

DENSITY PROFILE AND MICROMORPHOLOGY VARIATION OF DENSIFIED WOOD FROM THREE FAST-GROWING HARDWOOD SPECIES IN COSTA RICA

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(Received January 2020)

Abstract. This study evaluates 1) the effect of the thermo-hydro-mechanical densification process—using three temperatures, two compression times, and the presence or absence of steam, and 2) the effect of initial wood micromorphology on the density profile of densified wood of three low-density fast-growing hardwood species in Costa Rica (*Alnus acuminata*, *Vochysia ferruginea*, and *Vochysia guatemalensis*). Four density profiles in the densified wood of the three species resulted from the densification temperature and the initial micromorphology of the wood. The initial diameter of vessels affects the compression stage during the densification process and causes the formation of irregular density profiles. Therefore, this is the most important element in determining the type of the density profile. The wood of *A. acuminata* (with small-diameter vessels) densified at 180°C tends to produce more uniform density profiles than the other two species that have larger diameter vessels. The time of compression and the use or not of steam as an initial stage in the densification process did not influence the types of density profiles obtained. Similarly, the type of wood tissue and wood pattern had no effect on the type of density profiles. In conclusion, uniform and regular density profiles in densified wood are more likely to be achieved at high temperatures and with small-diameter vessels.

Keywords: THM densification, vessels, temperature, tropical species.

INTRODUCTION

There are various methods of wood densification. Among these, mechanical densification by transversal compression enhances the resistance and properties of low-density woods (Wang and Cooper 2005; Fang et al 2012). This compression is usually performed at temperatures above the glass transition temperature of the cell wall of wood's various

components, so that they deform instead of breaking when buckled (Laine et al 2014). This action of temperature during the densification process and its relationship with glass transition of the cell wall of wood during the time when compression force is applied cause different effects on anatomical elements of the wood, so that specific density profiles are produced through the thickness of densified wood (Kutnar et al 2009; Rautkari et al 2011a).

The density profile represents the variation of density through the thickness of densified wood, and it is a relevant attribute because it affects the

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physical and mechanical properties (Rautkari et al 2013). The variation in density occurs because when transversely compressed, wood deformation (which is due to the collapse of the weaker, or less resistant to compression, anatomical elements) is not homogeneous (Blomberg and Persson 2004; Wang and Cooper 2005), producing an irregular density profile. In addition, the density profiles developing in compressed solid wood depend on other factors, such as the initial MC of wood, wood grain orientation, press temperature, and time of compression (Rautkari et al 2011b).

Appropriate densification processes allow for obtaining uniform density profiles (Navi and Heger 2004; Sandberg et al 2013). The thermo-hydro-mechanical (THM) densification process is a widely used densification method for achieving uniform density profiles, as it prevents damage to the wood structure when compressed (Navi and Heger 2004; Sandberg et al 2013). A suitable wood densification process is achieved through the combined action of water steam, temperature, and compression strength. The moisture induces a mechano-sorptive effect and further softens the wood, enabling mechanical compression of wood without cell wall fracture (Bao et al 2017). The heat treatment can improve resistance to decay (Huang et al 2012), decrease hygroscopicity (Metsä-Kortelainen et al 2006), and improve dimensional stability (Esteves et al 2007).

Most research regarding THM densification have been conducted on wood from coniferous species and in close systems (Navi and Heger 2004), and scarcely on wood from tropical hardwood species whose anatomical structures are more complex and have greater influence on the result of the process (Navi and Heger 2004). This is because the compression properties of wood depend on its micromorphology (hierarchical structures): frequency, size, and distribution of anatomical structures (Darwis et al 2017), which in case of hardwood species are dominated by vessels, fibers, and rays arranged in more complex matrixes (Gibson 2012) than the fiber tracheids of conifers (Fratzl and Weinkamer 2007).

Alnus acuminata, *Vochysia ferruginea*, and *Vochysia guatemalensis* are fast-growing hardwood species used in commercial reforestation programs in Costa Rica (Moya 2018). Lately, these species have been used in the development of THM densification processes, and it has been observed that the densification process and the densified wood properties of these three species were influenced by the initial density of the wood (Tenorio and Moya 2021). Relevant studies have demonstrated the relationship between wood density and distribution, form, and frequency of the different anatomical elements in hardwood species (Jacquin et al 2017). Therefore, the initial morphology of these wood may have a clear relationship with the density profile and properties of wood obtained after densification.

The objective of this study was to evaluate the effect of a thermo-hydro-mechanical densification process (using three temperatures, two compression times, and use or not of water steam) and the initial micromorphology of wood on the density profile of densified wood of three low-density fast-growing hardwood species in Costa Rica (*A. acuminata*, *V. ferruginea*, and *V. guatemalensis*).

METHODOLOGY

Material and Sample Preparation

Wood of *A. acuminata*, *V. ferruginea*, and *V. guatemalensis* from forest plantations in the provinces of Cartago and Alajuela in Costa Rica was used. The trees used were around 8 yr old, therefore presented low heartwood content (Tenorio et al 2016). The anatomical features of these species are detailed in Table 1. Samples of 300 mm × 70 mm × 20 mm (long × width × thickness) diameter were prepared from each species. The type of the sawing pattern of the wood, that is, flat, quarter, or rift sawn (Fig 1) was determined, and the sample tissue, that is, sapwood, heartwood, or a combination of both was identified. The percentage of pieces representing each characteristic was calculated (Table 2). Thickness, width, length, density, and MC were determined for each sample before densification (Table 2).

The density was calculated as the ratio between weight and volume determined by measuring initial

Table 1. Macroscopic and microscopic descriptions of the wood of the three species before the densification process.

Microscopic characteristics	Species		
	<i>Abus acuminata</i>	<i>Vochysia ferruginea</i>	<i>Vochysia guatemalensis</i>
Sapwood/heartwood boundary	Indistinct	Distinct	Distinct
Texture	Fine to medium	Fine to medium	Coarse
Grain	Slightly distinct	Straight	Straight to wavy
Growth ring	Diffuse	Indistinct	Indistinct
Porosity	Diffuse	Diffuse	Diffuse
Percentage of solitary pores	85	77	76
Pore frequency (pores/mm ²)	16	2-3	3
Length of vessels (µm)	150	346	340
Diameter of vessels (µm)	75	145	169
Fiber length (mm)	1.02	1.03	1.05
Lumendiameter (µm)	35	29	25
Wall cell thick (µm)	3	4	4
Ray height (µm)	299	580	229
Ray width (cell quantity)	1-3	1-3	1-3, 4-10
Ray frequency (ray/mm)	5	3	3
Ray type	Heterogeneous and nonstored	Heterogeneous and nonstored	Heterogeneous and nonstored
Ray type	Apotracheal diffuse	Paratracheal, scanty, vascentric, and lozenge-aliform	Paratracheal, scanty, vascentric, lozenge-aliform, and congruent
Banded parenchyma	Absent	Absent	Absent

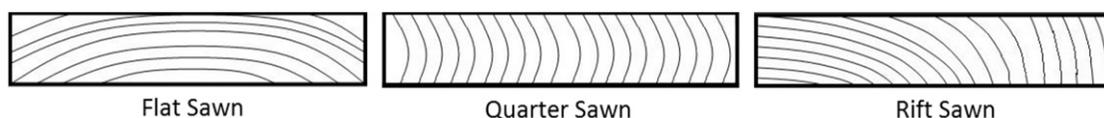


Figure 1. Types of wood patterns found for the three species.

thickness, initial width, and length. The MC was calculated as the ratio of the initial weight to the oven-dry weight, expressed as a percentage according to ASTM D-4422 (ASTM 2016) (Table 2).

The densification process was tested under three temperatures (140°C, 160°C, and 180°C for *A. acuminata* and *V. guatemalensis* and 140°C, 150°C, and 160°C for *V. ferruginea*); two compression times (10 and 15 min), and with or without water steam, as the initial stage before compressing wood. Consequent parameters performed were with 12 treatments and 10 samples per treatment, for a total of 120 samples per species. The differences in temperature for *V. ferruginea* in comparison with the other two species are due to the fact that when carrying out the first tests with 180°C, the surface of wood samples burned and in some cases parts adhered to the metal plates, making the evaluation process impossible. Hence, this species was analyzed with different temperatures.

The densification process for these three species described by Tenorio and Moya 2021 consisted of three stages: 1) stage 1, steaming or heating, where half of the samples were applied with steam and heat for 10 min, while the other half were only exposed to heat; 2) stage 2, compression, where the wood samples were compressed perpendicular to the grain until reaching the target thickness of 9 mm

(degree of compression of 55%) for 10-15 min, at the temperature maintained in stage 1; 3) stage 3, stabilization, where the samples were kept compressed and heated but without load application for additional 10 min.

Evaluation of Densification Process

The thickness of each piece was determined at the conclusion of stages 2 and 3 of the densification process (compression and stabilization thickness). After the process of densification, the width, length, weight, and density of each wooden piece were determined. The final density (after densification) was calculated as a relation between weight and volume determined by measuring the stabilization thickness, width, and length.

The ratio of compression was calculated as the ratio of initial thickness to the compression thickness, expressed as percentage. The percentage of densification was calculated as the ratio between the initial density (before the densification process) and the final density (after the densification process).

X-ray Densitometry

Density profiles were determined for densified and undensified wood of each species. For each

Table 2. General characteristics of the wood of the three species before the densification process.

Species		<i>Alnus acuminata</i>	<i>Vochysia ferruginea</i>	<i>Vochysia guatemalensis</i>
Initial thickness (mm)		19.7 (0.02)	20.0 (0.03)	20.4 (0.02)
Initial wood density (g/cm ³)		0.43 (0.03)	0.45 (0.05)	0.39 (0.05)
Initial MC (%)		9.97 (0.83)	10.68 (1.13)	12.56 (0.57)
Type of wood pattern (% of samples)	Flat sawn	60.00	30.83	63.33
	Quarter sawn	10.83	25.83	2.50
	Rift sawn	29.17	43.33	34.17
Type of wood tissue (% of samples)	Sapwood	78.33	5.83	30.00
	Heartwood	20.83	45.83	39.17
	Sapwood and heartwood	0.83	48.33	30.83

The values in parenthesis mean SD.

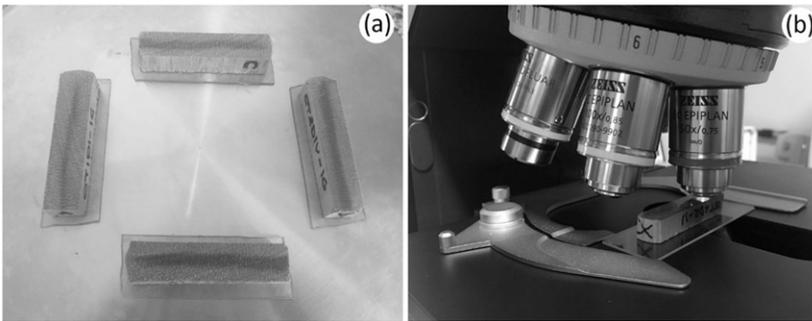


Figure 2. Densified wood samples placed in the sander holder (a); polished densified sample placed in the microscope (b).

species, 10 samples per densification treatment were used, measuring 50 mm × 50 mm × densified thickness obtained in the densification process, and 10 samples of undensified wood with dimensions 50 mm × 50 mm × 20 mm in thickness were used. Weight, length, width, and thickness were determined for each sample. The density was measured at intervals of 0.1 mm through the thickness of the specimens using an X-ray densitometer QMS, Model QDP-01 (Quintek Measurement Systems, Inc., Knoxville, TN). The density profile was measured with respect to the specimen thickness.

Microscopic Examination

Sections of 10 mm × 50 mm × densified thickness taken from the samples were used to determine the density profiles. In case of undensified samples, sections of 10 mm × 50 mm × 20 mm were taken. All samples were polished in their transversal sections using a sander (Struers, model Tegramim 30, Cleveland, OH). The samples were stuck on the support as shown in Fig 2(a) using a double-sided adhesive tape. Sanding and polishing program used for all three species are described in Table 3.

After polishing, microscopic analysis (Zeiss, model Axioscope; Axicam 503; 50× lens, Oberkochen, Germany) was conducted to determine the anatomical structures of the wood samples (Fig 2 [b]). The undensified samples were also photographed in the reflexion mode using a 10× lens. The undensified and the densified polished samples were photographed using an Epson scanner (model Expression 12000XL, Epson America, Inc., Long Beach, CA) to obtain a macroimage and observe the density profiles.

Statistical Analysis

Compliance of the measured variables with the assumptions of normal distribution, homogeneity of variances, and the presence of outliers was verified. An analysis of variance was applied to verify the effect of the densification treatments (temperature, compression time, and use or not of steam) on each one of the variables obtained during the process of densification (ratio of compression, percentage of densification, and final density). Tukey's test was used to determine the statistical differences between the means of the variables previously indicated. An analysis of variance was

Table 3. Sanding characteristics used to polish the samples of the three species.

Sandpaper number	Sanding time (min)	Base speed (rpm)	Sample holder speed (rpm)
220	1.5	150	50
500	0.5	80	50
500	3.0	150	50
800	0.5	80	50
800	3.0	150	50
1200	0.5	80	50

applied to verify the effect of temperature, time, use or not of steam, the type of wood pattern, the type of wood tissue, and their interactions on the type of the density profile. It is important to clarify that analyses of variance for each one of the variables obtained during the process of densification and on the type of density profile were applied for each species. The variation between species was not considered. The analyses of variance and the Tukey test were performed using SAS software (SAS Institute Inc., Cary, NC).

RESULTS

Characteristics of Densification Process

Table 4 represents the results obtained as part of evaluation of the densification process. The three tested species showed approximately 55% ratio of compression. No statistical differences were observed between the treatments applied to *A. acuminata* and *V. ferruginea* for the ratio of compression. For *V. guatemalensis*, the treatment of 160°C with 15-min compression time and with

Table 4. Wood characteristics obtained in the densification process of the three wood species.

Species	Temperature (°C)	Time of compression (min)	Steam	Ratio of compression (%)	Percentage of densification	Final density (g/cm ³)	
<i>Alnus acuminata</i>	140	10	Yes	54.93 ^A (0.67)	88.16 ^A (5.61)	0.80 ^A (0.06)	
		10	No	54.56 ^A (0.35)	84.22 ^A (6.29)	0.82 ^A (0.06)	
		15	Yes	55.01 ^A (0.66)	82.77 ^A (11.13)	0.77 ^A (0.05)	
		15	No	54.94 ^A (0.77)	85.85 ^A (8.64)	0.82 ^A (0.05)	
		160	10	Yes	54.85 ^A (0.47)	88.45 ^A (8.94)	0.81 ^A (0.05)
		10	No	54.82 ^A (0.46)	86.22 ^A (6.63)	0.77 ^A (0.06)	
	180	15	Yes	54.85 ^A (0.55)	83.46 ^A (10.06)	0.82 ^A (0.05)	
		15	No	54.81 ^A (0.50)	80.03 ^A (12.87)	0.76 ^A (0.06)	
		10	Yes	54.35 ^A (0.43)	81.59 ^A (6.89)	0.76 ^A (0.07)	
		10	No	54.82 ^A (0.69)	88.12 ^A (12.53)	0.79 ^A (0.05)	
		15	Yes	54.88 ^A (0.44)	79.93 ^A (6.26)	0.78 ^A (0.05)	
		15	No	55.10 ^A (0.59)	89.48 ^A (9.15)	0.76 ^A (0.05)	
<i>Vochysia ferruginea</i>	140	10	Yes	55.11 ^A (0.97)	70.48 ^A (8.52)	0.78 ^A (0.12)	
		10	No	55.47 ^A (0.55)	72.95 ^A (11.22)	0.80 ^A (0.07)	
		15	Yes	55.57 ^A (0.58)	76.47 ^A (11.90)	0.81 ^A (0.08)	
		15	No	55.41 ^A (0.44)	70.32 ^A (10.41)	0.76 ^A (0.11)	
		150	10	Yes	55.41 ^A (0.67)	80.10 ^A (11.65)	0.84 ^A (0.05)
		10	No	55.00 ^A (0.83)	69.18 ^A (5.87)	0.76 ^A (0.11)	
	160	15	Yes	54.63 ^A (0.55)	77.60 ^A (11.72)	0.79 ^A (0.06)	
		15	No	54.98 ^A (0.99)	81.61 ^A (13.12)	0.81 ^A (0.09)	
		10	Yes	55.77 ^A (1.09)	77.34 ^A (8.82)	0.78 ^A (0.06)	
		10	No	55.57 ^A (0.72)	71.50 ^A (8.98)	0.80 ^A (0.05)	
		15	Yes	55.22 ^A (0.62)	75.04 ^A (7.48)	0.77 ^A (0.07)	
		15	No	55.35 ^A (0.69)	82.52 ^A (17.29)	0.77 ^A (0.08)	
<i>Vochysia guatemalensis</i>	140	10	Yes	56.49 ^A (1.78)	74.50 ^{ABC} (8.06)	0.66 ^{ABC} (0.04)	
		10	No	56.24 ^A (0.47)	69.85 ^{BC} (11.94)	0.67 ^{ABC} (0.06)	
		15	Yes	56.38 ^A (1.61)	82.00 ^{AB} (10.38)	0.63 ^{BC} (0.06)	
		15	No	56.08 ^A (0.54)	80.45 ^{AB} (7.85)	0.65 ^{BC} (0.05)	
		160	10	Yes	55.73 ^{AB} (2.21)	74.22 ^{ABC} (7.06)	0.67 ^{ABC} (0.04)
		10	No	56.43 ^A (1.66)	76.90 ^{AB} (15.33)	0.59 ^C (0.05)	
	180	15	Yes	51.66 ^B (6.20)	58.92 ^C (14.36)	0.70 ^{AB} (0.06)	
		15	No	55.92 ^{AB} (0.79)	77.74 ^{AB} (5.47)	0.68 ^{AB} (0.04)	
		10	Yes	56.97 ^A (2.65)	87.37 ^A (7.58)	0.74 ^A (0.04)	
		10	No	56.91 ^A (2.03)	78.54 ^{AB} (10.15)	0.67 ^{ABC} (0.06)	
		15	Yes	55.58 ^{AB} (1.83)	75.92 ^{AB} (10.92)	0.70 ^{AB} (0.09)	
		15	No	54.65 ^{AB} (5.80)	75.78 ^{AB} (8.81)	0.70 ^{AB} (0.05)	

The values in parentheses mean SD. Different letters for each parameter represent statistical differences between different treatments (significance level of 0.05).

steam application presented the lowest ratio of compression at 51.66%. The percentage of densification for *A. acuminata* was 84.86% on average and for *V. ferruginea* 75.47%. No differences were observed between the treatments applied. In the case of *V. guatemalensis*, the lowest densification percentage was 58.92%, shown by the treatment of 160°C, 15-min compression time, and steam application, whereas the highest was 87.37% with the treatment of 180°C, 10-min compression, and steam application (Table 4).

No differences were observed between the averages of final density in the densification treatments for *A. acuminata* and *V. ferruginea*; both species presented a final density average of 0.79 g/cm³ (Table 4). As for *V. guatemalensis*, some differences between the treatments appeared; however, the treatments at higher temperature presented higher density averages. The treatment at 160°C with 10-min compression without steam presented the lowest value of density average, 0.59 g/cm³, whereas the treatment at 180°C with

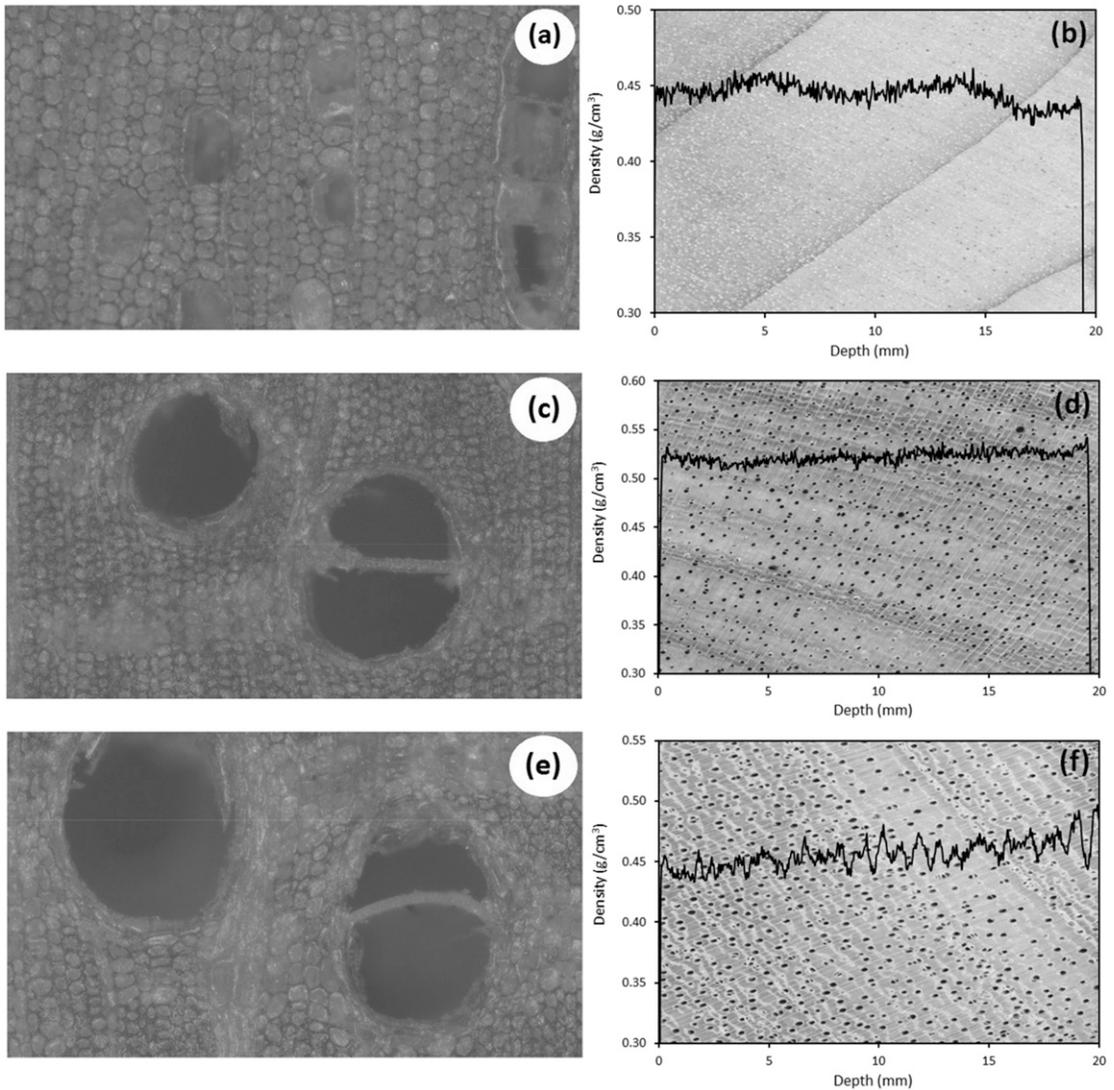


Figure 3. Anatomical features and density profiles of undensified wood of *Alnus acuminata* (a), (b), *Vochysia ferruginea* (c), (d) and *Vochysia guatemalensis* (e), (f).

10-min compression with steam presented the highest value of 0.74 g/cm^3 (Table 4).

Morphology of the Undensified and Densified Wood

Cross sections of the undensified wood micro-morphology of the three species are presented in Fig 3. The three species presented solitary and multiple diffuse vessels (Table 1). The three species studied also presented different anatomical features: *A. acuminata* presented a pore frequency of 16 pores/mm^2 with a small diameter ($75 \mu\text{m}$) and short length ($150 \mu\text{m}$); *V. ferruginea* presented 2.84 pores/mm^2 with a medium diameter ($145 \mu\text{m}$) and long ($346 \mu\text{m}$), and *V. guatemalensis* presented 2.88 pores/mm^2 with regular size diameters ($169 \mu\text{m}$) and long ($339 \mu\text{m}$ on average) (Table 1).

Fibers were irregularly arranged in rows perpendicular to the growth rings or parallel to the ray parenchyma, typical of nonstored fibers. The rows were crooked because of the presence of large vessels, whereas *A. acuminata* formed more regular fiber rows than other two species. The

shape and dimension of cross sections of fibers were irregular (Moya et al 2019). In *Vochysia* species, the shape of the fibers was round, square, and rhomboidal, and elliptical and rectangular shapes were also observed in tangential and radial section. *A. acuminata* features finer rays than those of the other two species, which were multiseriate, showing four to eight series per ray (Table 1) (Moya et al 2019) Round, square, and rhomboidal fibers, and elliptical and rectangular in tangential and radial direction, among other shapes, were observed in *Vochysia* species.

Figure 4 shows the anatomical structures in the cross section of densified wood of the three species. The effect of the densification process in the three species was observed by the size of their anatomical structures, and the differences between species occurred especially in the vessels. The fibers and rays were observed in areas of lower density of the profiles, as shown in Fig 4(a), (d) and (g). Although the fibers mostly maintained their original shape, some deformations of the densification process were already evident (Fig 4[a]). The rays were wavy, especially in *A. acuminata* rays,

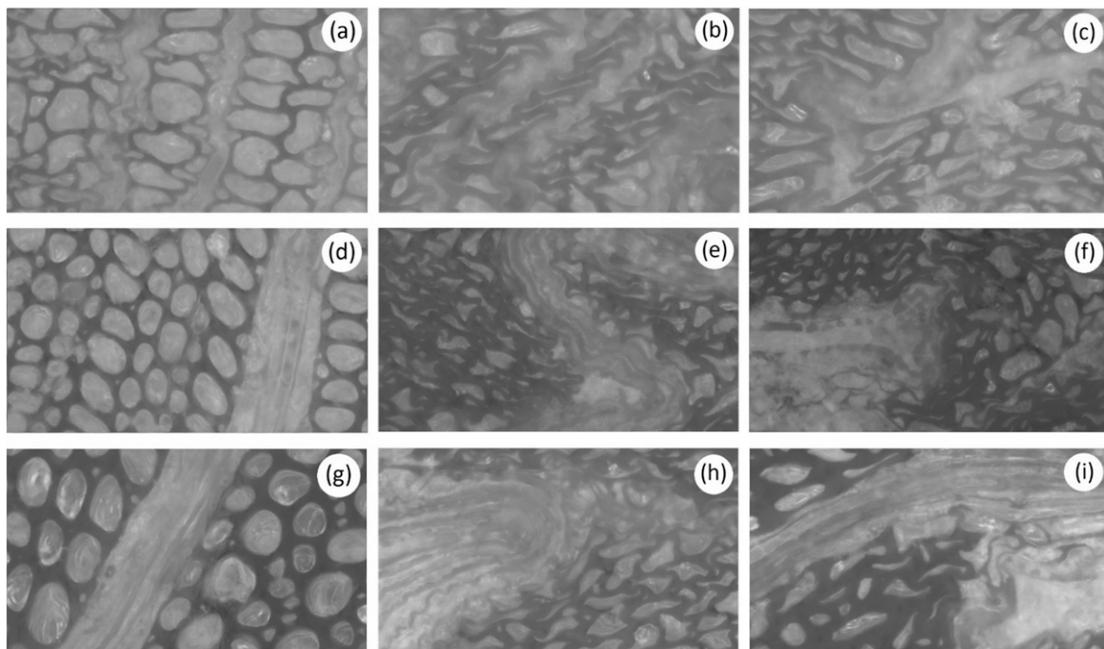


Figure 4. Anatomical features of densified wood of *A. acuminata* (a-c), *V. ferruginea* (d-f), and *V. guatemalensis* (g-i).

which were thinner than those of the other two species.

Figure 4(b), (c), (e), (f), (h), and (i) presented cross sections in areas of high density. The vessels tended to collapse completely, forming a row horizontal or perpendicular to the application of compression strength (Fig 4[c], [f] and [i]). Deformations occurring in the vessel caused the close rays to collapse and lose their original shape. Most fibers tended to take an “S” shape, especially those that were close to the collapsed vessels (Fig 4[f]). Importantly, in the case of the rays of *A. acuminada*, the frequency of the waves was greater than that of *V. guatemalensis* and *V. ferruginea*.

Density Profiles

The undensified wood of the three species presented almost uniform density throughout their

thickness (Fig 3[b], [d], and [f]). In the analysis for the densified wood, four density profile patterns were observed throughout the sample thickness for the three species: 1) the thickness center of the sample having density peak: it was possible to observe that the areas closest to the surface present lighter hue and more open pores compared with the central area of the sample, which was darker with almost closed pores (Fig 5[a]); 2) two high-density areas standing at the center of the sample: the surface and the center of the sample feature open pores and light hue, whereas the areas close to the surface had close pores and darker hue (Fig 5 [b]); 3) uniform density pattern and closed pores throughout the thickness of the sample: dark-colored sample (Fig 5[c]); and 4) one side of sample thickness had the highest peak density: an area close to the sample surface presents closed pores and dark hue, whereas the opposite area shows open pores and light hue (Fig 5[d]).

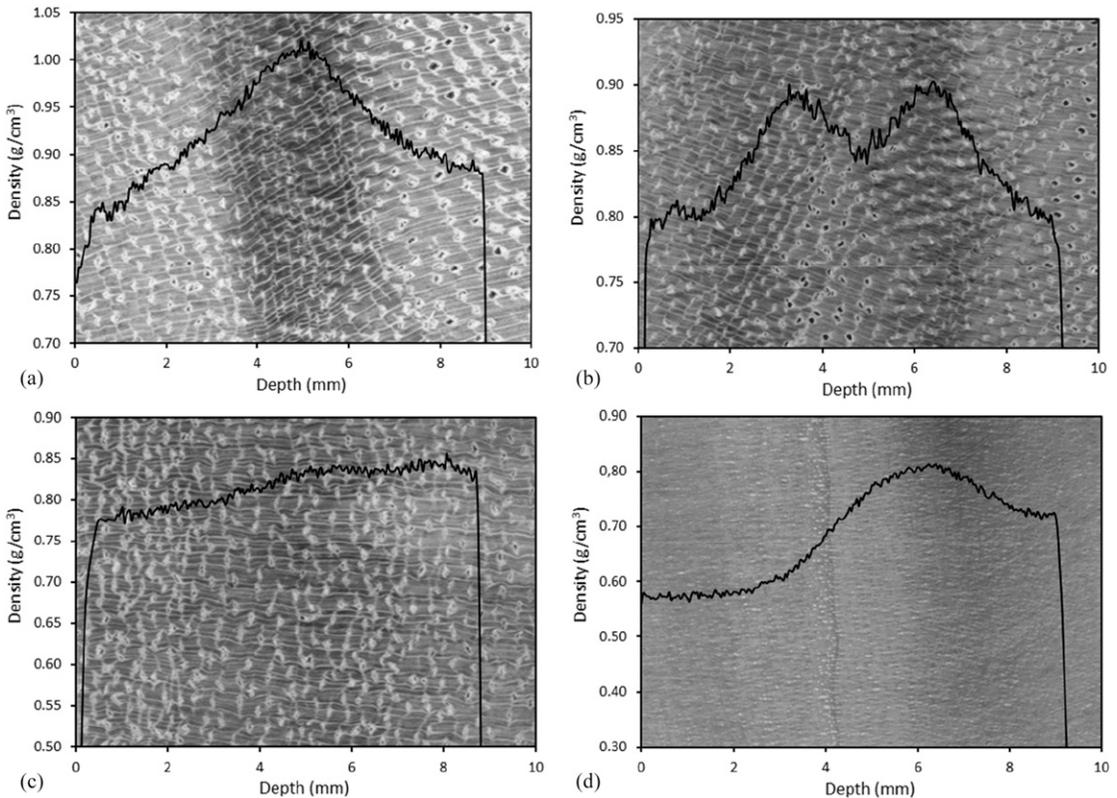


Figure 5. Profile density patterns of the densified wood of the three species, (a) profile type 1, (b) profile type 2, (c) profile type 3, and (d) profile type 4.

The variance analysis conducted to determine the influence of the densification treatments (temperature, compression time, and use or not of steam), the type of wood pattern, and wood tissue in the density profiles showed that only temperature affected the type of the density profile in all three species. But other interactions related to temperature were statistically significant, that is, temperature \times type of wood tissue in *A. acuminata* and temperature \times time and temperature \times steam in *V. guatemalensis* wood (Table 5).

Figure 6 shows the effect of temperature on density profiles for each species. For *A. acuminata* (Fig 6[a]), the percentage of samples with density profile 1 decreased with increasing temperature. Density profile 2 presented samples only at the lowest temperature (140°C). In density profile 3, the sample percentage increased with increasing temperature, and it is the profile with highest percentage of samples at highest temperature (180°C). Density profile 4 presented similar sample percentage at the three temperatures.

Regarding *V. ferruginea* (Fig 6[b]), density profile 1 showed the greatest percentage of samples at 150°C and 160°C. The percentage of samples with density profile 2 decreased with increasing temperature; as for density profile 3, sample percentage increased with temperature and with density profile 4 samples were only observed at the lowest temperature (140°C).

As for *V. guatemalensis* (Fig 6[c]), density profile 1 presented the highest sample percentage at three temperatures (140°C, 160°C, and 180°C). Sample percentage with density profile 2 decreased as the temperature increased. Samples with density profile 3 were only observed at the highest temperature (180°C), being this profile in the second place in this category of temperature, whereas density profile 4 was present in a very low percentage of samples at 140°C and 160°C.

DISCUSSION

The types of density profiles reflect the variation in the compression of the anatomical elements in the cross section of wood (Fig 5). Low-density regions are areas with vessels that maintain their original shape, whereas in high-density regions, the vessels are completely deformed (Fig 4), meaning that the densification treatment significantly changed the micromorphology of the wood of the three species (Figs 4 and 5).

Profile variation (areas of high and low density), mainly density profile types 1, 2, and 4, shows that reduction in the empty spaces did not occur uniformly. In this regard, Wang and Cooper (2005) pointed out that transversal compression of the wood is highly dependent on its anatomical structure, which means that deformation is not homogeneous, resulting in different density profiles in the three species studied (Fig 5). Areas of higher density

Table 5. Effect of densification treatments, type of wood pattern, and wood tissue on the density profiles of the densified wood of the three species.

Treatment	<i>Alnus acuminata</i>	<i>Vochysia ferruginea</i>	<i>Vochysia guatemalensis</i>
Temperature (A)	15.72 ^a	3.93 ^b	6.69 ^a
Time (B)	2.13 ^{NS}	0.03 ^{NS}	0.02 ^{NS}
Steam (C)	0.53 ^{NS}	1.39 ^{NS}	2.80 ^{NS}
Type of wood pattern (D)	1.58 ^{NS}	2.76 ^{NS}	1.57 ^{NS}
Type of wood tissue (E)	0.86 ^{NS}	0.19 ^{NS}	2.63 ^{NS}
A \times B	2.37 ^{NS}	0.23 ^{NS}	10.13 ^a
A \times C	1.87 ^{NS}	1.28 ^{NS}	5.73 ^a
A \times D	0.27 ^{NS}	0.67 ^{NS}	0.34 ^{NS}
A \times E	15.61 ^a	0.01 ^{NS}	0.46 ^{NS}
B \times C	0.02 ^{NS}	0.14 ^{NS}	2.30 ^{NS}
B \times D	0.30 ^{NS}	1.77 ^{NS}	0.17 ^{NS}
B \times E	0.29 ^{NS}	5.07 ^{NS}	2.22 ^{NS}
D \times E	1.48 ^{NS}	0.07 ^{NS}	0.74 ^{NS}

^a Statistical significance level of 0.05.

^b Statistical significance level of 0.1.

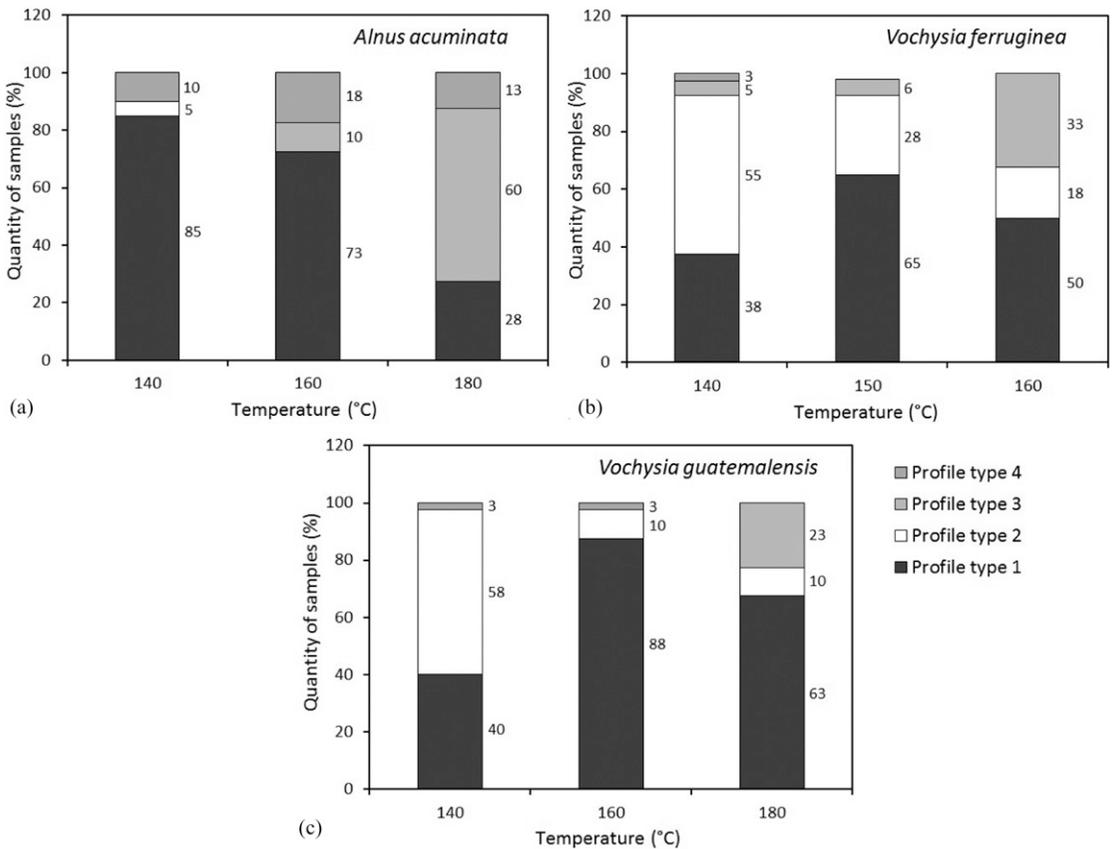


Figure 6. Effect of temperature on the density profiles of the densified wood of the three species.

showed greater collapsing of their structures, making the micromorphology of this area different from the micromorphology of the areas of lower density within the same sample (Fig 4).

According to Kutnar et al (2009), the morphology of densified wood depends largely on the percentage of densification. A high degree of densification causes a strong reduction in the empty spaces in the wood, evidenced in the high-density regions of density profiles 1, 2, and 4 (Fig 5[a], [b], and [d]). During the THM densification process, in these types of density profiles, the volume of the empty spaces is drastically reduced because the cells are deformed but their cell walls do not fracture. In these regions of high-density profiles, the vessels collapse and flatten in the direction of compression force, while the rays appear to buckle and the fibers take an “S” shape

in the areas of high density, especially the regions near the vessels (Fig 4[b], [c], [e], [f], [h], and [i]).

Likely, in the case of *A. acuminata*, a species with vessels of a smaller diameter (Table 1; Fig 3[a]) in relation to the vessels of *V. ferruginea* and *V. guatemalensis* (Table 1; Fig 3[c] and [e]), the compression transmission was performed more homogeneously, which led to a greater number of densified wood with density profile type 3 (Fig 6 [a]), that is, uniform density profiles throughout the thickness of the samples (Fig 5[c]). This effect of the vessel’s size can also be observed when comparing the densified wood of the other two species, where *V. ferruginea* has a larger number of samples with density profile type 3 in relation to *V. guatemalensis*, which has the largest diameter of vessels (Fig 3[c]).

Likewise, the distribution and size of the fibers and the characteristics of rays of each of the species also affect the formation of density profiles after compression. For example, in *A. acuminata*, the shape and size of the fibers present a regular arrangement, as stored fiber—distribution that does not occur in the other two species. Its regular fiber arrangement and greater frequency of ray bending compared with the other two species allow for a more uniform transmission of compression, so that less density variation or a greater number of density profiles of type 3 are achieved (Fig 5[c]).

In the case of the densification treatments used in this study (three temperatures, two compression times, and the use or not of steam), the type of wood patterns, and wood tissue, only the temperature and some interactions related to this parameter influence the type of density profiles of densified wood of the three species (Table 5). Although most of the densified samples of all three species had density profile type 1, there is a clear tendency to increase the percentage of samples with density profile 3 (Fig 3[c]) as the densification temperature increases, 180°C for *A. acuminata* and *V. guatemalensis* and 160°C for *V. ferruginea* (Fig 4).

This behavior is due to the fact that higher temperature enables relaxation of the inner stress and even minor thermal degradation of the cell wall components takes place, leading to a more stable state after compression (Laine et al 2014). More specifically, higher temperature might lead to breaking of the existing covalent and hydrogen bonds and the formation of new cross-linkages and hydrogen bonds between the cellulose and hemicellulose, fixing the deformation (Dwianto et al 1999; Navi and Heger 2004). By contrast, with lower temperatures, there is very little stress relaxation, and thus, the deformation is expected to be mainly elastic. The elastic energy is stored in the cell walls, and as the load is removed, the stress is released, causing immediate spring-back deformation (Dwianto et al 1999; Navi and Heger 2004). This could lead to formation of density profile types 1 and 2 (Fig 5[a] and [b]).

An important result observed was that the compression time, the use or not of steam, the type of wood pattern, the type of wood tissue, and their interactions on the type of the density profile were not significant in all species (Table 5). Then, the type of the density profile is determined almost exclusively by temperature, which allows the polymers and the anatomical features of wood to achieve flexibility to compress or deform during the densification process, resulting in one of the density profiles observed in the densified wood. Therefore, the effects of steam, type of wood tissue, or wood pattern are not important during the densification process of the wood.

Density profile type 4 (Fig 5[d]) was least frequent in the densification process (Fig 6). Although both metal plates were monitored to maintain stability and equal temperature throughout the process, one of the plates must have presented higher temperature than the other at some time, causing higher heat transmission on one side of the thickness of the samples, thus creating a zone of higher density than the opposite zone.

CONCLUSIONS

The densified wood of the three species presented four density profiles, where areas of high and low density are presented: 1) the thickness center of the sample having the highest density peak, 2) two high-density areas standing at the center of the sample, 3) uniform density pattern, and 4) one side of sample thickness has the highest peak density. The variation between high and low density is due to the variation in the compression of the anatomical elements in the cross section of wood. Areas with vessels that maintain their original shape are found in low-density regions, whereas in high-density regions, the vessels are completely deformed. The presence of density profiles was attributed to the temperature effects in the three species, but other properties such as compression time, use or not of steam, and the type of wood patterns or wood tissue did not present any effect on density profiles. Then the type of the density profile is determined almost exclusively by temperature and initial wood micromorphology. The initial size of the

anatomical structures, such as vessels, affects the compression stage during the densification process and causes formation of less homogeneous or irregular density profiles.

Profile variation (areas of high and low density), mainly density profile types 1, 2, and 4, is less desirable because there are irregular properties. Then, density profile 3 is desirable for its uniform density. There is a tendency to increase the percentage of samples with density profile 3, as the densification temperature increases in the three species, especially in *A. acuminata*, where the small diameter presence helped producing more uniform density profiles (type 3). But in *V. guatemalensis* and *V. ferruginea* wood, the presence of density profile 3 was lower in highest temperatures (180°C), attributed to larger vessels. Thus, it is essential to explore these two species more for appropriate density profiles.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Vicerrectoría de Investigación y Extensión of the Instituto Tecnológico de Costa Rica, to Ethical Forestry S.A. who contributed with the materials for this research, and to the staff of the Laboratório de Anatomia e Dendrocronologia, Departamento de Ciências Florestais of the University of São Paulo, for their help in carrying out the tests, especially to Fernanda T. P. Guedes. The authors thanks to María Teresa Vargas L. for translation and edition English.

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