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Drying behavior and decay resistance of rubberwood from steamed log and presteamed lumber

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ABSTRACT

The objective of this study was to evaluate the effect of log steaming and steaming prior to drying singly and both treatments together on the drying behavior and decay resistance of *Hevea brasiliensis* wood (rubberwood). Logs with a diameter of 34.6 ± 4.4 cm were used. Half of the logs were kept in their original condition, and the other half were steamed at 90°C for 36 h. Later, the logs were cut into flat sawn boards. Half of the boards were kept in their original condition, and the other half were presteamed at 90°C for 3 h after 1 h of heating-up. These boards were dried in a drying kiln. The drying defects, drying time, drying rate, and decay resistance of wood to the *Pycnoporus sanguineus* fungus were determined. The results showed that the steaming is not suitable for decreases in the time and the drying rates of this kind of wood, and it neither reduces the drying defects of boards. Furthermore, these treatments adversely affected the decay resistance of rubberwood to *P. sanguineus* fungi.

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Drying defects; *Hevea brasiliensis*; steamed logs; steaming prior to drying; wood drying

Introduction

The main problems regarding the use of *Hevea brasiliensis* (rubberwood), particularly as lumber, are due primarily to their intrinsic characteristics, such as drying defects such as warp, twist, bow, and splitting during the drying process[1–4]; fast biodegradation and susceptibility to fungi and insects after felling[2,5]; and high levels of growth stress.[4,6,7]

Steaming wood is a technique that may alleviate the problems during the sawing and drying processes, and it is applied for a variety of other purposes, such as to reduce growth stress levels,[8–10] change color, improve the dimensional stability,[11–14] increase the permeability[15] and drying rate, and reduce the initial moisture content (IMC), moisture gradient, and drying defects.[1,3,13,14,16–19]

When steamed at 54°C, the *H. brasiliensis* logs produce boards with higher end-cracks, where 704 and 239 mm are in their respective central and peripheral boards, whereas the steamed logs at 92°C present a greater relief of growth stresses, as observed by the smaller difference between the cracks' length in the central (394 mm) and peripheral (165 mm) boards.[20]

The drying process is the best way to add value to the lumber.[3,4,19,21] Although some kinds of wood, among them *Paulownia fortune*,[22] *Eucalyptus grandis*, and *Corymbia citriodora*,[23] present low liquid and gas permeability, the rubberwood is a relatively fast-drying wood[24] due to its high permeability.[25]

Steaming at 100°C for 5 h before conventional drying neither causes an increase in drying rate nor reduces the defects of *H. brasiliensis* lumber,[3] whereas the treatment at 90°C for 7 h causes a decrease of 11% in the board's end-cracks of rubberwood.[1] Steam at 110°C was injected intermittently in the vacuum-drying process, and surface cracks or cracking were eliminated to relieve drying stress in rubberwood boards of 25.4 mm thickness.[26] However, the log steaming before sawing is a new procedure for rubberwood and has neither been performed by the authors.

In addition, the heating of wood at high temperatures causes degradation of the hemicelluloses and in the amorphous regions of cellulose, it modifies the original properties of the material, especially when exposed under high humidity or steam.[12,24,27] Doi et al.[28] concluded that *Larix leptolepis* wood submitted at 120°C presents a decrease in the resistance to decay by fungus *Fomitopsis palustris*. According to the authors, temperatures of up to 120°C promoted the degradation of hemicelluloses and the generation of low-molecular-weight compounds (sugars fragments), which are highly attractive to fungi. These compounds

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will be cross-linked with the lignin and are unavailable for rot-fungus when heated to higher temperatures.

Thus, the aim of this study was to evaluate the effect of log steaming and steaming prior to drying singly and both treatments together on the drying behavior and decay resistance of *H. brasiliensis* wood.

Materials and methods

Collection of material

This study utilized trees from 53-year-old *H. brasiliensis* ungrafted from the Miraculous Water Farm, located in Tabapuã (20° 57′ 50″ S; 49° 01′ 55″ W), São Paulo, Brazil. After felling, the trees were sectioned into 3.0-m logs. In all, 33 logs with diameters of 34.6 ± 4.4 cm were used.

Two techniques to relieve growth stress in logs were used together: grooves and log steaming. Two grooves were machined to a depth equal to one-third of the radius of each log at 10 cm from the crosscut section in all logs, as recommend in the literature.[9,10,20,29]

Thermal treatments for wood

The steaming was applied to one part of the paired logs, and the other half of the logs were kept in the original condition (untreated). The logs were steamed for 36 h at 90°C and 100% relative humidity in a steamer that was equipped with an electric boiler with an operating pressure of 8 kgf/cm^2.

The untreated and steamed logs were cut into flat sawn boards using a twin band saw, and then, they were sawed into boards that were 28-mm thick. Subsequently, each board was cut in half along the transverse direction. Half of the paired boards were kept in the original condition, and the other half were reserved for steamed prior to drying (presteaming). The presteaming was conducted under saturated steam at 90°C for 3 h after 1 h of heating-up, as performed by several authors.[1,3,11,30]

The presteamed boards from the steamed logs were called *steamed logs* plus *presteamed lumber*. Then, the four treatments were analyzed: untreated, log steamed, presteamed wood, and steamed logs plus presteamed.

Determination of boards' drying rate and time in the kiln drying

A load with 246 boards was dried in the conventional dry kiln with a capacity of approximately 2.5 m^3 of wood. The aim of this drying was to verify the effect of several steaming treatments on the drying time and drying rate from *H. brasiliensis* lumber on the conditions of drying kiln. The drying schedule[2] shown in Table 1 was used.

Six boards of each treatment (untreated wood, log steamed, steamed prior to drying, and steamed logs plus presteamed) were used to determine the drying time and drying rate of *H. brasiliensis* lumber in the conventional kiln process. One resistive sensor of moisture content (mark-model LIGNOMAT ID NP6TXPPROBES) was placed into each one of the boards. During the drying process, these resistive sensors provided the moisture content of each board to the control system of kiln by radio frequency. At the end of the drying process, a curve of drying to each board was recorded. Thus, it was possible to determine the IMC and the drying rate (%/day) of each treatment by the moisture content of the boards and their drying times.

Evaluation of the board's drying defects

To evaluate the drying defects in *H. brasiliensis* lumber, the researcher determined how this drying stress was manifested in the lumber through the board-end splitting and warping (cupping, bow, spring, and twist) in the boards. The lengths of end-splits and the warping sag in the boards were measured after the drying process.

The indexes of the board's drying defects were obtained according to Eqs. (1) and (2) presented to standard IBDF[31] and performed according to Calonego and Severo[18]:

$$I_W = \frac{x}{L} * 100 \quad (1)$$

$$I_S = \frac{S}{L} * 100 \quad (2)$$

Table 1. Drying schedule to boards of *Hevea brasiliensis*.

Moisture content (%)	DBT (°C)	WBT (°C)	RH (%)	EMC (%)	DP
Heating	55	53	90	18	–
Up to 50%	55	52	85	15.6	3.2
50%	55	51	81	14	3.9
45%	55	51	81	14	3.2
40%	57	52	77	12.6	3.2
35%	57	52	77	12.6	2.8
30%	60	51	62	9.8	3.1
25%	65	53	54	7.5	3.3
20%	70	55	48	6.4	3.1
15%	80	60	40	4.9	3.1
10%	80	60	40	4.9	2.0
Equalization	80	70	64	8.0	–
Conditioning	80	76.5	86	14.0	–

DBT, dry-bulb temperature,°C; WBT, wet-bulb temperature,°C; RH, relative humidity, %; EMC, equilibrium moisture content, %; DP, drying potential.

where:

I_W, index of warping, %;
I_S, index of splits, %;
x, sag on board curvature, m;
S, end-splitting length, m;
L, boards size, m.

The bow, spring, and twist indexes were performed by the relationship between the sags measured and the board's length. The cupping index was determined by the relationship between the cupping measured and the board's width. The main end-split and the end-splitting sum indexes were determined, respectively, by the principal split and/or sum of the individual lengths of the splits in relation to the board's length.

Accelerated laboratory tests of decay resistance

ASTM D-2017[32] was used to evaluate the effect of thermal treatment on the biologic durability of *H. brasiliensis* wood. Samples tested were cut approximately 40 mm from the pith (juvenile wood) and 40 mm from the bark (mature wood) and measured 25 by 25 by 9 mm (tangential, radial, and longitudinal directions, respectively). Samples were obtained according to ASTM D-2017.[32] Although this standard requires only six samples, 15 samples obtained from five boards were used to characterize each of the treatments (untreated, log steamed, presteamed wood, and steamed logs plus presteamed for both juvenile and mature wood for a total of 120 samples).

The wood samples were dried at 103 ± 2°C, until they were of a constant weight. As recommended by ASTM D-1413,[33] the initial oven-dry weight of each test block was determined both before and after the decay laboratory tests. Subsequently, the samples were placed in a climatic chamber that was adjusted to 21°C and 65% relative humidity until it reached the equilibrium moisture content.

After sterilization, the test blocks were placed in the culture bottles, with the cross section face down on the feeder strip. The cultures of white-rot fungus *P. sanguineus*, which cause extensive decay in rubberwood[5] (collected from the mycology collection of the Laboratory of Forest Pathology from Department of Vegetal Production of FCA-UNESP, Botucatu, SP, Brazil), were incubated in an incubation chamber in the dark to promote the growth of the fungus at 26.7 ± 1°C and 70 ± 4% relative humidity for 12 weeks.

The percent weight loss in the individual test blocks was then calculated to provide a measure of the relative decay susceptibility or, inversely, the decay resistance of the untreated and several levels of steamed *H. brasiliensis* wood.

Statistical analysis

For the evaluation of IMC, drying rate, drying defects, and biologic resistance to decay fungi, a Kolmogorov–Smirnov's normality test at 5% significance was performed. All variables had normal distribution, except drying defects of boards.

Subsequently, a parametric one-way (ANOVA) test at 5% significance was performed while taking into account the thermal treatment, as well as the Tukey's test at 5% significance for the comparison of the means in IMC and the drying rate of boards.

A parametric two-way (ANOVA) test at 5% significance was performed while taking into account the type of wood and the thermal treatment, as well as the Tukey's test at 5% significance for the comparison of the means in the weight loss of wood exposure to fungus *P. sanguineus*.

For the drying defects of boards, a nonparametric Kruskal–Wallis test at 5% significance was performed while taking into account the thermal treatment, as well as the Mood's test at 5% significance for the comparison of the medians.

Results and discussion

Effect of steaming on initial moisture content and drying time and rate of rubberwood

The p values of the Kolmogorov–Smirnov's normality test for initial moisture content, drying times, and rates vary from 0.072 to 0.794. Table 2 shows the average values for the initial moisture content, total drying times, and rates of untreated *H. brasiliensis* lumber. Similar results were found by Srivaro et al.,[1] who concluded that lumber of *H. brasiliensis* dried from green to equilibrium moisture content took 117 h.

This study also showed that the drying rate above fiber saturation point (FSP) (8.1%/day or 0.34%/h) was lower than the drying rates obtained by other authors[1] for lumber of the same species, which exhibited values of 1.7%/h when dried at 60°C of dry-bulb temperature; whereas the drying rate below FSP (17.1%/day or 0.71%/h at 80°C DBT) was similar to that obtained in the referenced study (0.6%/h at 75°C DBT).

However, in the referenced study, the wood-drying process was performed in an oven with air ventilation (4 m/s) that was two times higher than that in this study (2 m/s), and the moisture loss above FSP that was caused by the biggest air velocities increases the drying rate of wood. Similar results were found by Theppaya and Prasertsan,[21] who concluded that the drying time of *H. brasiliensis* wood decreases with the increase in air velocity. Moreover, this behavior corroborates with that

Table 2. Effects of several levels of steaming on initial moisture content and drying times and rates of *Hevea brasiliensis* lumber in the conventional kiln process.

Treatments		IMC (%)	Total drying time (h)	Total drying rate (%/day)	Drying rate above FSP (%/day)	Drying rate below FSP (%/day)
Untreated	Means	62.6[a]	127.8[a]	9.7[a]	8.1[a]	17.1[a]
	C.V.	11.3	13.1	19.9	24.4	20.2
Log steamed	Means	58.6[a]	120.1[a]	10.2[a]	8.3[a]	21[a]
	C.V.	18.6	8	9.7	12.9	25.6
steamed prior to drying	Means	59.5[a]	101.7[a]	11.1[a]	9.5[a]	18.2[a]
	C.V.	31.5	21.4	23.4	29.9	32.4
Steamed logs plus	Means	57.5[a]	125[a]	10.1[a]	8.3[a]	18.3[a]
presteamed	C.V.	33.9	11.8	19.4	28.9	9.6

C.V., coefficient of variation, %, IMC, initial moisture content, %; FSP, fiber saturation point; Means followed by different letters in same column denote significant difference by Tukey test at 5% significance between treatments; same letters in same column denote nonsignificant difference.

attested by Theppaya and Prasertsan,[4] who concluded that below the FSP, air velocity plays an insignificant role in both drying rate and moisture diffusivity of wood.

In addition, this study shows the effect of several steaming treatments on the drying of *H. brasiliensis* lumber. As can be seen, in Table 2, the log steaming, steaming prior to drying, and steamed logs plus presteamed do not reduce the initial moisture contents nor improve the drying times and drying rates of rubberwood.

These results are different from those obtained by Alexiou et al.,[16] who concluded that the effect of presteaming at 100°C on *Eucalyptus pilularis* provided an increase in drying rate between 7 and 16%. They are also different from those presented by Severo et al.,[19] who concluded that the same treatment caused a decrease of 9.2% in the initial moisture content and an increase of 6.2% in the drying rate of *Eucalyptus dunnii*.

This effect was not observed in this study, and it may be explained by the higher temperatures adopted by the respective authors as well as by the difference of permeability between rubberwood and eucalyptus wood. The values of gaseous permeability in the longitudinal directions in the heartwood of *H. brasiliensis* were up to 286.5 cm^3/cm at m s[25], whereas those in *E. grandis* wood were up to 25 cm^3/cm at m s.[23]

The increase in the drying rate from eucalyptus and pine wood may be attributed to an increase in the permeability of the warts layer and the accessibility to the S3 layer from the cell wall, the thermal degradation by acid hydrolysis of the chemical components from the cell walls, and the mobilization and partial removal of extractives during the steaming[15,16,19], whereas that pitting of fiber from rubberwood is unoccluded and nonvestured and, thus, this wood presents little physical barrier to the flow of fluids.[25] Similar results were found by Liping and Oliveira,[30] who concluded that the presteaming at 90°C for 4 h is not an effective method to improve the permeability of *Abies lasiocarpa* wood.

The results corroborate with those presented by Ratnasingam et al.,[3] who concluded that the steaming prior to drying at 100°C during 5 h cannot increase its drying rate nor reduce the drying defects of rubberwood lumber. According to the authors, the minimum condition that promotes significant improvements in drying defects was 10 h.

Effect of steaming on drying defects of rubberwood

The *p* values of the Kolmogorov–Smirnov's normality test for all indexes of the drying defects of *H. brasiliensis* lumber were smaller than 0.001. Table 3 shows that the main end-split, end-splitting sum, bow, spring, cupping, and twist indexes of untreated rubberwood boards caused only by the drying process were 1.19, 2.07, 0.0, 0.0, 0.0, and 0.0%, whereas those of the respective defects after mechanical processing and the drying process together were 4.83, 6.18, 0.22, 0.62, 0.0, and 0.0%. Similar results were found by literature,[1,3] which concluded that the board's end-splits were the drying defects that occurred more in *H. brasiliensis* lumber.

In addition, this study shows the effect of several steaming treatments on the drying defects of *H. brasiliensis* lumber. As can be seen in Table 3, the log steaming, steaming prior to drying, and steamed logs plus presteamed lumber do not reduce both the defects caused only by the drying process and the defects produced during all forms of processing of the studied wood.

The log steaming and steaming prior to drying are procedures that improve both the yield and the quality of various kinds of eucalyptus lumber.[16–19] This effect was not observed in this study. This result was expected, because, as previously shown, the permeability of *H. brasiliensis* is better than that of eucalyptus wood, since the pitting of fiber of rubberwood is unoccluded and nonvestured and, thus, this wood presents little physical barrier to the flow of fluids.[25] This corroborates with the behavior observed in a study performed

Table 3. Effects of several levels of steaming on drying defects of *Hevea brasiliensis* lumber in the conventional kiln process.

			Defects index produced only by drying process (%)						Defects index after mechanical processing plus drying process (%)					
Treatments	N		P.S.	ΣS	Bow	Spring	Cupp.	Twist	P.S.	ΣS	Bow	Spring	Cupp.	Twist
Untreated	64	Median	1.19^a	2.07^a	0^a	0^a	0^a	0^a	4.85^a	6.18^a	0.22^a	0.62^a	0^a	0^a
		C.V.	211.7	156.1	169.9	173	142.7	206.2	147.9	133.9	78.6	40.9	142.7	188.5
Log steamed	58	Median	1.10^a	2.52^a	0.10^a	0.03^a	0^a	0^a	7.36^b	13.37^b	0.25^a	0.62^a	0^a	0^a
		C.V.	213.9	198.9	127.4	145.1	313.6	227.3	100.3	108.2	61.9	59.3	313.7	209.1
Steaming prior to drying	66	Median	0.70^a	1.92^a	0.05^a	0.04^a	0^a	0^a	4.44^{ab}	6.50^a	0.31^a	0.61^a	0^a	0^a
		C.V.	282.2	214.4	152.8	143.8	141.8	189	140.4	132.1	62.8	54	141.8	183.8
Steamed logs plus presteamed	58	Median	0.94^a	3.03^a	0.09^a	0^a	0^a	0^a	6.02^{ab}	8.75^{ab}	0.26^a	0.67^a	0^a	0^a
		C.V.	205	171.7	160	232.8	156.6	160.5	107.4	119.4	91.4	53.9	156.6	153.9

N, repeat number; C.V., coefficient of variation, %; P.C., principal end-splits; ΣC, board's end-splitting sum; Cupp., cupping; Median followed by the same letters in same column denote significant difference by Mood test at 5% significance between treatments; same letters in same column denote nonsignificant difference.

by Sik et al.,[24] who showed that the presence of low residual stress detected in both conventional and high-temperature dry rubberwood is reflected by the small moisture variation (<2%) between the surface and core of the lumber.

However, steaming prior to drying for 7 h[1] and 10 h[3] may reduce the drying defects of rubberwood. This is likely due to the fact that lumber had an extended steaming time. These authors[3] steamed the rubberwood between 5 and 15 h and concluded that the minimum condition that promotes significant improvements in wood drying variables is 10 h.

Thus, as the time used for steaming the lumber was lower than is recommended by literature,[1,3] we cannot dismiss the possibility that smaller drying defects may occur if longer time is used. However, if the steaming process is used to improve the permeability of the wood and reduces the drying defects, we can conclude that for a permeable wood[25] and of relatively fast drying,[24] at studied conditions, it is a technique that is not effective for further reducing the defects of rubberwood.

Effect of steaming on decay resistance of rubberwood to white-rot fungus

The p value of the Kolmogorov–Smirnov's normality test for weight loss of wood exposure to fungus *P. sanguineus* was 0.159. The weight losses were equal statistically ($p = 0.276$), respectively, 37.32 and 33.20% for untreated juvenile and mature wood samples from *H. brasiliensis* (Table 4) that were incubated with the white-rot fungus *P. sanguineus*. Based on these results, *H. brasiliensis* wood can be classified according to ASTM D-2017[32] in the class of moderately resistant to decay, one in which the weight loss due to decay varies between 25 and 44%. Similar results were found by Severo et al.,[5] who concluded that *H. brasiliensis* exposed to *P. sanguineus* showed a weight loss of 37.24 and 40.78%, respectively, to juvenile and mature wood.

In addition, the evaluations of samples submitted to the action of the white-rot fungus *P. sanguineus* indicated that there was a significant worsening in the decay resistance of *H. brasiliensis* wood with several steaming treatments.

The weight loss by decay for untreated wood and log steamed, steamed prior to drying, and steamed logs plus presteamed lumber in both juvenile and mature wood from rubberwood is presented in Table 4. This study showed that thermal treatments significantly increased ($p < 0.001$) the weight loss from juvenile wood samples incubated in a soil-block test of 7.1–10.3%, whereas in mature wood, the weight loss was increased from 15.2 to 27.3%.

This result is consistent with the results cited by Doi et al.,[28] who characterized the biologic resistance of *L. leptolepis* wood and concluded that 130°C was the minimum condition in the thermal treatment that

Table 4. Effects of several levels of steaming on decay resistance of juvenile and mature wood from *Hevea brasiliensis* to fungus *Pycnoporus sanguineus*.

	Juvenile wood (J.W.)				Mature wood (M.W.)				
Treatments	N	C.V.	WL (%)	↓ or (↑) (%)	N	C.V.	WL (%)	↓ or (↑) (%)	↓ or (↑) between J.W. and M.W. (%)
Untreated	15	21.4	37.32^a	–	15	18.9	33.20^a	–	11^{NS}
Log steamed	15	15.4	39.97^b	(7.1)	15	11.7	40.98^b	(23.4)	(2.5)^{NS}
Steaming prior to drying	15	9.4	41.18^b	(10.3)	15	11.5	38.26^b	(15.2)	7.1^{NS}
Steamed logs plus presteamed	15	15.9	41.18^b	(10.3)	15	15.9	42.27^b	(27.3)	(2.6)^{NS}

N, repeat number; C.V., coefficient of variation, %; WL, weight loss; Means followed by the same letters in same column denote significant difference by Tukey test at 5% significance between treatments; *within rows denote significant difference by *F* test at 5% significance between type of wood; same letters in same column and ^{NS}within rows denote nonsignificant difference.

promotes significant improvements in a wood's biologic resistance to the fungus *F. palustris*. The results corroborate with those presented by Severo et al.,[5] who concluded that only the thermal treatment above 200°C during 2, 5 h results in a significant increase in the decay resistance to the fungus *P. sanguineus* due to a significant reduction in the contents of sugars in juvenile and mature woods.

Doi et al.[28] explain that temperatures of up to 120°C promoted the degradation of hemicelluloses and the generation of low-molecular-weight compounds (sugars fragments), which are highly attractive to fungi and, consequently, increases the decay of wood treated in this condition. Other studies[5] showed that these compounds would be cross-linked with the lignin and unavailable for rot-fungus when the rubberwood has been heated to higher temperatures than those adopted in steamed treatments; furthermore, new molecules that act as fungicides would be produced.

Several authors[1,3,8–15,17,18,20] have shown that steaming is a technique that may solve several problems of various kinds of wood. However, in conditions applied by this study, the log steaming, steaming prior to drying, and steamed logs plus presteamed lumber cannot be applied for *H. brasiliensis* wood without adversely affecting the decay resistance of wood.

Conclusion

In verifying the effects of log steaming, steaming prior to drying, and the application of steaming logs plus presteaming lumber on the drying behavior and decay resistance of *H. brasiliensis* wood, it was concluded that the techniques are neither effective in decreasing the time and the drying rates of this kind of wood nor effective in reducing their drying defects. Furthermore, the steaming adversely affected the decay resistance of rubberwood to *Pycnoporus sanguineus* fungi.

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