damage (Figure3a and Figure 3g), while 33,33% presented severe damage (Figure 3b and Figure 3h) and only 16,66% showed complete damage (Figure 3c and Figure 3i) (Table 3). As for *V. ferruginea*, 50% of the samples showed moderate damage (Figure 3d); 16,66% showed severe damage (Figure 3e) and 33,33% complete damage (Figure 3f) (Table 3).

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Discussion

Densification process

Color is an important aesthetic feature in wood derived products (Jalilzadehazhari and Johansson 2019), particularly if intended for flooring (Nordvik *et al.* 2009). Here, because high temperatures were applied (180 °C for *A. acuminata* and *V. guatemalensis* wood and 160 °C for *V. ferruginea* wood) during the densification process, changes were observed in the color parameters of the wood of the three species (Table 2). Visually, these changes were perceived in the form of wood darkening caused by the decrease in the parameter L*. The darkening of the densified wood is attributed to the temperature (Salca *et al.* 2016), since it affects the wood's chemical composition (Pohleven *et al.* 2019). Color changes in the densified wood are caused by hydrolysis of the hemicelluloses (Candelier *et al.* 2016), and reduction of lignin, which is associated with the production of chromophore groups (Salca *et al.* 2016), and change to a darker color at high temperatures (Table 2). Hydrolysis of the hemicelluloses produces changes in parameter L*, while reduction of lignin produces changes mainly in parameter a* (Moya *et al.* 2012), which was reflected in parameters L* and a*, respectively, in the present study (Table 2). However, Matsuo *et al.*(2010) indicate that wood darkening resulting from a thermal treatment is due to the reduction of the parameter luminosity L* instead of the change in parameter a*. Therefore, in this study the behaviour of parameter a* disagrees with what Matsuo *et al.* (2010) point out.

Regarding color change (ΔE*), the ΔE* obtained after stage 1 (heating ΔE*) of the process was approximately 3 times greater than color changes after finalizing the densification process (densification ΔE*) for the three species (Table 2). The time of exposure to temperature in the stages of the process explains this difference. The exposure time for heating ΔE* was 60 minutes, while for densification ΔE* it was only 25 minutes, corresponding to stages 2 and 3 of the process. According to Matsuo *et al.* (2010) the values of ΔE* increased logarithmically with the exposure time of the wood: the longer the exposure time, the greater the ΔE*. The same authors indicate that the changes are cumulative, which means that the total ΔE* of the wood is given by the sum of de heating ΔE* and densification ΔE*.

The thermo-mechanical densification process developed in this study allowed obtaining values without statistical difference between the three species in relation to the final density of the densified wood. Nevertheless, as expected, differences were observed regarding the percentage of densification. *V. ferruginea* wood presented the highest initial density (0,45 g/cm³) but the lowest percentage of densification (Table 2) compared to *A. acuminata* and *V. guatemalensis* wood, which had lower initial density (Table 1) and higher percentages of densification (Table 2). To this respect, Tenorio and Moya (2021) point out that there is a high negative correlation between the initial density of the wood and the percentage of densification obtained, as confirmed in the present study´s analysis of the three species.

As for the spring-back values obtained in this study, from 3,62 to 5,61% (Table 2), they are much lower than those obtained for the same species using a thermo-hydro-mechanical densification process, where the spring-back obtained was greater than 10% for all three species (Tenorio and Moya 2020). The reduction in spring-back in this study is attributed to the heating time (stage 1) of 60 minutes, while in the previous study (Tenorio and Moya 2020) the heating time was 10 minutes. Spring-back reduction in this process results in greater stability of the densified wood (Inoue *et al.* 2008), which is ideal for flooring applications.

According to Sadatnezhad *et al.* (2017), time and temperature influence greatly wood fixation and can reduce spring-back. An increase in time during the heating stage, as occurred in the present study, increases the compression of wood and reduces the level of stress stored in the wood during densification. In addition, an increase in heating time affects the chemical composition of the wood (Inoue *et al.* 2008), because heating the wood to temperatures above 180 °C leads to degradation of components of hemicellulose and as a result, the stresses stored in the micro fibrils would be released (Norimoto *et al.* 1993, Dwianto *et al.* 1996) and the lignin will soften and flow to fill the space matrix that is in the wood fixing the wood dimensional stability (Darwis *et al.* 2017).

Inoue *et al.* (2008) also point out the importance of the adequate use of time and temperature as a treatment to increase the stability of densified wood. These authors indicate that there is a high correlation between the percentage of weight loss during the heating stage (stage 1 of the densification process) and wood spring-back, which is caused by loss of water and degradation of hemicelluloses during this stage. This behaviour was observed in the three species in this study. The determination of the weight loss of the samples (Table 2) demonstrated that the samples that presented more weight loss (*V. ferruginea* and *V. guatemalensis*) also showed less spring-back (Table 2). Hence, it can be affirmed that 60 minutes in stage 1 of the densification pro-

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cess increase the stability of densified wood of the three tropical species used by reducing wood spring-back.

Flooring evaluation

The values of shear strength in the glue line obtained for densified wood in the flooring evaluation, from 2,93 MPa to 6,20 MPa (Table 3), are comparable to those obtained for solid wood glued with polyvinyl acetate (PVAc) wood adhesives, but inferior to values obtained with urea formaldehyde (UF) wood adhesives. For example, Moya *et al* .(2015) in nine tropical woods, reported values in the range of 2 MPa to 4 MPa for PVAc-adhesive, which contains the values obtained for densified wood (Table 3); while for UF-adhesive the range of values varied from 8 MPa to 9 MPa, above the values found for densified wood (Table 3). Furthermore, another study conducted by Moya *et al.* (2015), confirms the behaviour described, with similar glue line shear strength when using solid wood with PVAc-wood adhesive and a lower value of glue line shear strength when using UF-adhesive. According to Fang *et al.* (2012) the densification treatment changes the wood's structure due to the temperature and pressure, which both reduce the interlocking surface or mechanical adhesion. Therefore, a reduction in the glue line shear strength in the densified wood should be expected. Additionally, changes in the properties of the wood, such as diffusion, absorption and in the wood's chemical structure can reduce the glue line shear strength.

A. acuminata densified wood obtained the highest average in shear strength (Table 3) of the three species. This is attributed to the fact that the densified wood of this species presented more compatibility with the adhesive utilized, resulting in reduced degradation of the structure of the wood during the process. *A. acuminata* densified wood presented less weight loss (11,8 %) during stage 1, with a glue line shear strength of 6,20 MPa (Table 3), compared to the other two species, which showed greater weight loss, approximately 12 %, and less glue line shear strength between 2,93 MPa and 3,61 MPa (Table 3).

The wear index value obtained for the densified wood of *A. acuminata* and *V. guatemalensis* was lower in relation to that of *V. ferruginea* wood (Table 3), because the densified wood of *V. ferruginea* is more susceptible to surface wear. This wear index behavior can be explained based on the values of final density and percentage of wood densification. *V. ferruginea* presented a lower percentage of densification, but a final density equal to that of the other two species (Table 2). The wear index of *V. ferruginea* was higher than that of *A. acuminata* and *V. guatemalensis* (Table 3), suggesting that a low percentage of densification may be associated with greater wood susceptibility to wear. The cause of the decrease in flooring quality may be less formation of covalent and hydrogen bonds and of new cross-linkages and hydrogen bonds between the cellulose and hemicellulose during densification (Dwianto *et al.* 1999, Navi and Heger 2004) in wood with low percentages of densification, as is the case with *V. ferruginea* in this investigation, because the fibers from one group detach more easily from the other group of fibers.

Regarding the values of residual deformation for the concentrated loading in the indentation test, although no differences were observed in the densified wood of the three species (Table 2), the average deformation obtained in the curves load vs. deformation was greater in *V. ferruginea* densified wood (8,50 mm) relative to the other two species (*A. acuminata* with 8,34 mm and *V. guatemalensis* with 7,54 mm) (Figure 1a, Figure1b and Figure1c). The result of this test indicates that *V. ferruginea* densified wood presents greater deformations for the same load than the other two species (less toughness), confirming the previous affirmation that the densified wood of *V. ferruginea* presents less quality than the other two species due to, as stated above, less formation of covalent and hydrogen bonds and of new cross-linkages of the wood components (Dwianto *et al.* 1999, Navi and Heger 2004).

Similarly, high values obtained for the residual indentation in the falling ball indentation test and the increased number of samples with moderate and complete damage in the surface indentation test in the densified wood of *V. ferruginea* (Table 3, Figure 3), demonstrate the lower quality of flooring made of this species compared to wood flooring from *A. acuminata* and *V. guatemalensis*.

As previously mentioned, higher wear index, increased residual deformation, high values of residual indentation for the falling ball indentation test and a greater number of samples with moderate and complete damage for the surface indentation test in densified wood from *V. ferruginea* are associated with a lower percentage of densification and high weight loss during stage 1 of the densification process. Thus, since the densified woods of *A. acuminata* and *V. guatemalensis* had better results regarding parameters of quality of flooring and a greater percentage of densification, they could present a better performance in flooring applications.

CONCLUSIONS

The thermomechanical densification process, with a 60-minute pre-heating stage 1 and constant temperature during the entire densification process, reduces wood spring-back by 5% and tends to improve the weight loss due to degradation of some of the wood's components, particularly, hemicellulose degradation with consequent effects on its properties.

The percentage of densification has an effect on the behaviour of the densified wood evaluated as flooring, even if the three species presented statistically similar values of final density. The low percentage of densification and high weight loss of the wood due to temperature and time of exposure in stage 1, cause *V. ferruginea* wood to present greater wear index, higher residual deformation, high values of residual indentation for the falling ball indentation test and a greater number of samples with moderate and complete damage in the surface indentation test than densified wood of *A. acuminata* and *V. guatemalensis*.

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