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STUDYING THE GRAMMAGE IN LVL PANELS GLUED WITH CASTOR OIL-BASED POLYURETHANE ADHESIVE: A POSSIBLE ALTERNATIVE TO FORMALDEHYDE RELEASING ADHESIVES.

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HIGHLIGHTS

Study of an alternative adhesive based in castor oil in LVL panels gluing.

Investigation of different grammages in order to save adhesive.

The grammage of 240 g.m^{-2} showed highest volumetric swelling in water among the adhesives.

Polyurethane showed better results for shear strength in the glue line.

Keywords:
Natural adhesives
Wood panels
Veneer gluing
Structural panel

ABSTRACT

Efforts have been done in order to decrease the human dependence on petroleum materials. This idea can be applied for wood adhesives and wood products. This study proposes to evaluate laminated veneer lumber (LVL) panels of *Hevea brasiliensis* produced with castor oil-based polyurethane and resorcinol formaldehyde in different grammages. Six rubber tree (12 years old) with diameters at breast height (DBH) > 25 cm were harvested to generate veneers (500 x 500 x 2 mm; length, width, and thickness, respectively) for the panels production. The veneers were pre classified by a non-destructive impulse excitation method (Sonelastic system). Seven veneers were arranged in the same grain direction to produce each LVL. The following grammages were used for each adhesive type: 240, 280 and 320 g·m^{-2}. The volumetric swelling of the panels, glue line strength under dry, wet and post-boiling conditions, and stiffness and strength in static bending tests in flatwise and edgewise positions were evaluated. The glue line was evaluated by optical microscopy. The panels with grammages of 240 g·m^{-2} had the highest volumetric swelling for both adhesives. As the grammage increased from 240 to 280 g·m^{-2}, the panel volumetric swelling decreased 32.53% for the resorcinol formaldehyde adhesive and 21.42% for the castor oil-based polyurethane adhesive. The panels glued with the vegetal polyurethane adhesive presented the best results for shear strength in the glue line. No significant statistical differences were found between the compositions for static bending. The results indicate that rubber wood glued with vegetal polyurethane has the potential to be used for production of LVL panels and consequently replace the petroleum based adhesives.

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INTRODUCTION

Petroleum is a non-renewable and finite source of energy used for production of fuels, plastics, adhesives, whose the final residues of this chain may cause several environmental problems. Among the derived products, it can be highlighted the polymeric adhesives. These products consist of polymers used in most materials which bonding is required, due to their ease of manufacturing. The main examples of these adhesives are urea formaldehyde, phenol formaldehyde and resorcinol. The problem with some adhesives, in special the urea formaldehyde, is the excessive release of formaldehyde, which can cause health problems as some types of cancer irritation of the skin, eyes, nose and affect the upper respiratory system in people which have continuous contact. Petroleum based adhesives therefore needs to be replaced by adhesives based in alternative and sustainable sources. With the green building practices gaining worldwide popularity, several green (or biobased) adhesives have been developed (Pizzi, 2006), mainly in order to produce formaldehyde-free adhesives. Some examples of biobased adhesives are: tannin-condensed based (Pichelin et al., 2006), lignin adhesives (Ghaffar and Fan, 2014), soya based adhesive (Muttil et al., 2014), among others. Although all these green adhesives have been developed, there are still challenges in finding the suitable chemistry to make these adhesives even more competitive when compared with the traditional petroleum-based ones. The civil construction sector has a high demand for materials with good mechanical strength, low cost and practical production. As a result, materials composed by wood and adhesive have been recently developed to enhance the structural properties of wood materials from deficits such as natural defects and knots. Some examples of these materials include glued laminated timber (glulam), cross-laminated timber (CLT) and laminated veneer lumber (LVL). LVL has the potential to be used in structural and non-structural applications such as construction and furniture industry, material for flooring and several other field (Lam, 2001). MOR and MOE of plywood/LVL are affected by a number of factors such as the tree species, tree quality, wood moisture, density, structure, number of plies, veneer thickness and type of adhesive (Bekhta et al., 2020). Similar to plywood, LVL is produced with thin veneers, usually ranging from 2.5 to 4 mm in thickness, however, the structural plywood is composed by crosswise layers, which are designed with the grains of adjacent layers oriented perpendicularly each other. Brazil is not an industrially producer of LVL, reason because this product has been the focus of academic research in certain laboratories and research centres across the country (Lara Palma and Ballarin, 2011). Therefore, there is a need for research on species from Brazil or from commercial forests, especially non-conventional wood species. In addition, it is essential to define the best process parameters for production of LVL with satisfactory properties to be used in civil construction.

In Brazil, the rubber wood obtained in the end of the latex production cycle is traditionally used as firewood. However, studies report that rubber wood has good workability characteristics (bonding, machining and insertion of nails and screws) and can be easily dyed (Lara Palma, 2010). The serviceability of LVL production depends on, firstly, the kind of wood and its preparation for use, secondly, the type and quality of the adhesive, thirdly, the compatibility of the gluing process with the wood and adhesive used, and lastly, the type of joint and assembly (Özçifçi, 2007). LVL is mainly intended for structural use and in wood constructions, such as stairs and flanges of I-beams (Gilbert et al., 2017), due to the greater strength in the longitudinal direction of the panel plane.

LVL has many advantages compared to solid wood. On wood piece, the influence of natural wood defects greatly affects the mechanical properties of the material produced. On the other hand, in LVL the defects of natural wood can be distributed evenly among the layers of veneer in order to minimize the influence of those defects on the strength (Eradoti and Awaludin, 2017). The LVL manufacturing process creates a strong and stable product that can reliably support large areas. A second important benefit is the veneering and gluing process that enables the production of large beams from logs with small diameters of many species, thereby providing efficient use of forest resources (Çolak et al., 2007). Studies on LVL have focused on topics such as: effects of the veneers positions of different species on the panel properties (Berger et al., 2018), LVL production from veneers recovered from early to mid-rotation (juvenile) hardwood logs (Gilbert et al., 2019), veneers bonded with expanded polystyrene (Del Menezzi et al., 2017), number of LVL layers (Özçifçi, 2007), loading direction on the mechanical properties of the panel (Burdurlu et al., 2007), emission of volatile organic compounds (Ayrilmis et al., 2016) and the combustion properties of LVL (Özçifçi and Okçu, 2008).

Adhesive saving in the gluing process is desirable and a strong point for being studied, as a consequence there is a reduction in formaldehyde release levels and cost savings. The ideal final product would be produced with the least amount of adhesive as possible but with no loss in the mechanical strength. Most studies use phenol-formaldehyde or resorcinol formaldehyde resins with a grammage 180 to 320 $g.m^{-2}$ to form panels (Çolak et al., 2007).

This paper focuses on the relation between the grammage and the mechanical behaviour of LVL beams produced from Brazilian rubber wood. In this context, the aim of this study was to develop a type of LVL produced with castor oil-based polyurethane and resorcinol formaldehyde adhesive with three different grammages in order to save adhesives with no loss in mechanical quality.

MATERIAL AND METHODS

Obtainment and preparation of the raw material

Six *Hevea brasiliensis* trees (12 years old; clone RRIM 600) with and diameter at breast height (DBH) > 25 cm were harvested from a rubber plantation (spacing 5 x 5 m) located in Nepomuceno (21°17'33"S, 45°10'41"W; altitude 904 m), Minas Gerais State, Brazil. Logs with 0.60 m were removed from the base of each tree and heated at 70 °C for 24 h in water for obtainment of wood veneers with dimensions 500 x 500 x 2 mm (length, width and thickness, respectively). The mean specific density of the veneers was 0.675 g·cm^{-3} (moisture ~12%). The veneers were dried in a forced air oven until reach 8% moisture content (dry mass basis).

Classification of the veneers

The veneers were classified by impulse excitation technique with a Sonelastic system (ATCP, São Paulo, Brazil). The system consists on a bars support where the veneers are placed and mechanically stimulated by an impulse device, producing sound waves that propagates through the veneer, being captured by a microphone. The data obtained pass by a processing centre and is used to determine the elastic constant (Figure 1). The veneers were classified by the dynamic modulus of elasticity (dMOE), therefore dMOE greater than 1000 MPa intended for the LVL faces while those with dMOE lower than 1000 MPa were used in the core.

Production of LVL panels

The panels were composed of seven veneers arranged in the same grain direction. The adhesives were applied with a spatula over the surface of the veneers, being produced three LVL panels for each composition (Table 1). The adhesives studied were resorcinol formaldehyde (Cascophen RS 216-M) with the addition of 15% catalyst (prepared catalyst F-60-M; in relation to adhesive mass) and castor-oil-based vegetal polyurethane, bi-component, in proportion of 1:1.5 from component A (prepolymer) to component B (polyol) (Table 2).

TABLE 1 Grammages studied for both adhesives

Identification	Grammage (g.m^{-2})	Adhesive
RF_240	240	Resorcinol formaldehyde
RF_280	280	
RF_320	320	
VP_240	240	Vegetal polyurethane
VP_280	280	
VP_320	320	

TABLE 2 Parameters for production of the LVL panels

Parameter	Resorcinol formaldehyde	Vegetal polyurethane
Apparent viscosity (25 °C) (cP)	500.26	430.63
Solids content (%)	72.75	79.43
pH	7.17	7.0
Pressure (MPa) / time (h)	1.47 /24 (room temperature)	

After pressing, the panels were placed in a climatized environment with temperature 20 ± 2 °C and relative humidity 65 ± 5% until the mass stabilization.

Evaluation of the LVL panels

The apparent density of the panels was determined according to NBR 9485 (ABNT, 2011) standard by the evaluation of four samples (50 x 50 x 18 mm). Similarly, the volumetric swelling was determined by the evaluation of four samples (30 x 20 x 15 mm) (length, width, and thickness, respectively) specimens were used, following the TS 4086 (1983) standard. The samples were dried in an oven (103 ± 2 °C) until constant mass and had the mean thickness measured with a calliper. Posteriorly, the samples were immersed in water until the samples reach constant thickness. In the end of the immersion period,

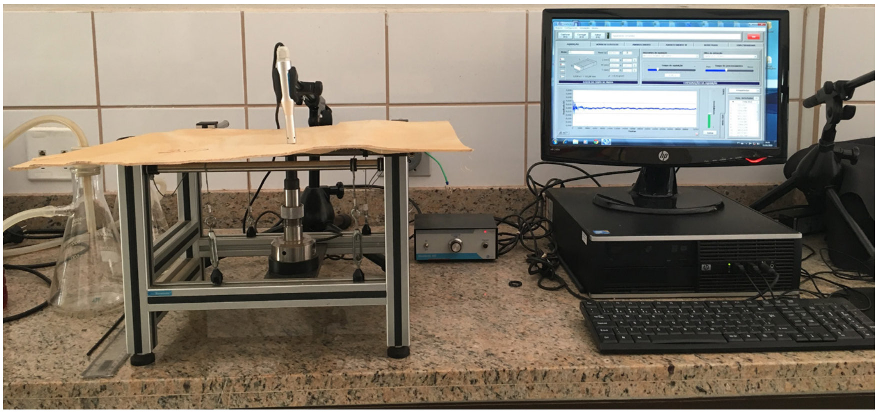

FIGURE 1 Sonelastic system: classification of the veneers by impulse excitation (flatwise position).

the samples were measured again. The volumetric swelling was calculated by the following equation 1, where *VS* is the volumetric swelling, V_{sat} is the saturated volume and V_{dry} is the dry volume.

$$VS = \frac{Vsat - Vdry}{Vdry}\ x\ 100 \qquad [1]$$

The shear strength in the glue line was obtained by the evaluation of twelve samples, described in Figure 2, cut according to the D-2339-98 (ASTM, 2017) standard. The tests were performed under dry, wet and post-boiling conditions, with four samples per condition. For the dry condition test, the samples were kept in a climatized environment with temperature 25 ± 2 °C and RH 60 ± 2%. For the wet condition, the test was performed after 24 h of samples immersion in distilled water. For the post-boiling condition, the samples were boiled for 30 min and then cooled in a distilled water at room temperature. The tests were performed in a pneumatic testing machine (model I 4230, Contenco-Pavitest Cisalhamento 1.01-0) with a load speed 0.6 mm/min. The shear strength was calculated by dividing the maximum load supported by the area of the glued wood veneer subjected to the shear. After rupture, the percentage of wood failures was quantified using a mesh chequered grid (1 mm). The percentage of wood failures was assed according to the procedures described in standard D-5751 (ASTM, 2019) standard.

The static bending test was performed in two positions: in *edgewise* position (six samples) and in the *flatwise* position (six samples) (Figure 3).

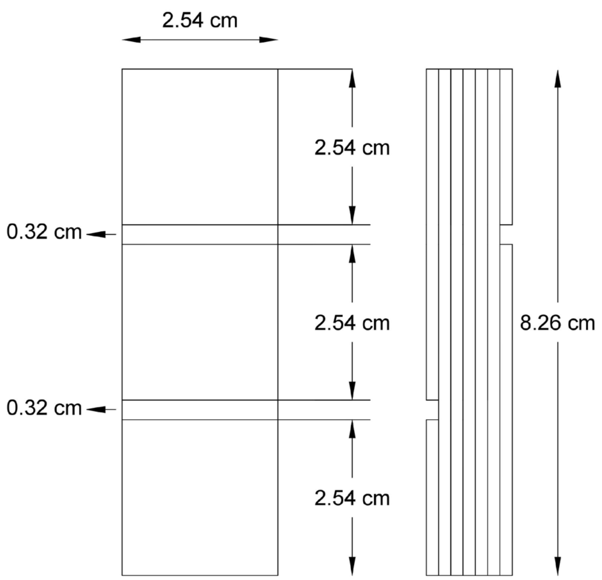

FIGURE 2 Sample for shear strength test; D-2339-98 (ASTM, 2017) standard.

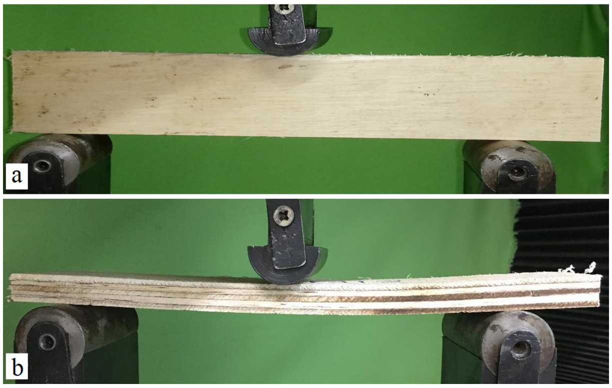

FIGURE 3 Static bending test: a) in relation to the axis of greatest inertia (edgewise) and b) in relation to the axis of least inertia (flatwise).

The samples were cut with dimensions 480 x 50 x 15 mm and tested in an Arotec servo-electric press equipped with a 300 kN load cell. In *flatwise* position, the D-3043 (ASTM, 2017) standard adapted to the final thickness of the LVL samples was followed, with speed test 2 mm/min, while for the *edgewise* position, the speed test adopted was 5.8 mm/min.

Study of wood-adhesive interface

The LVL samples were saturated in a vacuum pump until being soft to cut. The slides were obtained using a slip microtome (Leica SM 2000R). The cuts were washed, dehydrated and fixed on permanent slides with Entellan. The images were obtained by an epifluorescence microscope (Zeiss) connected to a computer (software Image Pro-Plus 5.1). The mean thickness of the glue line was obtained between the two extreme points of the sample, using the *ImageJ* software.

Statistical analysis

The results were subjected to analysis of variance (ANOVA). When significant differences between the results were found, the means were compared by Tukey's test. The analyses were performed at 95% probability using the Sisvar 5.6 software (Ferreira, 2014).

RESULTS AND DISCUSSION

Volumetric swelling

The LVL panels made with a grammage of 240 $g{\cdot}m^{-2}$ had the highest volumetric swelling for both types of adhesive used (Table 3). As the grammage increased, the volumetric swelling of the panels decreased.

The reduction of the volumetric swelling when the grammage increases from 240 to 320 $g{\cdot}m^{-2}$ was 32.53% for the resorcinol formaldehyde and 21.42% for the vegetal

TABLE 3 Mean values for the volumetric swelling and apparent density.

Composition	Volumetric swelling (%)	Apparent density g·cm⁻³)
RF_240	9.53 ± 1.73* B	0.698 ± 0.19
RF_280	6.44 ± 0.77 A	0.704 ± 0.14
RF_320	6.43 ± 0.76 A	0.725 ± 0.25
VP_240	8.08 ± 1.46 AB	0.719 ± 0.16
VP_280	7.26 ± 1.21 A	0.714 ± 0.22
VP_320	6.35 ± 0.42 A	0.744 ± 0.14

Means followed by the same letter in the same column are statistically equal by Tukey test at 95% probability. *Standard deviation

polyurethane adhesive. This behaviour can be explained by the low amount of adhesive at the glue line of the compositions with grammage of 240 g.m^{-2}. Higher amounts of adhesive applied result in better bonding quality, which consequently may result in greater dimensional stability for the panels when in contact with water. These better properties can be attributed to the resins which penetrate wood substrate through the cracks and reduce the chance of woody material to have contact with water and protect the woody material against the moisture absorption, restricting the changes in dimension (Zhang et al., 2018). Dimensional stability is an important property of wood, especially when used in humid conditions as the case of LVL panels used in furniture, train wagons and stairs.

The values obtained for volumetric swelling in this study were lower than those found by Percin and Altunok (2017), working with LVL panels produced with *Fagus orientalis* Lipsky wood reinforced with carbon fibre and obtained mean values of 15.83 and 13.61% for control and reinforced panels, respectively. On the other hand, the results were slightly higher than those for the rubber wood LVL panels tested by Kamala et al. (1999), which obtained volumetric swelling levels of 4.16%.

The shear strength did not showed significant statistical differences between the grammages to the same type of adhesive (Figure 4) in dry, wet and post-boil conditions, which means that a reduction in grammage did not affect the glue line under dry, wet or dry post-boiling conditions for the panels studied.

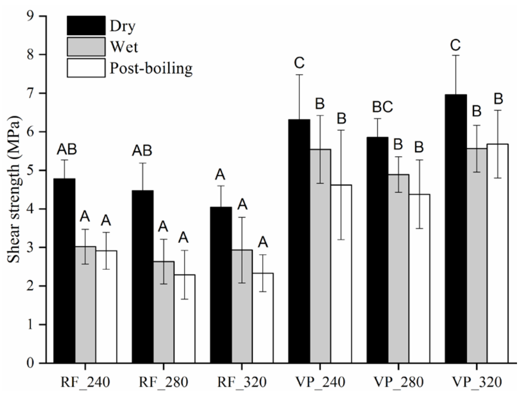

FIGURE 4 Shear strength values of the LVL panels (dry, wet and post-boiling conditions).

Comparing the two adhesives, the panels glued with the polyurethane adhesive showed the highest strength values in the three test conditions. The vegetal polyurethane adhesive was 22, 23 and 41% superior to the resorcinol for the panels produced with grammages 240, 280 and 320 g·m^{-2}, respectively, considering the dry environment. For the wet environment, the results were 45, 46 and 47% superior for the panels produced with grammages of 240, 280 and 320 g·m^{-2}, respectively. For the post-boiling condition the superiority was 37, 47 and 58% for the panels produced with grammages of 240, 280 and 320 g·m^{-2}, respectively. The shear strength results were superior for the dry condition. In this condition, the anchoring of the adhesive is not affected by water. With the increasing grammage of the LVL panels, the mean thickness of the glue line consequently increased and a thicker adhesive line was observed for the grammage 320 g·m^{-2} (Figure 5).

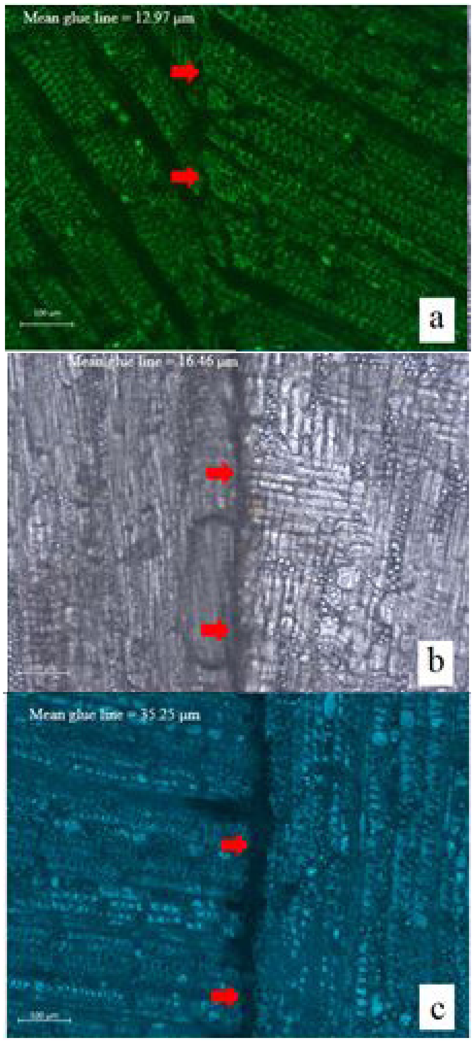

FIGURE 5 Glue line of LVL panels produced with polyurethane adhesive; a) grammage 240 g.m^{-2}, b) grammage 280 g.m^{-2} and c) grammage 320 g.m^{-2}. Red arrows indicate the glue line.

Due to the suitable viscosity of the polyurethane (430.63 cP), the glue line was uniform in its extension. Even for the lower grammages, it was observed the formation of adhesive anchoring hooks with the wood. This fact allowed the obtainment of good mechanical properties even with the grammages 240 and 280 g.m^{-2}. The density obtained for the veneers was 0.675 g.cm^{-3} (see Material and methods section), which allows good fluidity and suitable adhesive penetrability in the rays of the wood structure.

In wet condition, the water affects the anchoring hooks of the adhesive in the wood, weakening the bonds. In addition, water causes saturation of the fibres and consequently an increase in their volumes, which does not occur for the adhesive deposited on the glue line. In the post-boiling condition, the actions of water and heat are present at the same time, which can soften the wood and cause more significant weakening of the adhesive. These results, in general, comprised high wood failure percentages (Figure 6; Table 4). Guimarães Junior et al. (2015) obtained stress values ranging from 4.2 to 6.7 MPa for the dry condition, ranging from 4.1 to 5.3 MPa for the wet condition and ranging from 2.9 to 4.2 MPa for the post-boiling condition, working with LVL panels of *Eucalyptus urophylla*. The glue line can be classified as non-anchored, i.e., with insufficient wetting (Iwakiri, 2005). Similar behaviour was observed by Trianoski et al. (2015), working with plywood of *Melia azedarach* and finding statistically equal shear strength in dry and wet conditions for grammages of 160, 180 and 200 g.m^{-2}.

The wood failure percentages were higher for the polyurethane adhesive for the three grammages studied, which confirms the good adhesive-wood anchorage

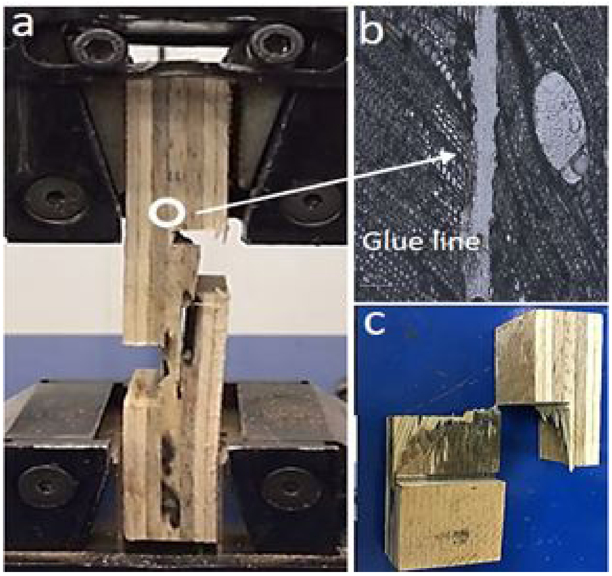

FIGURE 6 a) Shear test in LVL sample; b) highlight in the glue line (320 g·m^{-2}); c) sample after the rupture.

TABLE 4 Shear strength and wood failure of the panels (dry, wet and post-boiling conditions)..

Composition	Dry		Wet		Post-boiling	
	Shear strength (MPa)	Wood failure (%)	Shear strength (MPa)	Wood failure (%)	Shear strength (MPa)	Wood failure (%)
RF_240	4.78 ± 0.49*	62.5	3.02 ± 0.45	12.5	2.91 ± 0.48	37.5
RF_280	4.47 ± 0.72	37.5	2.63 ± 0.58	25	2.29 ± 0.63	37.5
RF_320	4.04 ± 0.56	12.5	2.93 ± 0.85	25	2.33 ± 0.48	25
VP_240	6.31 ± 1.17	100	5.54 ± 0.88	75	4.62 ± 1.42	100
VP_280	5.85 ± 0.49	100	4.89 ± 0.46	75	4.38 ± 0.89	87.5
VP_320	6.96 ± 1.02	100	5.56 ± 0.61	100	5.68 ± 0.88	87.5

shown in figure 5. All shear strength in the glue line results obtained reached the minimum requirement (1 MPa) of the European Standard EN 314-2 (1993), regardless of the wood failure percentage. When holes are located in a region of high shear, the failure starts with cracks forming close to the hole running parallel to the grain, where occur the stress concentration (Musselman et al., 2018). In woods with low density, a large portion of adhesive may penetrate into the wood cell lumen instead of the cell walls, resulting in a starved glue line (Pizzi and Mittal, 2011). As previously discussed, the density obtained for the veneers was 0.675 g.cm^{-3}, which is considered medium density according to Iwakiri (2005). Medium density wood, combined with a suitable adhesive viscosity prevents the formation of "starved" glue lines, when there is an excessive penetration of adhesive in the wood. When the adhesive is excessively viscous and/or the wood has a high density, a non-anchored glue lines can occur, which does not allow the anchoring of the adhesive. There were no significant differences between the compositions for MOE and MOR in the *edgewise* and *flatwise* positions (Table 5). In *flatwise* position (see figure 3) the applied load is orthogonal to the veneer faces, and in *edgewise* position the acting force has a direction parallel to the glue lines (Müller et al., 2015). There is not several literature available on the mechanisms of strength and failure of LVL tested in the *edgewise* position.

The strength of wood based panels may be critical with respect to the *edgewise* load-bearing capacity of the beam cross-section (Fan, 2012). The presence of the non-horizontal skins in the *edgewise* position prevented the premature failure of the core material and resulted to ductile behaviour (Manalo et al., 2010). When LVL was impacted radially, only the wood veneer in the LVL surface absorbed the impact energy (Bao et al., 2001), as can be observed in Figure 7.

The MOR values obtained for the *edgewise* position were higher than the *flatwise* position. For MOE, the highest mean values were obtained for the *flatwise* position. The MOE of a material measures its stiffness, therefore if the material presents high MOE, a

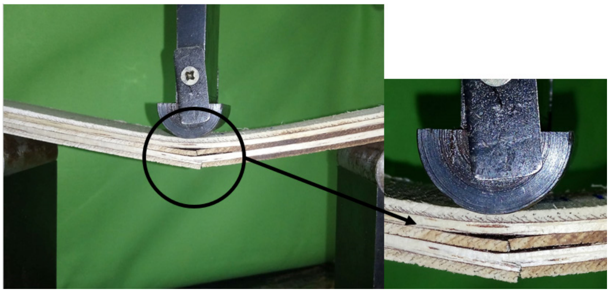

FIGURE 7 Static bending test in the flatwise position highlighting the rupture of the sample.

TABLE 5 Modulus of elasticity (MOE) and rupture (MOR) values in static bending for edgewise and flatwise positions.

Composition	Edgewise position		Flatwise position	
	MOE	MOR	MOE	MOR
	---------- MPa ----------			
RF_240	3554.19 ± 97.23*	197.03 ± 12.66	9039.06 ± 319.31	94.34 ± 1.40
RF_280	3500.44 ± 173.22	201.91 ± 3.48	7729.67 ± 715.76	64.99 ± 10.00
RF_320	3478.68 ± 75.15	205.00 ± 3.30	9744.80 ± 365.74	80.17 ± 11.43
VP_240	3380.47 ± 86.44	201.44 ± 6.43	9004.12 ± 234.51	86.67 ± 14.11
VP_280	3443.71 ± 392.32	182.14 ± 14.97	8712.55 ± 37.36	71.05 ± 15.02
VP_320	4068.83 ± 99.76	246.42 ± 27.10	8528.47 ± 601.49	101.88 ± 11.89

high mechanical stress must be applied to deform it. It can be said that the LVL was more deformable in the *edgewise* position. Manalo et al. (2010) observed by analytical calculations, that the contribution of the core in the flexural stiffness is approximately 10% in the *flatwise* direction and more than 25% in the *edgewise* position. The failure of the composite sandwich beam in the *edgewise* position occurs only when the fiber composite skin fail in compression.

The strength properties of edge glued wooden panels (EWPs) are depend on many factors such as mechanical and physical properties as well as the material compaction with the adhesive and the interfacial adhesion or interphase quality (Çöpür et al., 2007; Ayrilmis et al., 2009). Comparisons of the effective bending stiffness and the predicted bending stiffness indicate that these values were substantially consistent in the *flatwise* direction (Qi et al., 2017). In most structures, as roof trusses, floor joists, wooden members are planned *edgewise*. For specific application, as scaffolding planks, the *flatwise* MOE may be critical (Steffen et al., 1997). Beams in *edgewise* position fail in skin compressive failure while beams in *flatwise* fail in progressive core shear failure and tensile in the bottom. The composite sandwich beams in the *edgewise* position fails at a higher ultimate bearing load than that of beams in *flatwise* position (Zhang et al., 2019). The higher stiffness in the *edgewise* position occurs due to the LVL layers are spatially at the same distance for calculation of the relative moments of inertia because the layers are all positioned in an equivalent way in relation to the neutral line of the set (Müller et al., 2015). In theory, all of the veneers that compose the beam are equally employed during compression at the upper veneer and during tensile at the lower veneer of the beam cross-section. Orienting all veneers in one direction improves the mechanical properties of the product in the grain direction (Ardalany et al., 2012). The skins located at the top and bottom carry the flexural load and the inner core, the shear. In beams and similar applications, structural components are used in the *edgewise* orientation for higher strength and stiffness (Manalo et al., 2010).

In particular, sandwich panels in *flatwise* position are widely used for structural roofs, floors, walls, and bridge decks. Similarly, several bridge decks have been constructed by nailing together timber placed in the *edgewise* position (Johnson, 2002). The interactions between local deformations, size and geometry of the cells are important components of the different *flatwise*-loading behaviour observed in these tests. There is no defined standard in the literature for the performance of LVL panels in static bending tests. Some studies obtained results in which the strength and stiffness were higher for the *flatwise* position, although this trend was not observed in all the panels produced. Iwakiri et al. (2010) and Iwakiri et al. (2016) found superior strength results for the *edgewise* position, even though in certain compositions, the *flatwise* position was superior. Berger et al. (2018) tested the influence of the veneers position of *Corymbia citriodora* and *Hovenia dulcis* on LVL panels and found very similar flexural strength values for both positions *flatwise* and *edgewise*.

For the *edgewise* MOE, the values ranged from 3380.47 to 4068.83 MPa. These results were close to those obtained by Buligon et al. (2015), working with LVL panels of *Pinus elliottii* (4257.75 MPa). On the other hand, Berger et al. (2018) found MOE values ranging from 9214 to 14928 MPa for LVL panels produced with *Corymbia citriodora* and *Hovenia dulcis*. The higher values obtained by the authors were probably due to the higher wood density of the *Corymbia citriodora* (0.898 g.cm^{-3}) while the *Hevea brasiliensis* had a density 0.550 g.cm^{-3}. For *edgewise* MOR, the values ranged from 182.14 to 246.42 MPa. These values were higher than those found by Müller et al. (2015), studying LVL panels composed of *Eucalyptus saligna* and *Pinus taeda*, finding mean values varying between 94 and 132 MPa. However, the presence of the non-horizontal skins in the *edgewise* position prevented premature failure and made the composite sandwich beams fail in ductile failure mode (Manalo et al., 2010).

For the *flatwise* MOE, the values varied between 7729.67 and 9744.80 MPa, which were lower than those observed by Guimarães Júnior et al. (2015), with values ranging from 1,0408.6 to 12,558.2 MPa studying LVL panels produced with five clones of *Eucalyptus urophylla* wood. However, the results were higher than those observed by Lima et al. (2013), studying the mechanical properties of LVL panels from Amazonian species and obtaining MOE in the *flatwise* ranging from 4739.88 to 5473.85 MPa. For the *flatwise* MOR, the values ranged from 64.99 to 101.88 MPa. Values similar to the present study were obtained by Buligon et al. (2015), who found a 76.09 MPa for MOR in the *flatwise* position.

CONCLUSIONS

LVL panels were produced with different grammages in order to save adhesive and use a formaldehyde-free type of binder, as polyurethane. The variation in grammages, the effectiveness of non-destructive tests on the panel veneers and the mechanical properties of the panels has been presented. An increase in the grammage in the glue line caused a reduction in the volumetric swelling of the panels, being 32.53% for the resorcinol formaldehyde adhesive and 21.42% for the polyurethane adhesive. The shear tests under dry, wet and post-boiling conditions were not influenced by the different grammages of the compositions for the same type of adhesive; however, the panels produced with polyurethane had the highest mean values under the three test conditions. The percentage of wood failure was higher for the polyurethane adhesive, with mean value 100% for the dry condition of shear strength. The three grammages evaluated showed good adhesive-wood anchorage. The highest mean MOR values were obtained in the *edgewise* condition and that for the MOE was obtained in the *flatwise* condition. The panels with lower grammage values had the highest mean volumetric swelling for the LVLs studied. In contrast, a reduction in grammage did not affect the shear strength of the glue line or the stiffness of the beams. Therefore, LVL panels produced with *Hevea brasiliensis* wood with grammage 240 g.m^{-2} are suitable for saving adhesive and reduce the release of formaldehyde to the atmosphere.

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